STRUCTURES & MATERIALS • ENVIRONMENTAL QUALITY SYSTEMS

NAVSEA
NAVAL SEA SYSTEMS COMMAND

NAVAL SURFACE WARFARE CENTER

CARDEROCK DIVISION

TECHNICAL DIGEST

DECEMBER 2001

SIGNATURES & SILENCING SYSTEMS • HULL FORMS & PROPULSORS

VULNERABILITY SURVIVABILITY SYSTEMS

DESIGN & INTEGRATION TECHNOLOGY • MACHINERY SYSTEMS & COMPONENTS

MISSION STATEMENT:

To provide research, development, test and evaluation, fleet support, and in-service engineering for surface and undersea vehicle hull, mechanical and electrical systems, and propulsors; provide logistics R&D; and provide support to the Maritime Administration and the maritime industry.

SIGNATURES & SILENCING SYSTEMS

HULL FORMS & PROPULSORS

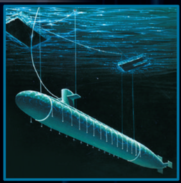
MACHINERY SYSTEMS & COMPONENTS

STRUCTURES & MATERIALS

VULNERABILITY SURVIVABILITY SYSTEMS

ENVIRONMENTAL QUALITY SYSTEMS

DESIGN & INTEGRATION TECHNOLOGIES







NAVSEA NAVAL SEA SYSTEMS COMMAND

CARDEROCK — 00/CT02

DECEMBER 2001

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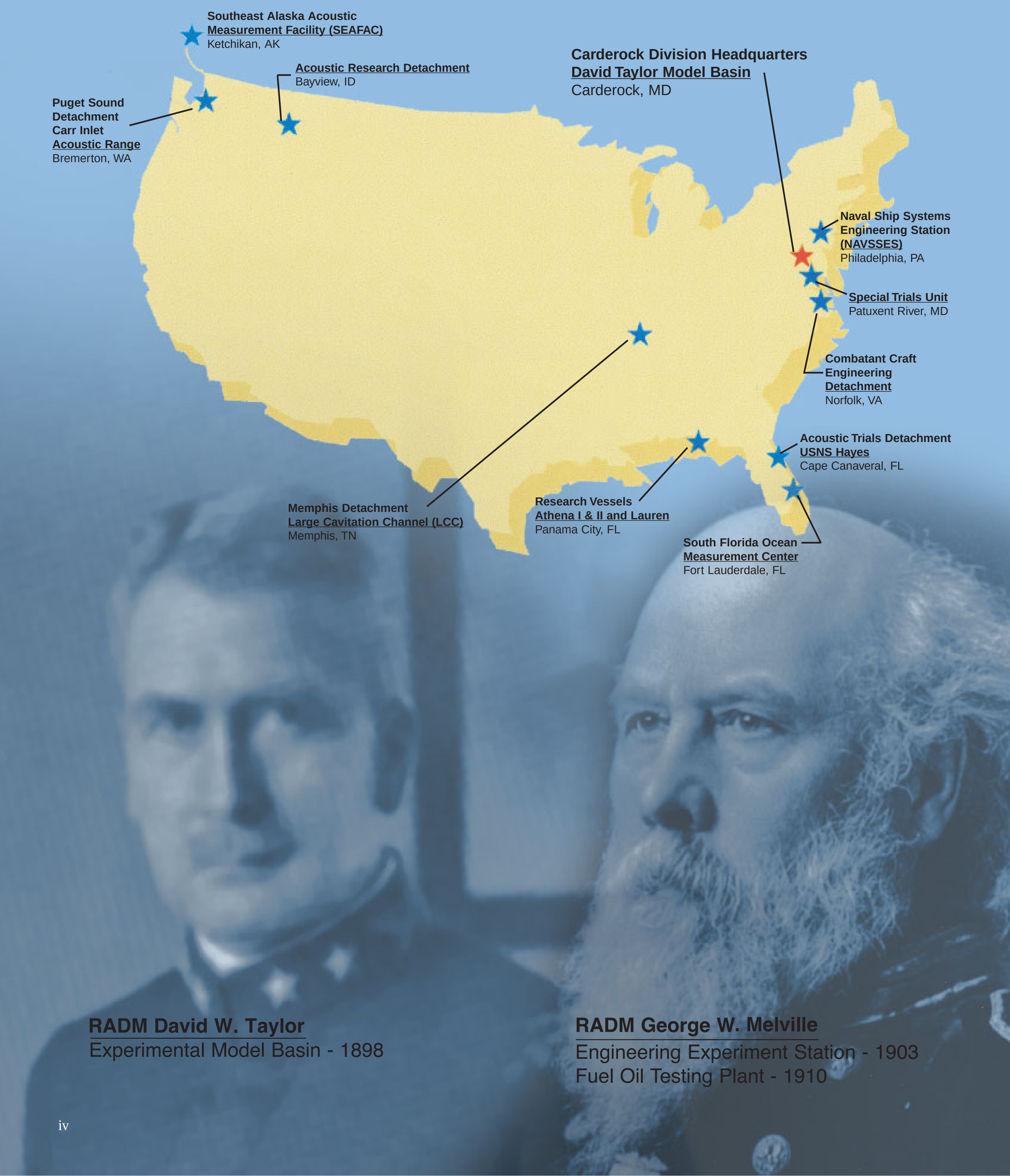


RADM David W. Taylor
Experimental Model Basin - 1898

RADM George W. Melville
Engineering Experiment Station - 1903
Fuel Oil Testing Plant - 1910

Steven W. Petri, Capt., USN
Commander
Carderock Division
Naval Surface Warfare Center

James A. Fein
Executive Director
Carderock Division
Naval Surface Warfare Center

Foreword

For more than one hundred years, the world renowned facilities and dedicated scientists and engineers of the Carderock Division, Naval Surface Warfare Center have served the Navy, the Maritime Industry, and the Nation. From humble, turn-of-the-century beginnings as an Experimental Model Basin at the Washington Navy Yard, an Engineering Experiment Station in Annapolis, and a Fuel Oil Testing Plant in Philadelphia, the Division has emerged to provide technical leadership for hull, mechanical, and electrical systems, and logistics R&D for surface ships and submarines encompassing *keel to masthead and cradle to grave*. Our unique facilities now stretch from Ketchikan, Alaska to Fort Lauderdale, Florida. With the addition, over time, of four research vessels and eight measurement and trials detachments, the Division has truly become full-spectrum, linking science and engineering in research, design, acquisition, testing, and operational support for the Fleet.

Today's modern ships and submarines are complex systems called upon to operate in a highly sophisticated environment with demanding requirements. Their design requires not only in-depth knowledge and skills in each of the particular ship design disciplines but a breath of knowledge spanning related areas of expertise; what has become commonly referred to as *Systems* or *Design Integration*. The design of a ship's hull form or propulsor demands expertise in hydrodynamics if desired efficiencies, speed, and payload are to be achieved. But, the hull, propulsor, control surfaces, and appendages cannot be treated as separated entities; they must be "matched" to each other and to other ship characteristics in a single synergistic solution. Furthermore, the application of hydrodynamics alone does not meet the challenge of today's platforms. Vulnerability, survivability, affordability, and supportability requirements demand the application of skills in materials, structures, signatures and silencing, cost and military effectiveness analysis, manufacturing technology, logistics and life-cycle support analysis, and a host of other capabilities; technical capabilities for which the Division provides stewardship for both the Navy and the Nation.

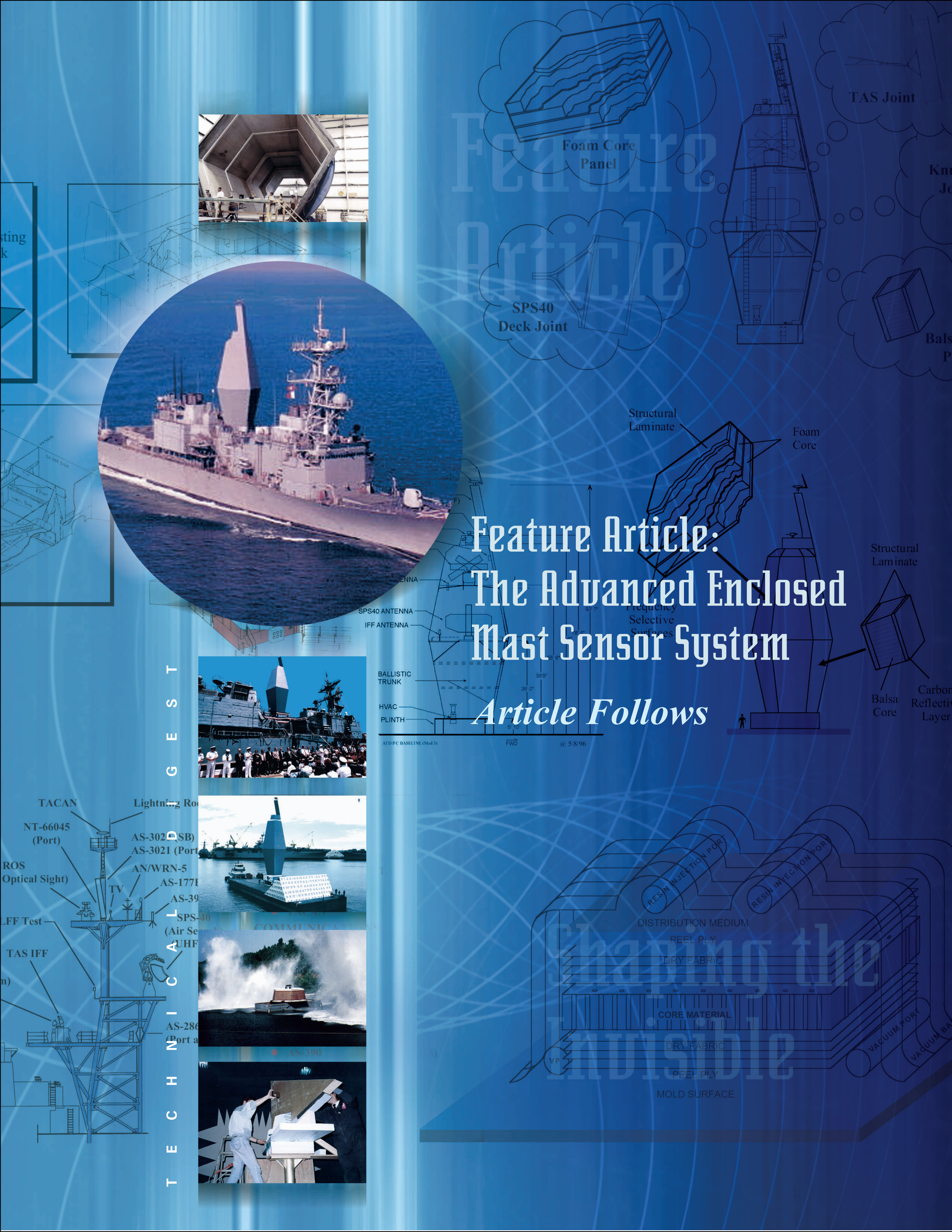
Our feature article on *The Advanced Enclosed Mast System* is a premier example of multi-disciplinary design integration. The technical depth of the interdisciplinary Navy/Industry team combined with the successful application of systems integration and concurrent engineering concepts to optimize the competing "design-space" demands of structures, materials, signatures, electromagnetics, and manufacturing has enabled the Navy to take a major step toward revolutionizing the topside design of future combatants.

The tragic events of September 11th, and the resultant war on terrorism, have clearly demonstrated the need for a strong and flexible military; one with a decisive technological superiority. In this Technical Digest we have brought together a compendium of recent projects, programs, and demonstrations across all seven of the Division's core areas of expertise. The technological accomplishments illustrate some of our contributions to the greatest Fleet in the world. We did not ask to fight a war on terrorism but when the war came to us we were prepared. The Carderock Division, like its counterparts throughout the country, is contributing its share of support to this battle. Some of our work this past year reflects these efforts. Our specialists in survivability, structures, and materials have supported the Naval Sea Systems Command with the USS COLE, including extensive inspection and analysis of the ship's damaged hull and equipment. Our efforts generated technical recommendations to improve survivability for the DDG and other classes of Navy ships. In addition, our Combatant Craft Department has supported acquisition of and modifications to appropriate watercraft for deploying ships to increase anti-terrorism force protection capabilities. Representatives of the Division's Survivability and Weapons Effects Department also helped install the Carderock Division-designed Threat Containment Units (TCU) at several of the nation's airports (see the article on *Commercial Aircraft Hardening*). The TCU is designed for use with explosive detection equipment deployed at airports for screening passenger luggage. It provides safe storage and transport of a suspected explosive device away from the terminal with minimal impact on airport operations.

Collectively and individually the papers presented in the Technical Digest demonstrate the Division's commitment to work with other Navy and government organizations, as well as industry and the university community to develop integrated solutions to the Navy's and the Nation's requirements and to the bridge the gap from *Research to Reality*.

Feature Article: The Advanced Enclosed Mast Sensor System

Article Follows



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Shaping the
Invisible

The Advanced Enclosed Mast Sensor System: Changing U.S. Navy Ship Topsides for the 21st Century

Eugene T. Camponeschi, Jr. and Kevin M. Wilson

The Advanced Enclosed Mast Sensor (AEM/S) System is the Navy's newest mast concept and will soon change the look and performance of future Navy surface ships. Developed under an Office of Naval Research (ONR) Advanced Technology Demonstration Program, the AEM/S System concept will reduce the ship's signature, improve its combat system and communication sensor system performance, and reduce its life-cycle maintenance costs. The interdisciplinary team from the Navy and industry met significant technical challenges in the areas of systems engineering, composite materials and structures, signatures, electromagnetics, integrated sensors, and low-cost manufacturing. In addition, the team adopted and implemented an integrated systems approach, that led to the success of the program. The AEM/S System was installed on USS ARTHUR W. RADFORD (DD 968) and passed rigorous at-sea trials. The success of the program led to adoption of the concept for forward and aft masts on the 12 SAN ANTONIO (LPD 17)–Class ships. This paper demonstrates that overcoming multidisciplinary technology challenges and focusing on total systems engineering solutions will enable the Navy to achieve significant reductions in life-cycle costs and manning, and improve war-fighting effectiveness in future ships.

Introduction

The Advanced Enclosed Mast Sensor (AEM/S) System Advanced Technology Demonstration (ATD) was programmatically and technically successful. This development began with 6.2 science and technology (S&T) programs in the areas of materials, structures, signatures, and electromagnetics. The Office of Naval Research (ONR) ATD integrated critical technologies, which had been advanced in the 6.2 S&T programs and enabled their successful transition to a revolutionary mast system installed on a warship.

The AEM/S effort represents the work of a highly motivated integrated team of scientists, engineers, and managers that scoped, planned, and executed a series of tasks to address a number of significant technical challenges. While traditional ship topside design engineering focuses on antenna placement and antenna performance, this project focused on "integrated topside design" with a scope that fully included materials, structures, signatures, outfitting, safety, and manufacturing. Achievement of fully acceptable antenna performance was a significant requirement and, in fact, the AEM/S System provided improved sensor performance through reduced blockage and also offered reduced life-cycle costs. Achievement of this result had to be balanced against other design requirements to realize greater overall performance of the ship.

An example of the complex technological challenges is seen in the trade-off between antenna performance and structural integrity. Stiff fibers and thick structural skins were desired for the complex hybrid composite sandwich panels to achieve optimum structural performance. Contrary to these desires, the antenna performance stakeholders wanted fibers with optimum dielectric properties and thinner sandwich panel skins to maximize the transmission of own-ship electromagnetic energy.

Communication among the MASTers, as the team members came to be called, was facilitated by extensive use of e-mail and video teleconferencing. Their operational style and active intercommunication greatly facilitated concurrent engineering. This proved to be extremely effective, and is being followed in other complex projects such as the *Low-Observable Multifunction Stack*, also covered in this Digest, and the ONR DDG 51 Helicopter Hangar Project.

System Design Drivers

The emergence of the AEM/S System concept began with the definition of its engineering requirements, which presented new challenges for this oddly shaped ship topside structure. In some areas, traditional design requirements were not available, or ship specifications were not applicable, so the MASTers relied on first principles to develop goals and requirements. For example, the structural requirements that guided design did not fully reflect ship deckhouse design requirements or traditional mast requirements, but a combination of both.

The SPRUANCE–Class destroyer, USS ARTHUR W. RADFORD (DD 968), ultimately chosen as the platform for full-scale at-sea trials and her combat and communications systems, dictated most requirements. Commissioned in 1975, she is 564 ft long with a displacement of approximately 9300 tons. She had two aluminum truss-style "stick" masts. The aft (main) mast, (Figure 1), was selected to be replaced by the AEM/S System. The footprint of the original mast was retained resulting in the inwardly tapered lower section of the enclosed composite structure that was joined to an aluminum "plinth" that acted as an interface with the main deck. Figure 2 shows this arrangement.

The AEM/S System structure, (Figure 3), is approximately 95 ft tall and 30 ft wide at its midsection. Weighing some 40 tons, it is the largest composite topside structure aboard a U.S. Navy ship. The hexagonal, bi-pyramidal shape was selected in a multidisciplinary trade-space that balanced signatures with electromagnetics (EM) and structural performance. It is made of upper and lower halves joined at the midsection with a bolted and bonded structural joint. The lower half of the mast is constructed of E-glass/vinyl-ester skins with a balsa core and a reflective, carbon-graphite ground plane. Its primary function is to serve as the structural support for the upper half. The upper half is an inward sloping, load-bearing structure designed and fabricated as a frequency-selective surface (FSS) radome. It is constructed using E-glass/vinyl-ester

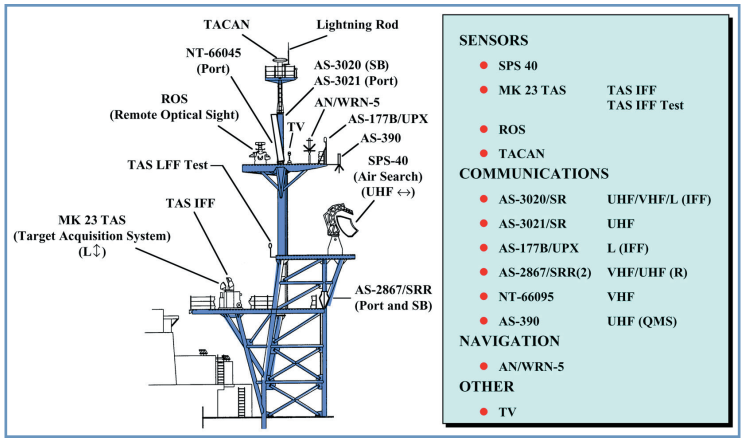

Figure 1. DD 968 main stick mast.

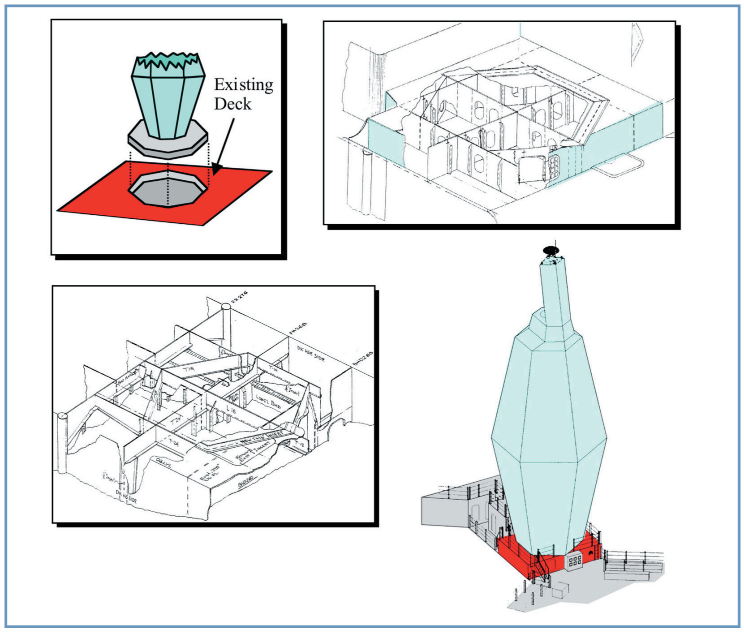

Figure 2. Mast/Ship interface.

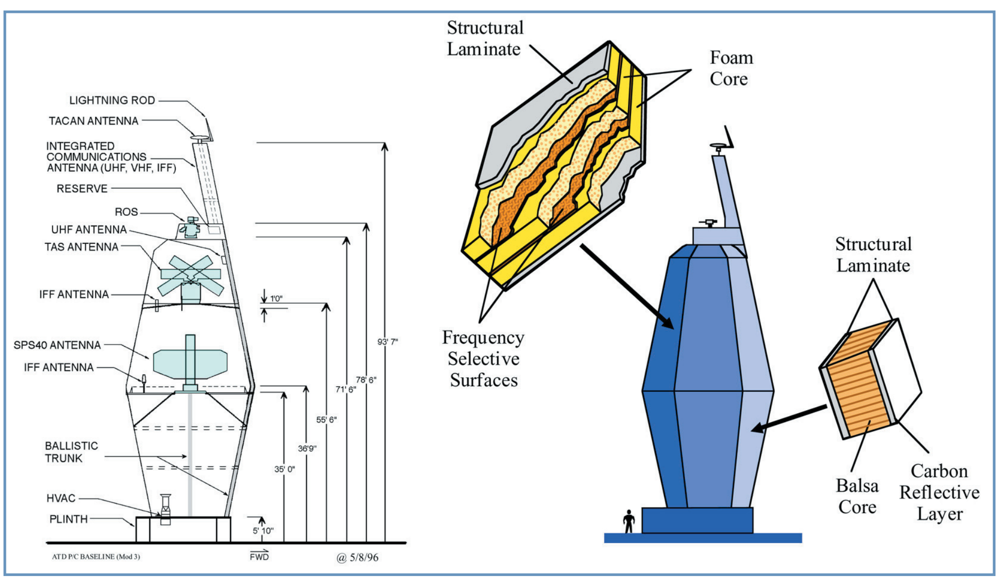

Figure 3. The AEM/S System with tailored material systems.

skins, circuit boards etched with anchor-shaped FSS elements and a structural foam core. It is transparent to the energy of the enclosed radars while being reflective to threat radars. This portion of the mast houses the SPS-40 and Mk-23 Target Acquisition System (TAS) radars and an identification friend or foe (IFF) antenna. An FSS stub mast, using the same FSS material system as the upper half of the mast, encloses additional VHF and UHF communications antennas. The AEM/S System was designed for a service life of 30 years, and the combat structural loading requirements included resistance to nuclear air blast and underwater shock, as well as ballistic protection.

Requirements and goals that were not originally part of the RADFORD design were laid out for the ATD to demonstrate the benefits that this concept provided for future ship operational performance. These included improved warfighting capability due to reductions in sensor blockage, false targets, and downtime; reduced life-cycle costs by having systems protected from adverse weather; and enhanced sustainability and maintenance in rough seas by allowing sailors to go aloft under conditions when such access would normally not be permitted.

Technology Challenges

A concurrent engineering process was required to address the technical challenge of this project. An integrated process team (IPT), which relied on "consensus-based management," was adopted by the AEM/S System Program Manager to execute the required concurrent engineering process. The team included personnel from ONR; NAVSEA; NSWCCD; SPAWAR Systems Center, San Diego; NRL; Ingalls Shipbuilding; Mission Research Corporation; Materials Science Corporation; Ohio State University; and Analysis & Technology. All MASTers were cross-educated in the requirements and technology issues confronting other members of the team, and each understood the importance of trade-offs, which needed to be made to yield a successful design.

Signatures

The AEM/S System provided clear benefits to the signatures area due to its "clean" design. On the other hand, it presented significant challenges due to the frequency-selective nature of the radome when combined with the geometry of the structure. The cavity formed by the large FSS radome was identified as a potential scattering source, which, at the time of development, was not supported by either of the predictive models used in its design and analysis - the Radar Target Strength (RTS) code or submillimeter wave-based physical scale modeling. Furthermore, the physical optics/physical theory of diffraction-based RTS code had limitations in predicting surface traveling wave phenomena that might be present in the large, faceted mast structure.

Other challenges in the signatures area were uncovered in IPT meetings when Ingalls Shipbuilding identified "fabrication artifacts" that would result from the Seemann Composite Resin Infusion Molding Process (SCRIMP)® (Figure 4). Ingalls went to great lengths to experiment with the fabrication design to minimize these artifacts, but since neither RTS nor submillimeter wave modeling could be expected to characterize the impact of these features, full-scale panel, edge, and joint components were fabricated and measured in the NRL compact range RCS measurement facility, (Figure 5).

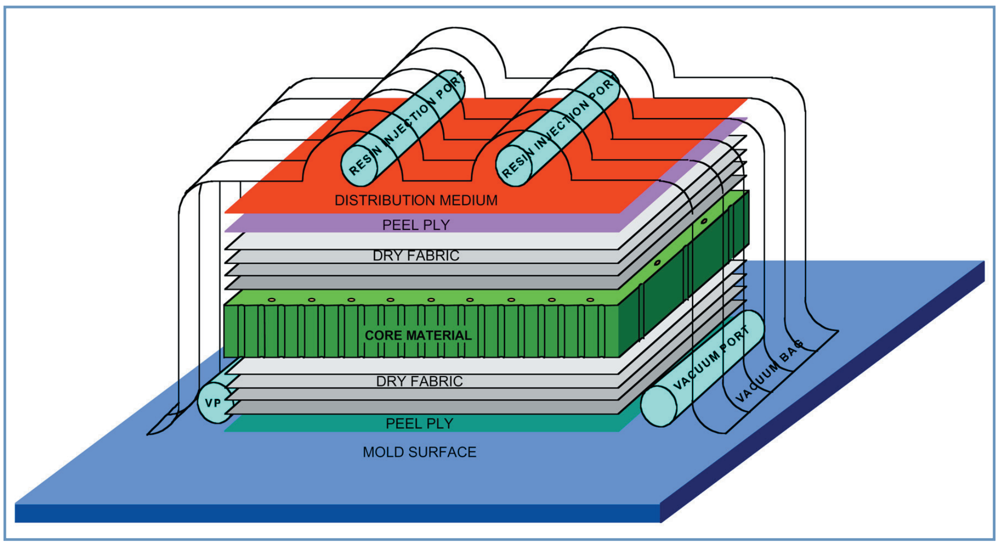

Figure 4. The Seemann composite resin infusion molding process (SCRIMP).

Figure 5. Signature testing of corner test article.

SCRIMP® is currently a registered trade mark of TPI, Warren, Rhode Island (formerly a trade name of Seemann Composites, Gulfport, Mississippi).

Signatures efforts culminated in the design, construction, and RCS measurement of a full-scale at-sea test article that would eventually be installed on RADFORD. Measurement of the large, low-observable mast in the requisite at-sea, multipath conditions demanded considerable innovation. An off-shore barge with the variable-speed, turntable-mounted composite mast and a clutter fence, (Figure 6), were combined with the NSWCCD Radar Imaging and Modeling System (RIMS) to provide total RCS and diagnostic imaging data to identify and analyze scattering sources. The resulting measurement, while identifying new and unexpected sources of scattering, confirmed that the AEM/S System would meet its RCS goals.

Structures

Structural design concepts and the hybrid composite materials used in them had to accommodate the low-cost manufacturing concepts being explored. Fibers and resins that offered the best structural characteristics were not the lowest cost materials available. Underwater shock, air-blast, vibration, overall stiffness, joint structural integrity, and fatigue throughout the life-cycle were a few of the major structural issues that needed to be addressed. In the absence of Navy-approved design methods for this new structural concept, comprehensive analysis and testing were necessary in order to demonstrate that the design met the stated requirements. The design concept and the associated margins of safety were confirmed through static and dynamic tests that ranged from the coupon level to the full-scale component level. Figure 7 shows the full-scale underwater explosion test that confirmed the structural integrity of the TAS platform and the joints that connected it to the structural sidewalls.

Materials

Challenges in the materials area included the verification that fibers, resins, core materials, and adhesives were compatible with each other and with the SCRIMP process while meeting temperature, moisture, long-term durability, cost, structural performance, and EM performance requirements. While each of these requirements could be considered challenging, when combined they presented trade-offs that sometimes seemed insurmountable. Unanticipated issues, such as excess penetration of resin into the structural core during the SCRIMP process, resulted in unacceptable excess weight and were addressed through rigorous experiments that yielded solutions practical enough for shipyard implementation.

Manufacturing and Nondestructive Testing

Significant challenges lay in the manufacturing area. A process to fabricate repeatable, high-quality, load-bearing components also needed to be affordable, adaptable to large-scale production, and compatible with the shipbuilding environment. The SCRIMP process was successfully demonstrated in ONR 6.2 structural composite projects, but had never been used on a structure as large as the AEM/S System, nor had it been used by Ingalls Shipbuilding. However, the engineers and technicians at Ingalls became experts in the SCRIMP process and were innovative in overcoming many production challenges. They modified it to eliminate undesirable fabrication artifacts and designed a rotating full-round-mold fixture, show in Figure 8. The fixture allowed the mast structure to be

Figure 6. Mast on barge for RCS measurements.

Figure 7. Target Acquisition System platform shock test.

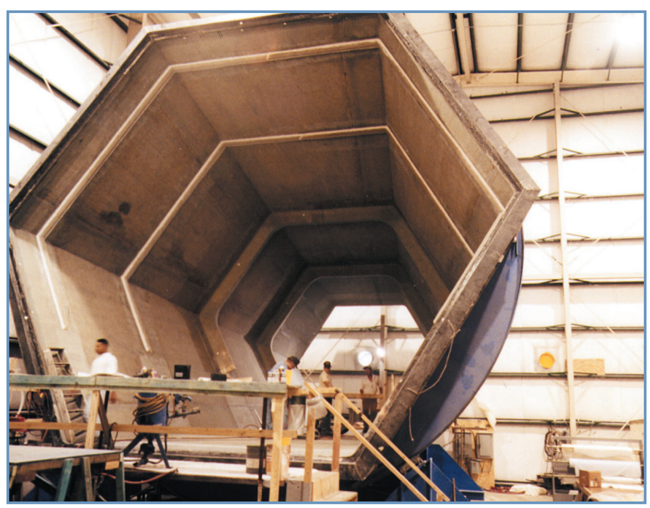

Figure 8. Rotating full-round-mold fixture.

turned during construction and permitted fabrication of each face and its associated joints in a down-hand fabrication process. They also devised a "liftable building" (Figure 9), to allow fabrication in a controlled environment and easy, post-fabrication handling of each full-size half of the mast. Hand-in-hand with the manufacturing challenges were nondestructive evaluation (NDE), (Figure 10), and flaw criticality challenges. The multilayered composite structure, with thousands of square feet of surface, needed to be inspected and anomalies needed to be detected and corrected. Structural analysis methods were used to develop the detailed inspection and repair criteria employed for the final AEM/S System.

Electromagnetics

The area of electromagnetics provided the challenge to design and demonstrate a cost-effective, manufacturing-friendly, and durable structural radome to meet the demanding performance requirements of the radars and communication antennas that would be enclosed. This required developing a hybrid composite structural radome within a design space that included FSS patterns, structural foams, adhesives, fibers, and resins to optimize antenna performance. The research and development performed by the electromagnetic experts was conducted in close collaboration with other experts on the team. For instance, the effect of manufacturing tolerances and the effect of moisture on material electrical properties were analyzed closely and assessed as part of the engineering development.

Radome design and analysis was performed using the Periodic Method-of-Moments (PMM) code. Tests on individual materials, radome component layers, full-thickness radome panels, and a full-scale EM radome were performed. The tests validated the electromagnetic characteristics and assured the critical radar performance requisite prior to installation on RADFORD.

In addition to the successful radome design, advances were made in predicting the performance of antennas enclosed in FSS radomes. Necessary algorithms were developed and implemented in the Numerical Electromagnetic Basic Scattering Code (NEC-BSC). Performance predictions were validated with scale-model and full-scale measurements.

A high-frequency (HF) antenna was designed based on an embedded, shared-aperture concept to achieve improved performance, reduce radiation hazards, and reduce signature. The HF antenna design was validated using a 1/48th-scale brass model of the DD 963–Class with the AEM/S System on board, and through full-scale tests during a temporary test installation prior to stepping of the mast on RADFORD.

Final validation of performance and electromagnetic compatibility for all antennas enclosed in the mast was made by full-scale shipboard tests on RADFORD.

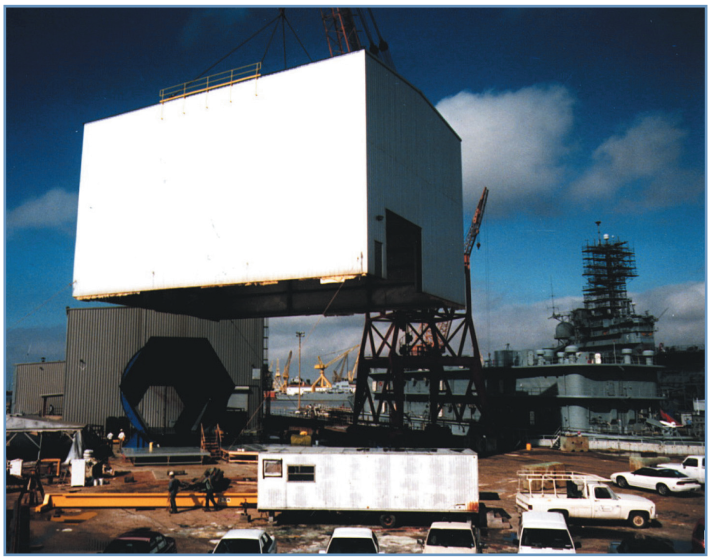

Figure 9. Liftable building.

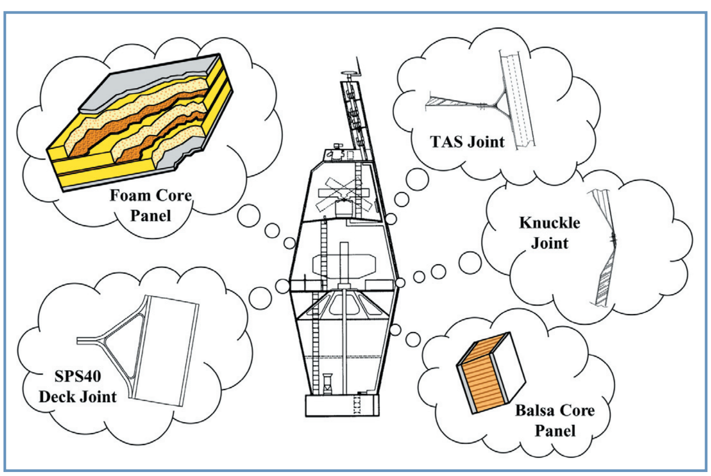

Figure 10. Critical areas for nondestructive evaluation.

System Integration

Each of the above technology areas presented a significant challenge and subsequent risk to the success of the ATD. When combined, they introduced the potential for, at best, technologists vying for design space and, at worst, no common solution space. While the many first-time implementations of materials and predictive tools forced focus within specific technology areas, system integration was key to the success of the AEM/S System. The structural, EM, signatures, and materials experts had to work hand-in-hand starting with what would normally be independent concept development during the 6.2 applied research stage. The resulting system integration team addressed all features starting from the plinth at the foot of the mast up to the TACAN at the top of the stub mast, with no greater example than that of the FSS radome design.

The FSS radome system integration trade space might well be judged initially as overconstrained. Structural requirements alone included loads resulting from nuclear blast overpressure, seaway motions and shock, and vibration specifications. EM performance requirements were significant from the perspective that the radome must not degrade the in-band transmissions of the enclosed radars in any consequential way while providing the advantage of reduced sensor blockage. RCS goals had particular influence on the shape of the structure and the out-of-band FSS performance. While many of these constraints would traditionally be independent, the system integration required for the mast established a highly complex series of relationships that were not obvious initially. Weight and cost rounded out the initial set of realities that the AEM/S System conceptual design had to solve.

The hexagonal cross-section of the radome was selected in a balance between structures, signatures, and EM performance. A series of concurrent parametric analyses was performed to assess the impact of the number of sides on the figures of merit in each technology area. For a given enclosed volume, in this case the size of the enclosed radars, an infinite-sided (circular) cross-section resulted in minimized weight and stress concentration. A circular cross-section also yielded excellent EM performance with existing spherical radomes providing the precedent. However, a reflective circular cross-section also resulted in the worst RCS. Immediate payoffs in reduced RCS were found in faceted shapes with the fewest sides being best (three resulting in a triangular cross-section). However, the triangular cross-section yielded a very heavy structure with poor expectations for EM performance when the radars were required to look into the acute corners of the radome. The final examination of these design trade-offs resulted in selection of the hexagonal shape.

The shape of the AEM/S System was a significant, but very basic, determination in the overall system integration process - it was just the beginning. At this stage, the materials technology area became a critical member of the trade space in the search for a viable design. Variables within the through-thickness of the radome included skin and core thickness, as well as their respective structural and EM properties. This balance determined the viability of the radome under structural loads, the EM performance, and, to a lesser extent, signatures. The structural design space was defined and provided to the EM designers to assess whether a radome design with acceptable (as opposed to optimal) performance existed concurrently. Performance predictions were made even while the design tools were being validated and the system integration spiral closed to yield a structural design with acceptable EM performance.

The FSS design trade space included the number of FSS layers within the radome through-thickness. Again, in-band and out-of-band performance predictions were made to evaluate FSS element shape, pattern spacing, layer-to-layer through-thickness spacing, and the number of layers. No signatures performance tool existed for evaluating the FSS performance and, as such, first principles techniques were applied to estimate the impact on total system RCS. The number of FSS layers in the radome design also impacted fabrication complexity with subsequent ramifications on structural integrity and cost. Again, these parameters were analyzed and balanced with the result being the relatively simple two-layer FSS design that was used in the mast.

As the effort transitioned from 6.2 to the 6.3 ATD, the primary system integration decisions for the radome had been made, but additional levels of integration were required. In particular, fabrication technology challenges now had to be considered along with structural, signatures, EM, and materials design issues. Many of the early, 6.2 conceptual design features assumed isotropic materials and perfect geometry. However, real world fabrication techniques that could be applied in a shipyard environment were critical to achieve cost goals. These techniques included the SCRIMP process, where resin is pulled through the structural preform using a vacuum. As such, a variety of small passages in the core material were required to adequately distribute the resin throughout the radome. The resin distribution passages would remain resin-filled after fabrication and, from an EM and signatures perspective, become permanent discontinuities in the otherwise isotropic dielectric structure of the radome. Few analysis tools were available. Radome components were fabricated and measured to evaluate alternate fabrication designs, quantify the impact on EM performance and signatures, and define the trade space. Many innovative fabrication techniques were conceived, implemented, and tested, eventually leading to a fabrication design that was validated for materials compatibility and structural, EM, and signatures performance.

Additional details were added to the system integration mixture while the fabrication design was maturing. The details included platforms to support the radars and a ballistic trunk for the associated wave-guides and wiring. These features had negligible impact on signatures because they were enclosed within the FSS radome. However, the balance between structural integrity, EM performance, materials, fabrication design, cost, and weight significantly challenged the available trade space. The platforms and ballistic trunk were of particular concern with respect to EM performance, because the reduced sensor blockage benefits of the AEM/S System could easily be outweighed by increased radar side lobes resulting from energy interacting with these structures. Again, concurrent analyses and testing were performed on sub-optimal designs (for any single technology) that led to a design that was sufficient (for all technologies).

Other Technology Challenges

The examples noted above are only a sample of the numerous and varied technological challenges faced by the MASTers, (Figure 11). However, they provide insight into the complex, interdisciplinary, systems integration approach that was needed to develop, assess, and trade-off the technologies required to meet program objectives. Other significant challenges faced by the engineering team

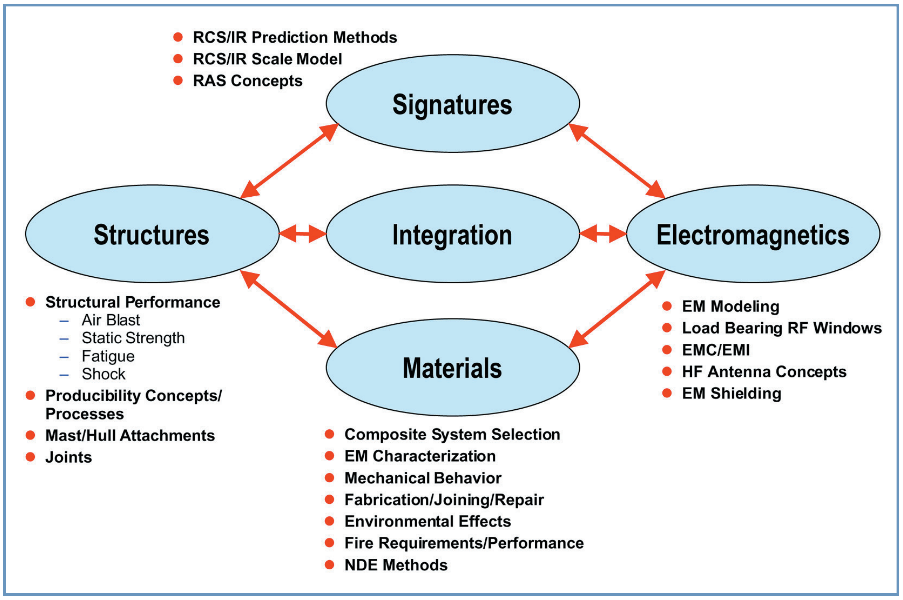

Figure 11. Supporting technologies.

included lightning protection, electrical bonding and grounding, personnel access and safety, fire safety, and flight-deck certification for helicopter operations. While seemingly mundane when compared with the primary technology areas, the MASTers recognized quickly that solutions must be developed if the mast was to be allowed on RADFORD, let alone ships of the future.

Concept Demonstration and Transition

The many engineering trade-offs that were debated, and eventually validated through analysis and testing, coalesced into the final configuration. The culmination of the ATD was the stepping of the mast on RADFORD in a formal ceremony on 17 May 1997. During this ceremony the entire project team became RADFORD "shipmates."

The AEM/S System officially was put to the test during the 1-year at-sea deployment of RADFORD that began in October 1997, (Figure 12).

While the ATD plan allowed for the contingency to remove the AEM/S System from RADFORD, at-sea tests were so successful that VADM Henry C. Giffin III, Commander, Naval Surface Force, U.S. Atlantic Fleet, relayed the following message on 11 May 1998.

"The Advanced Enclosed Mast/Sensor System installed on board USS RADFORD has performed beyond expectation. CNSL desires to leave the AEMS/S System on board RADFORD for the remainder of this ship's service life. This confirms ref.a. Well done to all MASTers".

From the early stages of the ATD the project team monitored on-going and emerging ship acquisition programs that might offer an opportunity to transition this new concept into the Fleet. At the beginning of the ATD, the SC 21, later to become DD (X), was considered a potential opportunity for such transition. However, an earlier opportunity emerged in the Landing Platform Dock (LPD 17) acquisition.

In early 1996, the MASTers showed the LPD 17 Program Office how the advantages of the AEM/S System concept could help meet signature and other requirements of the LPD 17–Class. Encouraged by the interest shown by the program office and recognizing major differences in the requirements for the LPD 17 relative to RADFORD, the MASTers developed a risk mitigation plan detailing the engineering steps to make the transition.

Under the sponsorship of ONR, NAVSEA, and SPAWAR, the next-generation AEM/S System program was initiated in October of 1996, to develop and demonstrate the engineering design details necessary to meet LPD 17 mission requirements. This project, like the ATD, was composed of an interdisciplinary team from industry and the Navy. A major objective was to provide the LPD 17 industry alliance with the knowledge, details, and confidence to

Figure 12. USS ARTHUR W. RADFORD (DD 968) underway.

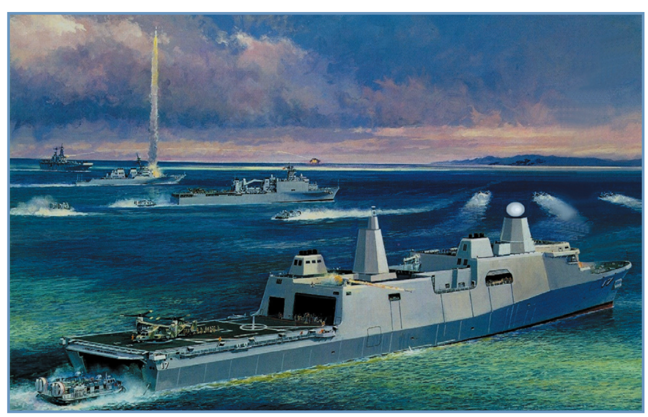

Figure 13. LPD 17 Landing Platform Dock with AEM/S System.

embark on the detailed design and production of two AEM/S Systems to serve as the fore and aft masts for the lead ship of the LPD 17–Class, (Figure 13). This objective was met successfully in February 1999, when PMS 317 approved the Avondale Alliance field modification request (FMR 120), marking the initiation of the engineering design and manufacturing production process for the AEM/S Systems for LPD 17. Manufacturing of the first LPD 17 AEM/S System components began on 23 March 2000.

Summary

Technologies, which are part of NSWCCD core programs such as composite materials and structures, signature control, ship survivability, and low-cost composite manufacturing, became cornerstones of the engineering concept that developed into the AEM/S System. Through a consensus-based IPT approach, the industry and Navy team focused their enthusiasm, talents, and energy on a common goal. The approach and resulting team and goal led to the successful demonstration of the AEM/S System on RADFORD, and the decision to install this concept on the LPD 17–Class. It will forever change the way future U.S. Navy surface ships are designed and constructed to enhance their war-fighting effectiveness.

Acknowledgments

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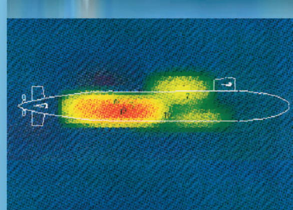
Kevin M. Wilson *earned a B.S. degree in mechanical engineering at the Virginia Polytechnic Institute. He was the Signatures "master" for the AEM/S ATD which subsequently lead to receipt of the group award of the Dr. Arthur W. Bisson Prize for Naval Technology Achievement sponsored by the Chief of Naval Research.*

Silencing

Signatures and Silencing Systems

Overview Article Follows



Signatures

TECHNICAL DIGEST

S I G N A T U R E S & S I L E N C I N G S Y S T E M S

The people and facilities represent the Navy and the nation's capability to develop technologies and methodologies to reduce ship (including submarine, unmanned vehicle, and craft) signatures. Silencing products are the development of silencing requirements, silencing technology, materials, equipment and systems necessary to ensure that all Navy ships have the lowest possible acoustic, radar, infrared, electro-optical and magnetic signatures that are cost effective and compatible with the ship's mission. In their application, the products reduce the signature(s) at its source, reduce the signature(s) before it is radiated, and/or impede the return of threat sensor energy to its source.

Signatures and Silencing Systems: An Overview

Brian E. Bowers and James H. King

This paper identifies and discusses the entire panoply of signatures that arise from the presence of a vessel on or below the ocean, and their significance in terms of operational performance. The physical ship-design features contributing to various signature characteristics and levels are presented and their relative significance discussed (within classification constraints). The record of ship silencing and signature performance advancement since the 1960s is reviewed. Major signature reduction technology development drivers are identified. The technical papers in this core equity area are introduced and related to current and future technology development. A strategy to achieve and maintain U.S. Navy ship signature advantage in the presence of budgetary and other challenges is offered.

Introduction

A primary NSWCCD mission since WWII has been to promote, through technology development and performance evaluation, achievement of U. S. naval surface ship and submarine signature control that will ensure operational superiority. The Division collects signatures on all pertinent Fleet assets and conducts research, development, test, and evaluation (RDT&E) in all aspects of ship signatures and signature control. Historically, NSWCCD supports the Naval Sea Systems Command (NAVSEA) in the successful development and implementation of signature control and silencing technology in all major combatants and support ships. The content of this paper is limited by virtue of the fact that all information must be at the unclassified level.

Operational stealth can be considered a measure of the ability of a ship (surface ship, submarine, or other naval vehicle) to operate undetected against specific threats in designated mission areas. It is highly desirable for ships to embark on assigned missions with a degree of stealth that provides a necessarily low level of vulnerability to detection, classification, and localization by threat sensors.

A ship's stealth is controlled not only by its own signatures, but equally by the capabilities of threats that take advantage of and exploit the ship's signature characteristics. Consequently, while advances in silencing and signature reduction improve a ship's stealth, advances in threat capabilities reduce the ability of a ship to operate undetected (i.e., reduce the ship's level of stealth). It has been the nature of ship design, accelerated in the late 20th century, to require progressive signature improvement to maintain an acceptable level of stealth.

Generally, signatures can originate passively (and be detected by passive threat systems) from sources onboard, and actively as a result of scattered directed sound (sonar ping) or radar energy, against moving and stationary ships. All of a ship's individual signatures are related to its operational stealth. As the weakest links of a chain control the chain's utility, so a ship's operational stealth is controlled by the progression of most observable/detectable signatures. The threat migrates to the stealth vulnerability.

Signatures can be acoustic (propagation by mechanical vibration of physical particles), electromagnetic (EM) (propagation by periodic variations in electric and magnetic fields), or other observable entities that result from ship-design or ship-system components, singly and in combination, dynamic and static. Purposeful operational transmissions such as electrical/mechanical signal transmissions of communication, navigation, weapons launch and active emissions of radar and sonar are signatures that are detectable by threat sensors, but are not the focus here.

A variety of pertinent ship signatures are listed in Table 1. The table summarizes the signature characteristics, related sources and mechanisms, and the nominal upper limit of the distance (range) at which the signature may be detected by modern sensor technologies. Radiated noise (passively detected) and the sonar target echo (active detection) are both acoustic, and therefore can propagate great distances underwater. Much submarine silencing has been accomplished over the last several decades, so that current U.S. submarines are only marginally detectable under the best of circumstances. Many of the sources of radiated noise also negatively influence performance of own-ship sonar systems, in active and/or passive mode. Such sources often simultaneously contribute to the self-noise of hull-

Table 1. Principal sources and detection ranges of typical signatures (generalized).

Signature	Energy [Medium where signature is detectable], (Range of Wavelengths)	Examples of Source	Upper Limit of Detection Range
Radiated Noise	Acoustic [Water] ($\sim 10^{+3}$-10^{-2}m)	Propulsor; hull, appendage (structure, materials and shapes); hull and appendage openings; machinery excitation of hull.	Long range (100+ miles)
Sonar Target Echo (TS)	Acoustic [Water] ($\sim 10^{+3}$-10^{-3}m)	Hull system, superstructure, appendage materials and shapes; substructures.	Long range (100 miles)
Radar Target Echo (RCS)	EM [Surface, Air] (~50m-3cm)	Hull system, superstructure, appendage materials and shapes; substructures.	Long range (150 miles)
Infrared (IR) (Thermal Emissions)	EM [Surface, Air] ($\sim 10^{-3}$-10^{-6}m)	Hot stacks, vents, discharges; hull, appendage, equipment, and material thermal sources; thermal wakes.	Long range (50 miles)
Electro-Optical	EM [Surface, Air] ($\sim 10^{-5}$-10^{-7}m)	Hull system, superstructure, appendage material and shapes, and surface covering.	Long range (10 miles)
Electrical	EM [Water] (~25m, multiples of ~25m)	Electrical systems.	Short range (yds)
Magnetic Anomaly	EM [Water]	Local change in magnetic field (earth or deployed) due to ferrous ship materials.	Short range (yds)
Turbulent Wakes	Kinetic [Water]	Propulsor; turbulence from ship boundary layer and appendages.	Long (satellite) or short range
Bioluminescence	Biologic [Water]	Microorganism disturbances.	Short range (yds)
Bernoulli Pressure	Potential [Water]	Surface displacement and static pressure changes.	Long (satellite) or short range

mounted and towed sonar arrays, thereby reducing the range at which a threat can be detected.

The EM signatures (radar target echo, infrared, and electro-optical) shown in Table 1 are important because surface ships and surfaced submarines also can be detected by relatively remote threat sensors. Although the electrical and magnetic signatures generally require threat sensors to be in close proximity to the ship, these signatures are crucial because coastal regions offer relatively easy deployment of those sensors. As an example, the littorals provide an ideal environment for acoustic, magnetic, pressure, and electrical influence-activated weapons (mines).

Figure 1 illustrates and relates acoustic, radar, IR, and electro-optical signatures of submarines and surface ships to regions and design aspects of the ship that are most prominent in controlling those signatures. Various sources associated with these regions and design features have been demonstrated to control signature temporal, spectral, and spatial characteristics. Some acoustic quieting technology developed for submarines over the years has been applied successfully to surface ships. Figure 1 also presents general equations related to the detectability of radar, IR, and acoustic signatures by threat sensors. Properties of the ship, local sea environment, and threat target must be accounted

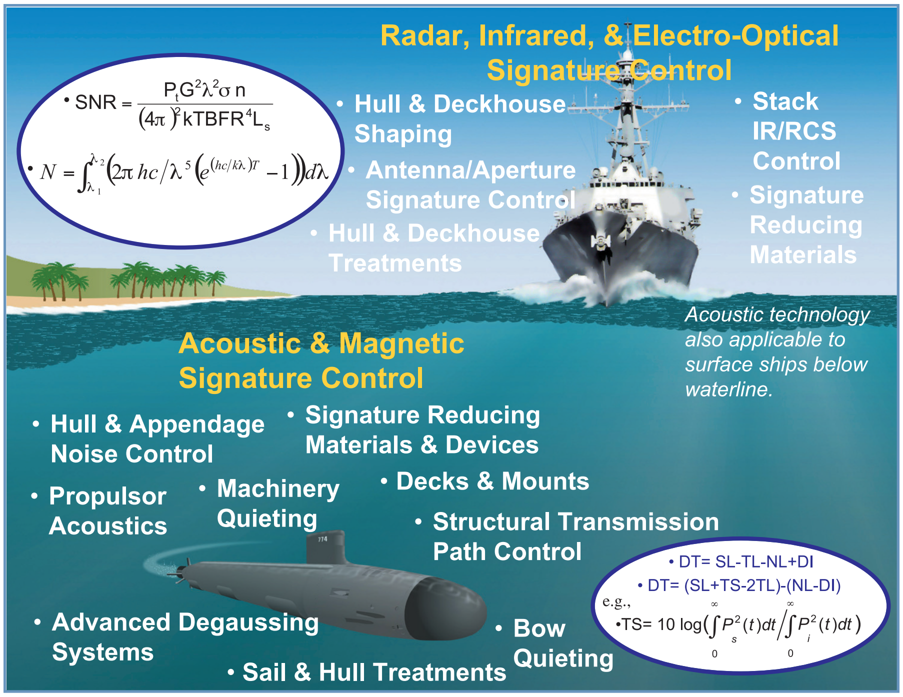


Figure 1. End-to-end, above-and-below ship signature control.

for in the passive and active sonar equations (identified in blue) in Figure 1. The determination of the variable properties is usually very intricate, as shown by that for target strength, for example. U.S. Navy ship characteristics such as general and local geometry, material, external and internal structure, and quieting devices impact some sonar equation parameters (such as target strength where geometry, materials, and hull vibration control $P_S^2(t)$), providing a range at which the ship is detectable to a threat sensor. Similarly, these types of ship characteristics are strongly represented in the equations governing signal-to-noise ratio of a radar echo (top), and infrared radiance, N. Range, R, may be determined directly from the radar equation once the other parameters are defined.

Signature Control Development and Application

Until the mid-1960's, responsibility for ship signature control was distributed across the individual Navy activities engaged in ship and system component design. Operational performance was impacted severely as a result of unintended design conflicts because of the sensitivity of signatures to multiple ship design component interactions. The Chief of Naval Operations (CNO) established strict performance and management requirements in recognition of the need for multi-disciplinary acoustic silencing technology development and ship design management. This led to the establishment of a very successful central ship acoustic signature silencing office within NAVSEA which functions to this day (currently Ship Signatures Group, NAVSEA 05T) and has been expanded to cover all ship signatures.

Signature control begins with quantitative measurement of signature characteristics, and development of a physics-based understanding of signature sources and mechanisms. Systematic signature measurements have been, and are, obtained during a variety of full-scale trials on all classes of submarines and surface ships while under controlled conditions, and with supporting signature diagnostics. The Office of Naval Research (ONR) funds applied research and advanced development for technologies and tools that are used in next generation ships. NSWCCD has developed and adopted effective computational models covering surface ship and submarines, and maintains and cultivates the world's largest ship signature database. As a consequence, the effectiveness of new-ship design features can be evaluated effectively in model-scale with great savings in time and cost.

Figure 2 illustrates the relative radiated-noise reduction achieved in submarines and surface ships since 1960. Monumental improvements in own-ship sonar performance have been achieved simultaneously because, in addition to reduced radiated-noise components, other less-radiating shipboard sonar self-noise sources have been quieted concurrently. Aircraft carrier silencing is shown to be essentially unchanged over time only because available Navy silencing technology generally has not been applied; however, it may well be applied to next-generation carriers.

Figure 3 illustrates the relative nominal reduction in surface ship RCS and IR signatures for most classes of sur-

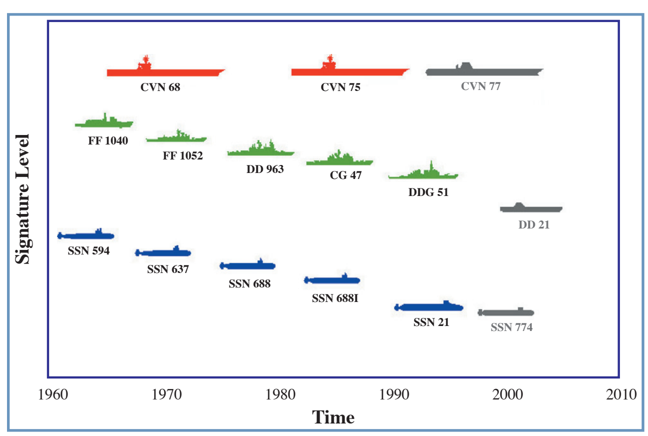


Figure 2. Historic improvement (1960 to 2000) in ship silencing (NAVSEA figure).

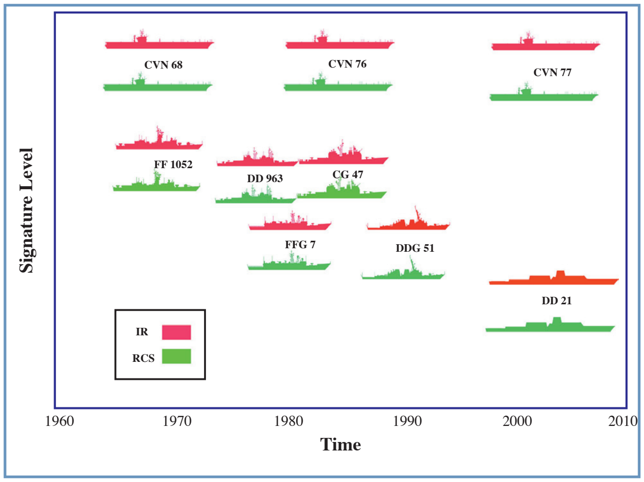


Figure 3. Historic improvement (1960 to 2000) of radar cross section and infrared signatures.

face ships since 1960. While important advances are continuing to take place for RCS reduction, electromagnetic signature control is still relatively immature.

Future Technology Development

Maintaining stealth in the presence of improving threat capabilities will require significant signature advancements. In addition to improved threat capabilities, changes in operational areas, such as operating in littoral regions in closer proximity to a multitude of threats and threat sensors, effectively reduce the level of ship stealth.

Technology developments are required and must respond to current and emerging threat capabilities to achieve adequate stealth performance. The temporal, spectral, and spatial characteristics of ship signatures that can be exploited by threat sensors must be quantified; their sources and mechanisms identified and understood; and effective approaches developed to mitigate sources that compromise stealth.

The technical challenges to achieve the signature characteristics and levels necessary in the future for ship stealth goals will be much more formidable than in the past. The easy technical problems have been solved. The major challenge will be development of sufficient scientific understanding of how sources and materials interact within complex ship structures to produce a signature that can be exploited. This will place a premium on development of procedures and equipment to quantitatively measure signatures. The measurement challenge involves achieving greater fidelity in current signature spectra, and measurement capability extension to new/expanded acoustic and EM signature spectra.

In pursuing technology development, the relative priority of individual signatures must be defined to support both Science and Technology (S&T) and the Research and Development (R&D) investment decisions. Expansion of operational missions to littoral regions has vastly increased the type and number of threats, especially to U.S. submarines. While focusing on littoral regions and their unique stealth demands, the need for stealth in the presence of continuing threats along the transit routes to littoral area operations cannot be ignored. Consequently, a computational capability adequate to determine relative signature priority on a mission basis is a major need. Such a capability must permit anticipating own-ship detection and detectability against threats in all candidate mission environments.

Maintenance of a core capability within the Navy for ship signature scientific advancement is a priority challenge. Significant investment has been made in Navy technical intellect and facilities that has resulted in evolutionary ship signature achievements, and permitted operational mission successes. Reduced research and ship program budgets have slowed progress in signature technology advancements, and are beginning to degrade the signature core intellect and affect other equities and facilities. The challenge is to maintain a core scientific capability sufficient to advance signature technology and satisfy future threat challenges and operational missions.

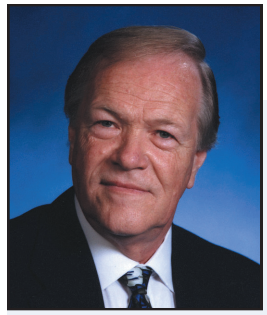
As we begin the 21st century, it is anticipated that the number of Fleet units will decrease while our requirement to operate in harm's way will increase. Clearly, specific measures are needed to ensure that adequate ship signature technology is available and applied in the future to achieve required stealth levels. The following are offered:

- Continue centralization of ship signature oversight responsibility at the NAVSEA level.
- Maintain a ship signature database, core intellect, and facilities to support Navy and shipyard RDT&E.
- Develop improved measurement capabilities for new or arising signature spectra.
- Continue to assess evolving technical threats and potential operating environments to identify changing ship stealth needs.
- Continue development of basic stealth technology that requires many years to mature.
- Continue development of physical and computational tools necessary to effectively predict and economically support ship signature improvements.
- Aggressively demonstrate ship stealth technology.
- Apply stealth technology on a systematic, mission-driven, balanced basis to counter evolving and arising priority threats.

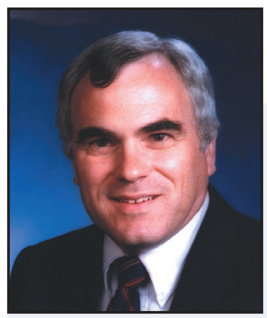
Technical Papers

The five technical papers that follow have been selected to illustrate some of the key areas of the signature mitigation process: full-scale measurement to quantify and diagnose signature characteristics and sources; research involving verification of controlling signature sources, and definition and verification of signature-reduction approaches; and development of signature reduction solutions. The first two papers address full-scale measurement of ship acoustic and EM (radar and IR) signatures. The theory and nature of these signatures, associated measurement instrumentation, and practical aspects of quantitatively measuring surface ships and submarines under realistic operational conditions is discussed. The critical relationship between full-scale measurement facility capabilities and ship signature reduction is illustrated.

The third paper addresses ship acoustic signature reduction research and the use of large physical models and computational analysis tools. The highly successful Large-Scale Vehicle (LSV) submarine model is described along with its background, scientific theory, and application in support of acoustic research. An example of a signature reduction solution is presented in the fourth paper. This paper discusses technologies developed and demonstrated under the low observable multi-function stack (LMS) advanced technology demonstration (ATD) project. They will support achievement of radar and infrared signature goals for advanced surface ship integrated topside hull design concepts. The fifth paper (an example of a solution necessitated to expand ship mission requirements on an existing class) addresses the development and evolution of the magnetic signature degaussing system deployed on the LPD–17 class of amphibious assault ships. This paper illustrates the basic development and application of a stealth technology required on surface ships due to the expanded mission requirements made necessary for conducting littoral operations.



***Brian E. Bowers** received his B.S. and M.S. degrees in mechanical engineering from Catholic University. He joined the Naval Surface Warfare Center, Carderock Division (NSWCCD) in 1965, and became deeply involved in program management of submarine bow dome, ACSAS, and basic R&D programs. He was an original contributor to the efficacy of large-scale submarine model flow-noise testing to provide valuable full-scale information. From 1986 to 1997, he was employed as a contractor supporting a variety of projects associated with submarine acoustics and signature control. In 1997, he rejoined NSWCCD as a senior engineer in the Hydroacoustics and Propulsor Development Branch, and later the Stealth Systems Office, where Mr. Bowers was involved in a broad range of signature issues for the Signatures Directorate. He currently manages all propulsor acoustics programs within the Directorate.*



***James H. King** is head of the Electro-magnetic Signature Technology Department, Signatures Directorate, at the Naval Surface Warfare Center, Carderock Division (NSWC-CD). During the last decade Mr. King has supervised the technology development and engineering for electromagnetic and other observable signatures. He led the early development of the Low Observable Multi-Function Stack ATD; developed EM signature control strategic plans; directed the exploratory development program, which defined design/cost/effectiveness impacts of signature control and concepts for future topsides; and initiated the conceptual RCS design for the LPD-17–class of amphibious assault ships. Mr. King holds a B.S. in naval architecture and marine engineering from Webb Institute, and a M.S. in systems engineering from George Mason University.*

Ship Acoustic Signature Measurements

Michael L. Marsh and Thomas N. Keech

Submarine and surface ship acoustic signature measurements provide the U.S. Navy with knowledge of the detectability of their ships and the critical information necessary to maintain mission readiness, develop enhanced capabilities to meet emerging threats, and evolve the technology to help design tomorrow's Fleet. For decades, NSWCCD has been the Navy's chief ship signature acquisition and measurement authority. This paper discusses the variety of acoustic signatures, and how past ship signature mitigation has necessitated the design and use of improved Navy facilities and equipment to measure current and future signatures.

Introduction

The stealth superiority of all U.S. ships against foreign threats is vital to the preservation of national security. With current emphasis on regional and littoral conflict capability, submarines are being tasked to operate close to shore and in shallow waters, thereby increasing the potential for detection and exploitation of various acoustic signatures. Also, littoral operations have elevated the importance of surface ship signature control.

The Navy uses signature measurements of their ships to determine their detectability under a broad range of operational scenarios. Signature acquisition and mitigation, whether for new ship designs or backfit fixes, require a broad range and depth of measurement and diagnostic capability composed of three fully integrated elements: full-scale ship measurement platforms and facilities; core intellect to diagnose root causes and mechanisms; and physical, analytical, and numerical modeling to gain technology advancement.

World-class expertise, developed through formal education and experience in a variety of technical disciplines and ship systems operations, is needed to successfully execute the Navy's ship signature measurement acquisition requirements. These disciplines include acoustic and hydrodynamic sciences, hydroacoustics, (sonar) target physics, structural acoustics, material and measurement technologies, diagnostic techniques, signal analyses, threat signature interpretation, and the physics of sound wave propagation. Knowledge in ship systems operations includes sonar technology, the nuclear propulsion plant, rotating and electrical machinery, weapons launch, and ship architecture. This expertise is applied at all levels, from data acquisition and interpretation to trial reports, signature briefings, and advanced ship and component design.

A principal NSWCCD mission is to provide full-spectrum stealth enhancements for current and future Navy submarines and surface ships through development of signature control technologies. Such products are developed cost effectively and brought to Fleet implementation to ensure that all Navy ships have the lowest possible signatures to maximize mission effectiveness and operational readiness. Acoustic ship signatures are critical because they are detectable by threat sensors at relatively remote positions. The U.S. Navy obtains and collects extensive measurements of these signatures, and the processes and equipment to acquire the measurements are discussed below.

Acoustic Signature Measurements

NSWCCD is the Navy's expert on ship acoustic silencing. To maintain stealth and acoustic superiority, continual measurement of submarine acoustic signatures is critical. The Naval Sea Systems Command (NAVSEA) sponsors the Submarine Acoustic Signature Maintenance Program (SASMP), which is executed by the Signatures Directorate of NSWCCD. SASMP is the mechanism established to monitor submarine acoustic performance, correct identified acoustic deficiencies, and maintain acoustic health. SASMP satisfies two critical Navy needs. The first need is to provide acoustic engineering for new submarine design and construction, and for ship alterations and backfits. The second is to support the Fleet's tactical requirement to satisfy mission objectives based on anticipated threats and its ability to exploit acoustic vulnerabilities. Carderock Division also provides acoustic measurement and expertise to the surface ship community. The main areas of support include Surface Ship Radiated-Noise Measurement (SSRNM) trials on certain Battle Group combatants, post-construction acoustic trials on USS ARLEIGH BURKE (DDG 51)–Class ships, and various special evaluations/Fleet support efforts to resolve unique, ship specific, acoustic problems.

Two important acoustic ship signatures are measured: radiated noise, and sonar target echo (target strength). In addition, on-board measurements of sonar self-noise, platform noise, and structureborne noise are commonly acquired, or monitored real-time, to determine sonar performance, aid in noise diagnostics, and support signature health and maintenance. Sonar self-noise is the noise measured through the sonar in the vicinity of its sensor array; platform noise is the noise measured at defined omni-directional hydrophone locations. Structureborne measurements usually are accelerometer measurements obtained at a number of hull, appendage, and substructure locations. Low radiated-noise and target strength levels allow a Fleet vessel to operate relatively undetected; whereas low sonar self-noise levels allow the submarine to more readily detect distant targets. These measurements provide Navy ships with their complete acoustic posture.

Figure 1. World's best ship acoustic measurement platforms, equipment, and diagnostics.

Measurement Platforms and Equipment

Acoustic measurements of Fleet ships have been acquired for many decades to ascertain the operational detectability and essential health of ships and on-board systems. From 1960 to 1990, MONOB (YAG-61) and DEER ISLAND (YAG-62) (both East coast), and Carr Inlet Acoustic Range (CIAR) (West coast) successfully collected the preponderance of ship radiated-noise signatures. Then, as now, acoustic measurements of self-noise and structureborne noise were acquired by on-board sonars and noise monitoring equipment, both of which have evolved over the last 40 years into highly automated, complex systems.

By the mid-1980s, the application of ship silencing technology was so successful that new measurement platforms and arrays needed to be developed and deployed to quantify our increasingly quieter U.S. submarine acoustic signatures. The Acoustic Measurement Facilities Improvement Program (AMFIP) was initiated in response to this need. This effort produced the technology and products to ensure that the U.S. Navy maintains the world's best capability to define the acoustic signature and vulnerability of all present and future quiet classes of submarines. Since the early 1990s, USNS HAYES (T-AG-95), used for acoustic measurements of submarines and surface ships on the East Coast, and the Southeast Alaska Acoustic Measurement Facility (SEAFAC), located on the West Coast, have successfully applied advanced acoustic measurement technologies to support the collection of ship acoustic data. Figure 1 shows the evolutionary development of today's acoustic signature measurement capability and identifies the factors that drove the development of this technology.

NSWCCD involvement in ship design for the earlier classes of submarines was driven mainly by the need to develop silencing solutions for previously constructed ships that resulted in ship alterations. In this regard, the Carderock Division was instrumental in the design of quieting features to incorporate into Fleet products, and acted as the acoustic silencing consultant to NAVSEA and its contractual agents. With the advent of the USS LOS ANGELES (SSN 688) and USS OHIO (SSBN 726)–Classes, and to a greater extent, the USS SEAWOLF (SSN 21)–Class –(due to silencing concerns), Carderock Division became more involved in the submarine design processes. This proactive approach allowed the Division to better bridge the gap between the R&D community and the ship construction community, and to provide the Navy with Fleet operational readiness through the use of cost-effective acoustic silencing technology. In accordance with cost-effective business methods, lessons learned from the SEAWOLF design, test, and evaluation are being applied to those of the new VIRGINIA (SSN 774)–Class submarine through various technology insertion programs.

Carderock Division's measurement facilities, HAYES and SEAFAC, are equipped with the most advanced, state-of-the-art measurement sensors, data recording systems, and signal processing suites. Both have completed their initial operating condition and are designed to support measurement requirements for the next 20 years. The HAYES measurement system consists of two AMFIP-developed volumetric, high-gain arrays (HGAs). Figure 2 shows the

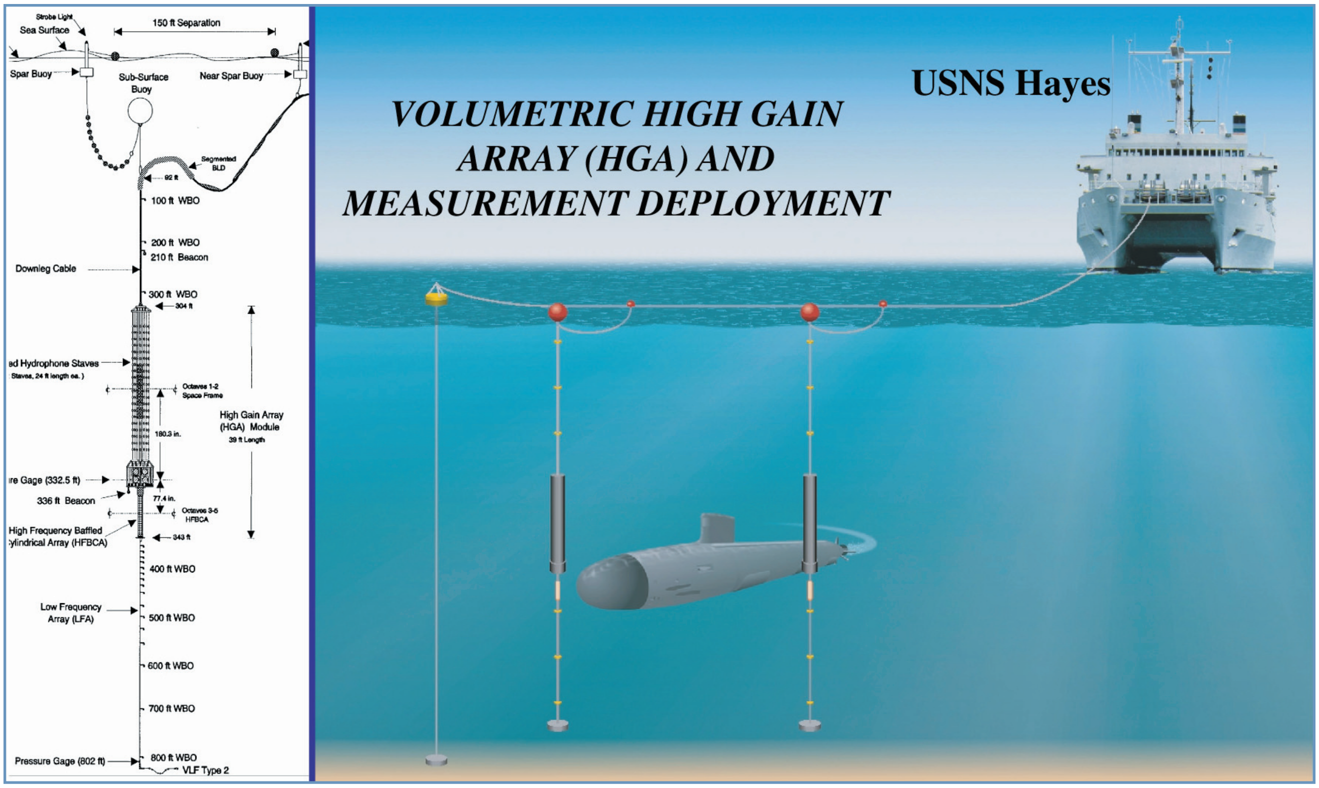


Figure 2. Leading edge signature measurement equipment.

HGA, and depicts the deployment of these arrays relative to the underway submarine track.

The vertical acoustic arrays are suspended by subsurface buoys, between which a submarine passes while operating at predetermined speeds, depths, and machinery/system line-ups. HGAs include omni-directional hydrophones, directive hydrophones, and other sensors. HAYES, moored several hundred yards away from the arrays, receives transmitted data via flotation cables at its laboratory, which houses the signal processing, real-time analysis, and data recording equipment. These systems are deployed from large winches on the forward main deck of HAYES.

Signal Processing and Acoustic Imaging

Today's quiet submarines led to the need for acoustic measurement arrays with very narrow beams and greatly enhanced discrimination against ambient noise. The HGA houses 1000 hydrophones nested in vertical staves; each HGA stands over 40 feet tall and weighs over 4000 pounds. The multichannel processing system operates on all data transmitted by the Telemetry Receiver Unit. The processing system is divided into three areas of operation: the HGA beam former; the high-resolution narrow-band processors referred to as the multichannel analysis extension; and other control, subsystem, and post-processing devices.

Signal processing and analysis instrumentation installed on HAYES, provides the capability to fully characterize the stationary and non-stationary (transient) submarine radiated-noise signature. Fast Fourier Transform pro-

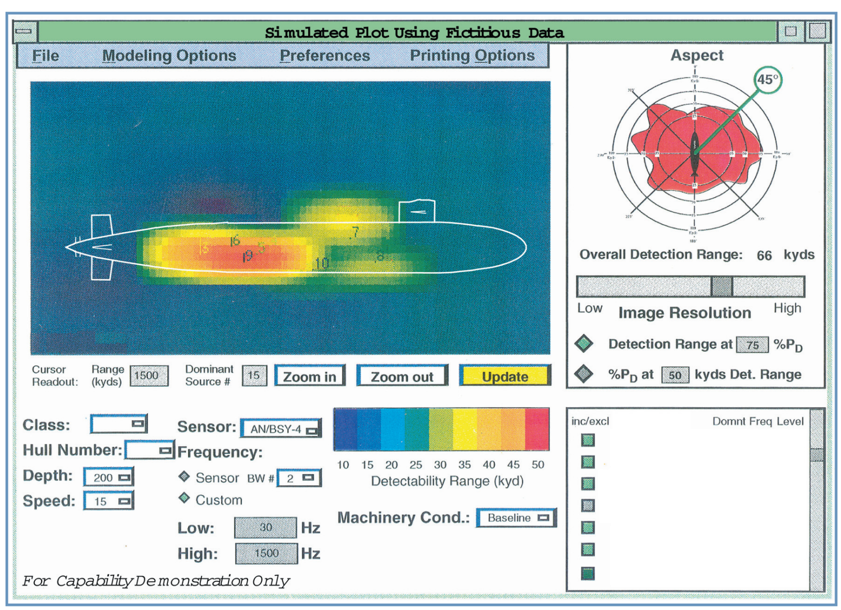


Figure 3. Advanced automated signal processing and acoustic imaging.

cessing provides frequency domain analysis of the steady-state submarine acoustic signature. Specialized time-frequency processing is used to measure and characterize the transient-noise signature. In addition, acoustic image processing is used extensively during submarine acoustical trials. Acoustic image processing provides the analyst with a data visualization tool to localize sources of submarine radiated noise along the ship hull.

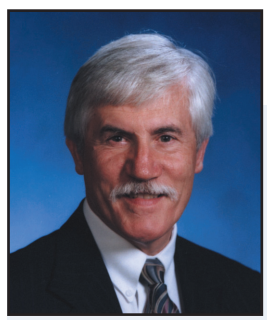
The HGA beam forming and processing system generates acoustic images for selectable frequency bands by processing the beam power for multiple steered image beams per detection bandwidth, and visually displaying the beam amplitude output in a hot (red) and cold (blue) color palette. The HGA acoustic image beam widths are designed to spatially over-resolve the ship hull at ranges very close to the HGA to provide accurate localization of radiated noise sources from the submarine. Figure 3 presents a simulated acoustic imaging plot (fictitious data). It demonstrates the current measurement capability to identify potential sources on a submerged underway SSN–Class submarine that may contribute to its radiated-noise signature. The yellow topside and keel regions, shown in Figure 3, strongly indicate sources associated with flow impacting external hull features; whereas the broad red-orange region is likely attributable to machinery-related sources.

Summary

Stealth is a system-level capability. Hence, the entire ship must be treated as a system, and silencing must be acted on systematically. Periodic far-field signature measurements and continual on-board diagnostic health and maintenance data collection over the life of the ship are critical to identify and correct noise problems. Also, they provide the knowledge necessary to develop the Navy's next generation of ships. Acoustic signature measurements on U.S. ships provide initial awareness and final verification to resolve critical noise problems. Acoustic measurements validate the quieting products that reduce levels at the source, interrupt the propagation of energy from the source, or impede the radiation to the threat receiver at the hull/water interface. Quiet ships, undetectable by current and projected threat platforms, sensors, and weapons, represent an unchanging Navy requirement to provide nuclear deterrence via the Trident submarines, intelligence collection, covert troop insertion, and full battle force interoperations.

Submarine and surface ship measurements provide the U.S. Navy with critical information to maintain current mission readiness, develop enhanced capabilities to meet emerging threats, and evolve the technology to help design tomorrow's Fleet. The intense rivalry and co-evolution of equipment to detect submarines and the diverse measures needed to reduce their signatures have characterized the entire developmental history of submarines. Research and development funds are being invested to equip future submarines and surface ships with new and dominant technologies, including acoustic and electromagnetic stealth. The "cat and mouse" game between submarine acoustic emissions and sonar detection - serially conducted in the ocean depths and now in coastal regions - continues.

***Michael L. Marsh** joined the Signatures Directorate of the Carderock Division, Naval Surface Warfare Center (NSWCCD) in 1987 and has supported a variety of test programs. During his tenure at NSWCCD, he has performed full-scale radiated-noise measurements and evaluations, model testing using the Intermediate Scale Measurement System (ISMS) Facility and served 3 years as the VIRGINIA–Class Hull, Mechanical and Electrical (Acoustic) Trials Manager. Mr. Marsh is head of the Radiated Signature and Performance Assessment Branch, which is responsible for measurement, analysis and vulnerability assessments of acoustic signatures for all U.S. ships. Mr. Marsh received his B.S. in mechanical engineering from West Virginia University and his M.S. in engineering management from George Washington University.*



***Thomas N. Keech** graduated from Virginia Polytechnic Institute with a B.S. in mechanical engineering. After joining the Naval Surface Warfare Center, Carderock Division (NSWCCD), Annapolis Detachment, he initially worked in the Machinery Silencing Department in machinery noise control. He joined the Radiated-Noise Branch in 1972 and became Branch Head in 1984. This branch is responsible for the acoustic signature analysis of all U.S. submarines and surface ships. Mr. Keech became the Chief Engineer for Signature Analysis (acoustic) in April 1998, but more recently his role was expanded to include vulnerability assessments. He is the author of over 40 technical reports and has frequently lectured on topics relating to the field of radiated acoustic signatures.*

Ship Electromagnetic Signatures and Measurements

William T. Stephens III and Paul M. Honke

Radar and infrared signatures are the principal ship electromagnetic signatures discussed in this paper. The value of radar and infrared signature measurements is presented as it pertains to different stages of the ship's life span, from initial design and development to decommissioning. Signature measurements of ships and submarines present unique problems due to the ships' size and the environment in which they operate. A variety of challenges in accomplishing these at-sea measurements are presented, including considerations of ship motion and the environment. Unique aspects related to signature measurement of new topside components are discussed. Evaluation of radar and infrared signature data is also discussed with the effects of measurement challenges considered.

Introduction

Radar and infrared (IR) signatures play an important role for any Navy craft operating safely on the surface of the water. With today's missions directed at regional and littoral operations, exposure to indigenous threat sensors and systems is elevated. Our ultimate goal in signature control is to break the "kill chain" of our adversaries' detect-to-engage sequence, to ensure the safety of our sailors and that the ship's mission can be completed successfully. Both U.S. and adversarial forces have detect-to-engage sequences whose respective effectiveness depends on capabilities in the areas of stealth, fire control, weapons, threat sensors, tactics, and many other important factors. The elemental "kill chain" from the U.S. force perspective is illustrated in Figure 1. The basic rings (functions) of the "kill chain" do not change from blue water to littoral operations. However, the means to execute each of the five functions in the detect-to-engage sequence can be variable depending on the operational environment. The hostile attacker must be able to detect, identify, localize, target, and engage our forces. The U.S. Navy's signature control efforts are directed at breaking one or more of these links to prevent a successful attack. Obviously, it is preferable that we break this chain as early as possible in the process.

Figure 1. Elemental detect-to-engage sequence and impact of signature reduction.

Any of the signatures of U.S. vessels detected by threat sensors contribute to the efficiency of our adversary's detect-to-engage sequences. In the littorals, many more sea- and land-based threat sensors and influence weapons may reside. Two of the most distantly detected electromagnetic signatures are radar and infrared signatures.

Radar Signatures and Measurements

Radar signature control has been applied in many areas to reduce the susceptibility of our ships to hostile threats. Historically, ships have been built proudly with upright deckhouses and right angles. As it turns out, this is not the way to build ships to reduce radar signatures. These physical features tend to reflect radar energy right back at a hostile radar system. Deliberate efforts at radar signature control have reduced the radar signature of current ships as well as future ships in the research and design phase. One of two things must happen to the energy of the hostile radar system to reduce the radar signature. It must be reflected in a direction away from the threat or absorbed and dissipated so it is not reflected.

The Navy must measure ships to determine their radar cross section (RCS) and verify signature reductions. A ship's RCS is a measure of the amount of energy reflected back to a hostile radar system. The "cross section" is not necessarily comparable to the physical size of the ship, but to the apparent size presented to directed radar energy. The less energy reflected back in the direction of the threat sensor, the lower the RCS of the ship. Lower RCS values contribute to breaking the kill chain. Signature measurements are performed with an instrumentation radar system specially designed for ship RCS signature measurements. Over the years, these systems have been developed, along with technology advancements, to meet the changing needs of radar signature measurement.

Ships are unique in their RCS measurement needs. They must be measured "in their element," floating on a complex reflecting sea surface, with the ship undergoing irregular motion caused by the seaway. The ship and its environment comprise the total ship signature. The environment presents unique challenges in the measurement and evaluation of RCS signature data. Ship RCS measurements can be enhanced or diminished, depending on environmental characterictics. Correct interpretation is essential to the proper evaluation of radar signatures.

Instrumentation has been designed to record and/or telemeter a variety of environmental data to the shore radar site. Onboard test instrumentation also records ship heading, roll, and pitch to interpret the 3-dimensional aspect of the ship correctly. It is critical that this attitude data be collected because a ship's RCS can be highly aspect-dependent.

U.S. Navy ships are deployed around the United States and around the world. Often, it is not practical to bring ships to a central location, nor is it practical to maintain these measurement systems at distant locations on a permanent basis. This has led to the development of customized mobile/portable measurement systems with the capability to be deployed to distant locations, and to be setup, operated, and retrieved with a minimum of time and cost. This has allowed us to verify signatures of a variety of Navy assets at many locations in a cost-effective manner.

As the ship performs maneuvers, the radar system must track the ship, in range, azimuth, and elevation, to ensure that the radar system is sampling the signature data properly. Range tracking is performed electronically by the radar hardware by sampling the radar return from the ship in "early" and "late" range gates of the radar. By comparing these range gates, another range gate can be directed to automatically adjust the sample range as the ship changes range during maneuvers. Azimuth and elevation must be tracked by steering the measurement antenna to follow the ship as it performs maneuvers. Optical tracking is not always possible because sometimes tests must occur in low visibility conditions (e.g., darkness or fog). Automatic antenna tracking is used to track under these conditions, by receiving Global Positioning System (GPS) telemetry from the ship or by tracking the ship with a marine search radar system. The position information is used to electronically direct the antenna to follow the ship being tested.

In addition to developing the facilities to measure the RCS of our ships, we must also provide some diagnostic capability to the measurements. Just knowing the magnitude of the RCS does not help us to identify specific areas of the ship that give rise to the signature. Identification of these problem areas is essential to apply corrective action and reduce the overall RCS. Navy instrumentation and software have evolved to provide high-resolution imagery of ships through advanced signal processing techniques. In this way, we can identify problem areas specifically and target that area with signature reduction techniques.

High-resolution imagery is accomplished by sampling the ship at many discrete frequencies. This frequency sampling is processed by an inverse Fourier transform to achieve high-resolution imagery in the range direction. This permits the analyst to determine where, along the ship, the highest amount of radar energy is being reflected. By further processing the data as the ship rotates, it is possible to determine where high energy returns are coming from in the cross range. In this manner, analysts can isolate problem areas of the ship and identify them for corrective action. Some of this processing occurs in real time as the data is collected and some is performed in post processing. In any case, all data can be processed on site for immediate feedback on the RCS signature of the ship.

Infrared Signatures and Measurement Systems

NSWCCD is committed to develop and field state-of-the-art infrared measurement systems. The infrared systems encompass both long-wave and mid-wave technology, and their performance is driven by both scanning and staring architectures. Infrared and electro-optic measurements can be made from virtually any location using a combination of helicopter-, ship-, and land-based sensor systems. GPS transducers are installed at the sensors, at a base station location, and aboard cooperative targets. The position of the target and its location relative to the sensor suite can be accurately calculated using this combination of GPS equipment and commercially developed software. This is important because range is needed to calculate atmospheric transmission losses and orientation of the target is often a consideration for solar loading and aspect-dependence of the target's signature.

The infrared and electro-optic systems have been used at NSWCCD to make a variety of radiometric measurements of full- and model-scale targets. A portable shelter is used to house the measurement systems to deploy during land-based tests. The shelter affords protection for the equipment and provides a base station for test operations. The portable shelter can be used aboard ship when warranted. Other equipment installation techniques have been used to accommodate the customers' needs.

For helicopter-based radiometric measurements, a three-axis gimbal mount has been custom designed and built to deploy the infrared and electro-optic instrumentation as shown in Figure 2. This arrangement has provided great flexibility in making measurements. Virtually any view, look-down angle, or range can be achieved. The operator can remotely control the mount's 3 degrees-of-freedom (azimuth, elevation, and roll) to obtain a desired viewing angle. The helicopter is flown in various patterns around the ship as it moves through the water under different operating conditions. Typical flight patterns include radials at various ship aspect angles, circles around the ship, and close-up parallel fly-bys on port and starboard beams. Close-up measurements of the ship, its plume, and its wake are taken also.

Measurements at close range are emphasized to maximize resolution and to minimize the effects of atmospheric attenuation. Night and day measurements taken at different ranges during radial runs allow the atmospheric attenuation to be characterized. For safety reasons, night measurements are usually made at daybreak when there is no, or very little, solar loading.

In addition to the radiometric sensors, it is necessary to make auxiliary measurements to obtain "ground truth" information of environmental and target condition parameters that affect the measured signature. The auxiliary information collected during a trial includes environmental data such as solar loading and air and water conditions. The environmental information includes pyranometer, albedometer, and pyrgeometer data in addition to typical weather station measurements (temperature, barometric pressure, relative humidity, wind speed, and direction). A visibility/present weather sensor provides data on background luminance, precipitation, atmospheric extinction coefficient, and visibility ranges. Target and measurement system parameters such as ship-panel or compartment temperatures, exhaust-gas temperatures, the ship's location, heading, roll and pitch, the helicopter's altitude, and the helicopter's range and bearing relative to the ship are measured also and recorded as appropriate for each test.

Imaging radiometers, also called Forward Looking Infrared (FLIR) systems, can be used at sea and at many other locations to make full-scale infrared signature measurements of ships in the 1.5- to 5- and 8- to 12- μm wavebands. Filters are used to limit the bandwidth of the measurements when appropriate.

The FLIR produces TV-like images in which the pixel intensities are proportional to the apparent temperatures of the imaged scene as shown in Figure. 3. The apparent temperature can be determined with the FLIR's built-in thermal calibration references or with external calibration references. The reference calibrations are traceable to the National Institute of Standards and Technology (NIST). The FLIRS themselves are calibrated in a temperature chamber over the range of ambient temperatures expected during FLIR operation. This allows the data to be corrected for any differences in FLIR operating temperatures that can occur between calibration and measurement. Data, such as the gain and offset of each waveband, are also displayed with the image of the ship. The FLIRs produce U.S. standard video outputs with high spatial and thermal resolution. The images are recorded on videotape for further processing and analysis.

Figure 2. Helicopter-based radiometric signature measurement system.

Figure 3. Thermal images under varying environments using Forward-Looking Infrared (FLIR) measurement systems.

After a trial, the videotapes are played back and selected single-frame images are processed on an image processor. Processed images then can be converted into high quality hard-copy images using a printer with high spatial and gray-scale resolution. Color images, used to enhance signature details, can be produced also. Carderock's image processing capabilities include a technique to produce a high-resolution composite image of the entire side of a ship. Examples of IR images of air, land, and sea-based targets are provided in Figure 3.

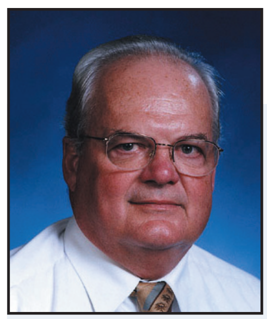
Summary

Threats around the world are evolving constantly to be smarter and harder to defeat. The technical capabilities of the professionals behind these threat systems should not be underestimated. It is important to keep current with the capabilities of these threats and provide measurement system upgrades that will evaluate RCS and infrared signature vulnerability with respect to these threats. This can take many forms, such as expanded frequency coverage, signal processing improvements, and smarter hardware that attempts to counter signature control efforts.

The actual reduction of ship signatures creates another challenge in measurement technology. As the RCS and infrared signature of our ships are reduced, we must upgrade measurement capabilities so that these smaller signature levels can be accurately measured and evaluated today and in the future. This requires that more and more sensitive systems be developed and used for measurements.

As threats continue to evolve and ship designs improve, the need will continue to drive measurement system development to meet the many challenges presented to the measurement community. It is critically important to stay on the front edge of technology to provide the signature verification necessary to ensure that our ships are as good as they can be when we ask our sailors to go into harm's way. Our sailors' safety and the success of the missions they perform depend on it.

***William T. Stephens III** is a senior engineer in the Signatures Directorate at the Naval Surface Warfare Center, Carderock Division (NSWCCD). He received his B.S. in electrical engineering from the University of Maryland in 1986. Following graduation, he worked in private industry supporting system integration of the Navy's Vertical Launch System for surface ships. Since 1989, Mr. Stephens has worked at NSWCCD in systems development of radar signature measurement technology. In 1991, he became the project manager of the Radar Imaging Measurement System. He has overseen the development of radar system technology directed at meeting the evolving needs of a variety of Navy programs. Currently Mr. Stephens is responsible for the planning and execution of a wide range of radar signature tests for purposes that span from basic research to test and evaluation.*



***Paul M. Honke** began his career as a cooperative education student in the Ship Acoustics Department at NSWCCD while completing his B.S. degree in mechanical engineering at Virginia Polytechnic Institute in 1969. From 1973 to 1978 he accepted a position at the National Highway Traffic Safety Administration, where he conducted research in motor vehicle inspection. Mr. Honke returned to the Division in 1978 and performed analytical studies in ship vibration. He transferred to the Central Instrumentation Department where he was responsible for designing and implementing automated data acquisition systems. Following the formation of the Ship Electromagnetic Signatures Department in 1987, he managed several radar cross-section measurement and data reduction efforts on full-scale ships. He joined the Infrared Signature Control Branch in the Signatures Directorate in 1994 as the Measurements Group Leader. Mr. Honke currently is detailed to the Ship Hull, Mechanical, and Electrical Science and Technology Division at the Office of Naval Research.*

Large-scale Vehicles: An Essential Element in Submarine Technology Insertion

John R. Spina and Drew P. Meyer

The ability to accurately predict the full-scale performance of candidate advanced technology insertions, and to minimize the cost of those insertions is crucial to understanding the projected capability and affordability of future submarines. This paper presents a discussion which shows that the use of large-scale submarine models as full-scale performance predictors and design evaluation tools has proven to be technically reliable and highly cost effective for technologies that impact ship stealth. Large-model facilities, including advanced acoustic and other measurement systems, are the result of a large Navy investment in maintaining the superiority of the submarine Fleet and are well-positioned to support future research and development efforts.

Introduction

This paper presents an argument for the use of unmanned, autonomous test vehicles - known as Large-Scale Vehicles (LSVs) - in submarine technology development and evaluation and describes current and future plans for these vehicles. Large submarine models have been used for over 30 years at the NSWCCD Acoustic Research Detachment (ARD), in Bayview, Idaho, to conduct a variety of studies leading to improved submarine acoustic and operational performance. The contribution of those early model tests to improved Fleet capability provided the necessary impetus for the Navy to invest in a much more complex test vehicle, one that was self-propelled and would serve as a test bed for advanced propulsor concepts and potential technology insertions. The first vehicle of this type was designated LSV 1 (named KOKANEE) and was delivered to the ARD in 1987. The success of this vehicle drove an initiative to create a more capable second vehicle, designated LSV 2 (named CUTTHROAT). Figures 1 and 2 compare the characteristics and capabilities of the two vehicles. CUTTHROAT will be delivered to the Navy early in FY02. The vehicle names are taken from species of fish indigenous to Lake Pend Oreille, which is the site in Northern Idaho where the vehicles are based and all tests are conducted. A pictorial of the lake is shown in Figure 3.

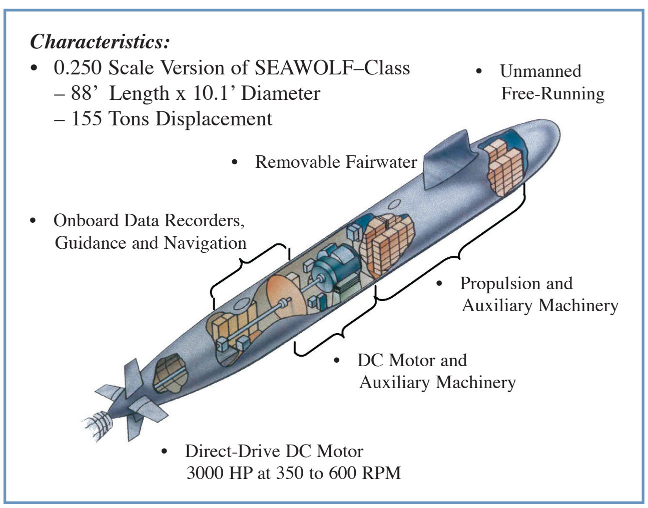


Figure 1. Large-scale vehicle KOKANEE (LSV 1).

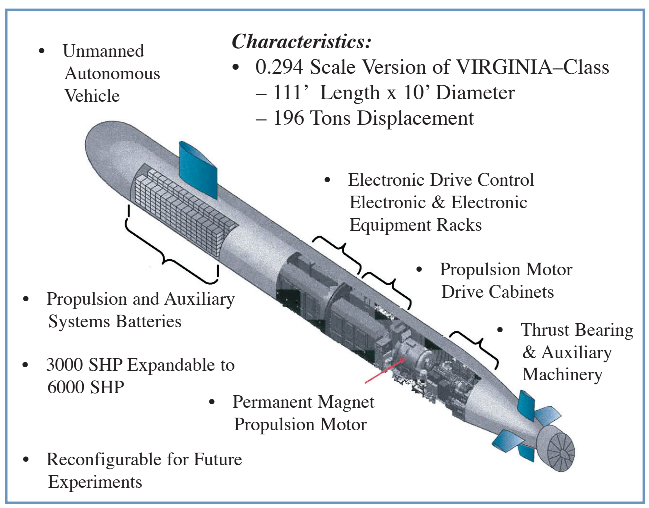


Figure 2. Large-scale vehicle CUTTHROAT (LSV 2).

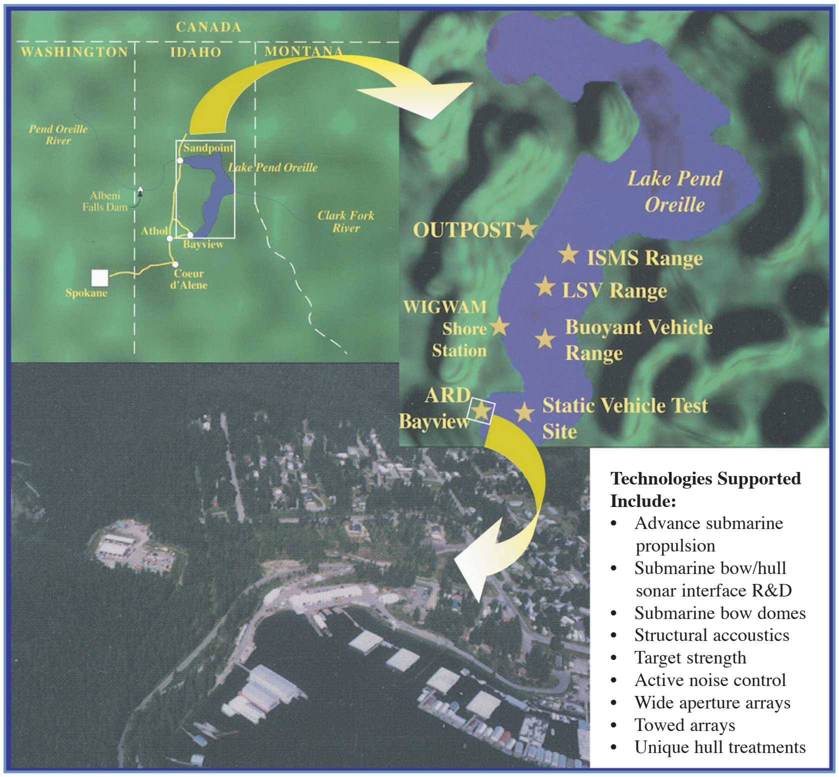


Figure 3. Acoustic Research Detachment, Bayview, Idaho.

Large-Scale Vehicles

Large-scale vehicles generally are described as test vehicles that model features of a planned or existing full-scale submarine to some appropriate scale factor and level of detail. The vehicles are self-propelled and unmanned, and carry an extensive suite of guidance, navigation, control, and data acquisition electronics, in addition to systems necessary to propel and control the vehicle. The vehicles are battery-powered and are fully autonomous. A powerful onboard computer controls the vehicle during mission execution, acquires onboard data, and independently recognizes and responds to faults and casualties. A photograph of LSV 1 surfaced near the operations range is provided in Figure 4.

The choice of scale for the LSVs was dependent on a variety of factors. Generally, LSVs should be run at full-scale speeds to better match flow-induced forces and verify powering predictions. LSV 1 was operated in a flow regime where the Reynolds Number of the vehicle at test speed overlapped that of the full-scale vessel, because the primary mission was to evaluate the hydroacoustic and hydrodynamic performance of an advanced propulsor concept. This, coupled with a hydraulically-smooth surface condition, was intended to provide some degree of scaling of boundary layer growth. In this manner, inflow to the propulsor would be representative of that experienced by the full-scale vessel, and data would be scalable. Given Reynolds Number overlap as a guide, and considering the practicality of vehicle size and speed, the result was a scale factor of about 0.25. Constructing vehicle and propulsor test hardware at this scale was not an issue from a fabrication standpoint. Geometric detail to control performance could be achieved using conventional fabrication methods. From a powering perspective, sufficient energy could be stored in lead acid batteries to power a conventional direct-current motor for the time necessary to acquire acoustic data at the speed necessary to overlap the full-scale Reynolds Number.

Significant evidence existed from previous model tests to support the use of this scale factor in terms of structural acoustic considerations. That is, hull and propulsor structural response to excitation would result in scalable acoustic radiation characteristics and enable accurate prediction of full-scale performance. Furthermore, model-handling facilities and experience at ARD were nominally geared to models of this size.

Hydroacoustic considerations require that the vehicle have certain scaled structural features to preserve its ability to predict full-scale performance. Vehicle lines and offsets should be scaled for all types of evaluations. For direct acoustic radiation from the propulsor, the geometry of vehicle propulsor components must be related to the full-scale unit either through direct geometric scaling, or scaling of flow into and within the unit. Also, the model and full-scale

Figure 4. Surfaced LSV 1 on range in Lake Pend Oreille.

propulsors should have equivalent material properties. For direct acoustic radiation from the vehicle hull where low-frequency response is the principal issue, the shafting system from the thrust bearing aft and major features of the pressure hull and superstructure require precise geometric scaling. These features should be scaled to simulate low-frequency hull flexure and accordion-mode dynamics. As with the propulsor, the vehicle and parent vessel should have equivalent hull material properties. The distribution and mount stiffness of large masses within the hull (e.g., batteries and the main motor) must be accounted for in this calculation.

Operational systems are designed to support mission execution, including scaling of certain maneuvering capabilities and ship safety considerations. Mission execution involves control of the vehicle, storage and application of propulsion energy, acquisition of research and development (R&D) data, and managing the environment within the vehicle. Scaling considerations include control-surface slew rate and rate-of-change of motor speed. Ship safety involves sensing ship state, preventing operations outside of a prescribed envelope, and taking independent action to control and recover the vehicle in the event of a casualty. Operational systems include all components within the vehicle and the external systems and components that support vehicle control, data acquisition, and vehicle handling. A schematic of the LSV test range and operations profile is presented in Figure 5.

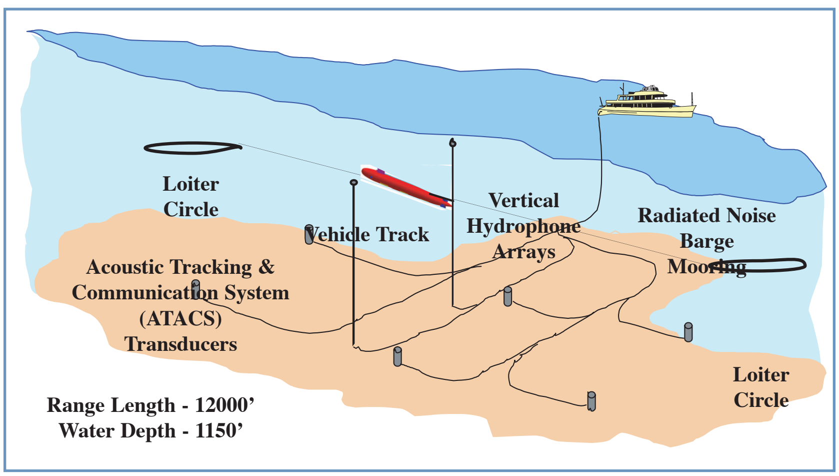


Figure 5. LSV range and operations profile.

Measurement systems are designed to provide the user with accurate and timely data on which to base performance assessments and full-scale predictions. These systems are located onboard the vehicle and within the LSV acoustic operating range. All measurements are linked through a common clock to aid in data analysis. Measurement systems are constantly evolving through technology push and user requirements pull. Whereas the original data acquisition concept for LSV 1 focused on standoff external radiated-noise measurements, experience has shown that a much greater understanding of the underlying physics of hydroacoustic and hydrodynamic propulsor performance can be obtained using an extensive complement of onboard sensors.

Why Use Large-Scale Vehicles?

Large-scale vehicles are, by nature, relatively expensive to build and use compared to most small-scale model tests and analytical studies. However, compared to full-scale tests, very large cost savings are possible with many other benefits derived. The same is true for the time required to execute a trial. When full-scale platforms are employed for R&D, trial needs must be anticipated well in advance, because the availability of full-scale platforms diminishes as the number of submarines is reduced. Mission requirements take precedence, and there is little or no flexibility once a time-slot has been committed.

The choice of which approach to employ obviously depends on the type and quality of data needed, and other factors such as knowledge of scaling laws, adequacy and availability of facilities, and evaluation time available to produce the results. For example, consider the case where KOKANEE was used to support SEAWOLF propulsor selection. If a full-scale submarine had been modified to support the trials, the cost would have been four to five times higher (approaching $1B) and the duration of the trials four to five times longer. Additionally, the quality of the results rivals, and often exceeds, that which can be obtained using a full-scale ship. In this case, small-scale was not an option, because the geometric details of the model propulsor that controlled performance could not be duplicated at a scale much smaller than that of KOKANEE.

Large-scale vehicle data will support the development and validation of computational codes used to predict full-scale maneuvering characteristics by providing an intermediate data point between small-scale radio-controlled models and full-scale platforms. For certain maneuvers, empirical data acquired at small scale can be adjusted using the intermediate data point to account for viscous effects (Reynolds Number differences), improving the accuracy of force and moment predictions, and the resulting ship state.

Large-scale vehicles offer a significant advantage in the areas of flexibility and risk management compared to full-scale platforms. While the consequences of damaging or losing a large-scale vehicle are substantial, there is no comparison when those possibilities are considered for a full-scale manned submarine. As a result, maneuvering situations that are necessary to return required data -but would be unacceptable for a full-scale submarine to perform - can be performed by a large-scale unmanned vehicle if carefully controlled. Built-in safeguards including fault identification and response, and automatic independent emergency override controllers support careful maneuvering control.

The effectiveness of submarine acoustic stealth technology insertions generally are judged on the basis of whether the insertion provides a reduction in radiated signature. The naturally occurring physical features of Lake Pend Oreille offers a unique combination of attributes which are especially favorable for submarine acoustic stealth assessments: deep water, in excess of 1000 ft over a 20 square mile area; very low ambient noise; and it is virtually free of tidal currents. The test environment at the ARD, combined with the success-evolved resident measurement facilities, is unequalled anywhere in the world.

Experience in the Use of Large-Scale Vehicles

The initial concept for large-scale vehicle propulsor evaluations was to enable designers to down-select from a short list of candidates whose characteristics were governed by data from analytical studies and small model tests. The principal source of data that allowed the down-selection process to advance was from the LSV Radiated- Noise Data Acquisition and Analysis System. As techniques to analyze and understand LSV data matured, two benefits became clear: (1) the vehicle could be used to great advantage to better understand the underlying physics of noise from advanced propulsors, and (2) data acquired onboard the vehicle (from accelerometers, load cells, pressure transducers, and other devices) could provide improved insight into signature controlling factors, and hence guide design changes. As a result, an expanded onboard measurement system was installed as the VIRGINIA–Class model trials were commencing on LSV.

As the push to complete model trials for SEAWOLF diminished, some time was allocated to hydrodynamic studies. Specifically, studies were conducted to understand near-surface depth keeping, how flow forces and moments were applied, and their influence on ship state. As a result of these studies, the next large-scale vehicle (LSV 2, CUTTHROAT) will have an expanded suite of equipment on board to measure parameters that control the maneuvering capability of submarines. The advantage in using a vehicle whose scale factor is closer to full-scale values is improved ability to predict full-scale performance for those maneuvers where Reynolds Number scaling is critical.

Propulsor Evaluation Trials

LSV 1, KOKANEE was delivered to Lake Pend Oreille in March 1987. After approximately 8 months of outfitting and preliminary checkout, SEAWOLF propulsor evaluations started in November 1987. The trials essentially concluded in 1995, but additional short trials have been scheduled periodically to consider improvements in the propulsor for follow-on ships of that class. Over 50 major variants were tested during the initial trials periods. In 1995, the first VIRGINIA–Class propulsor was tested on KOKANEE. Again, more than 50 major variants have been evaluated since that time, and trials are continuing with significant trials planned for FY02. As with SEAWOLF, additional short trials may be conducted to refine the units to be installed on follow-on ships of the VIRGINIA–Class.

The next challenge for propulsor designers, in addition to making propulsors more affordable, will be to meet radiated-noise signature objectives for the year 2015. LSV 2, through the application of more stringent acoustic quieting specifications, will be well positioned to support the assessment of propulsor devices designed to meet these new requirements.

Maneuvering Trials

Small captive and radio-controlled model tests will continue to support most submarine maneuvering evaluation requirements and hydrodynamic studies for the foreseeable future. However, recent maneuvering trials using LSV 1 have shown that for investigation of phenomena where Reynolds scaling plays a significant role, large-scale vehicles provide more reliable data in predicting full-scale performance. The trials examined near-surface depth keeping and attempted to understand from ship-state parameters the magnitude and location of forces applied to the hull and control surfaces, without actually measuring the forces. The results compared very favorably with full-scale measurements. Unlike LSV 1, the design of LSV 2 will allow the direct measurement of forces and moments on the sail, control surfaces, and propulsor. These attributes, along with a significant improvement in the ability to establish the accurate position of a vehicle throughout a maneuver, will make LSV 2 a very valuable tool for the hydrodynamicist and ship control engineer.

Other Trials

The geometry of the lake and the surrounding topography provided an ideal arrangement for tests and evaluations that depend on the detection of acoustic, electromagnetic, or other types of non-acoustic signatures. For instance, a portable radar may be used at a vantage point near and above the LSV operating range to determine the radar cross-section variability of one or more advanced sail design options for a surfaced large-scale vehicle. LSVs have been used very successfully in such tests.

John R. Spina *is head of the Large-Scale Systems Demonstrator Office, Signatures Directorate at NSWCCD. He has been involved in, and managed the conceptual design, construction, and utilization of Large-Scale Vehicles since 1967. After receiving his B.S. in mechanical engineering from Drexel Institute, he became the first Cooperative Education graduate to accept employment at Carderock. Early assignments included submarine and surface ship full-scale trials and R&D evaluation of silencing devices and towed arrays. After receiving his M.S. in mechanical engineering from Catholic University, he became head of the Special Equipment Branch, with responsibility for management of large-scale model utilization at the Acoustic Research Detachment. In 1987, he became head of the Submarine Acoustics Research Division, and currently is NSWCCD manager for KOKANEE (LSV 1) and CUTTHROAT (LSV 2).*

Drew P. Meyer *is the chief engineer for Large-Scale Vehicles in the Signatures Directorate at NSWCCD, and is resident at the Acoustic Research Detachment in Bayview, Idaho. He graduated from the U.S. Naval Academy in 1980 with a B.S. in mathematics. Mr. Meyer received nuclear training from the Navy and has 9 years of Navy Nuclear Submarine operational experience. Since 1989, he has been performing engineering and conducting tests associated with a variety of R&D projects on the Large-Scale Vehicle, KOKANEE. He is the Division's expert on the operations of autonomously controlled submarines. Mr. Meyer is presently coordinating a team of engineers and technicians that are preparing to accept and operate the Large-Scale Vehicle, CUTTHROAT.*

Signature Reduction and C4I Technology for a Low Observable Multifunction Stack

William R. Bird, Raymond J. Ratcliffe, and Robin D. Imber

Signature control and Command, Control, Communication, Computer & Intelligence (C4I) antenna technologies that are necessary to support integrated topside concepts for modern warships are under development as part of the Low-Observable Multifunction Stack (LMS) Advanced Technology Demonstration (ATD) project. The LMS project is demonstrating two advanced exhaust suppresser systems enclosed in a low-signature composite structure containing embedded SATCOM antennas. These technologies were developed to meet specific signature goals for ship topside components that were derived from candidate signature budgets developed for future combatants. The LMS ATD is an Office of Naval Research sponsored project. Execution Management for the LMS is provided jointly by NAVSEA and SPAWAR, and Technical Management is provided by NSWCCD

Introduction

The topside design of modern warships is characterized by many conflicting requirements. Two of these are the requirement to use stealth to maximize the survivability of ships and the requirement to find ways to increase the tactical and strategic communications capability of forces afloat to support emerging network-centric warfare doctrines. Stealth, for our next generation of warships, means control of all signatures. For topside considerations this requires control of the Radar Cross-Section (RCS) and Infrared (IR) signatures. As currently envisioned, these requirements translate to "clean" topside architectures using multispectral signature control materials and specific treatments for IR signature sources. Unfortunately, the desire to increase communication capability using current technology would mean the placement of high scattering antennas on this "clean" topside structure. However, the development and application of new and emerging technologies can provide solutions to these problems.

Under the LMS ATD, several technologies are being developed that address dominant topside signature control issues and provide a way to increase communication capability for ships. In particular, the LMS project is demonstrating two advanced exhaust suppresser systems enclosed in a low-signature composite structure containing embedded Satellite Communication (SATCOM) antennas. The concept for the LMS is shown in Figure 1. The LMS technologies work with other technology developments like the *Advanced Enclosed Mast/Sensor (AEM/S)* (featured in this Digest) and the Multifunction Electromagnetic Radiating System (MERS) to provide an array of options to design and implement clean topside concepts that reduce ship signatures significantly and provide important improvements in ship C4I and combat system capabilities.

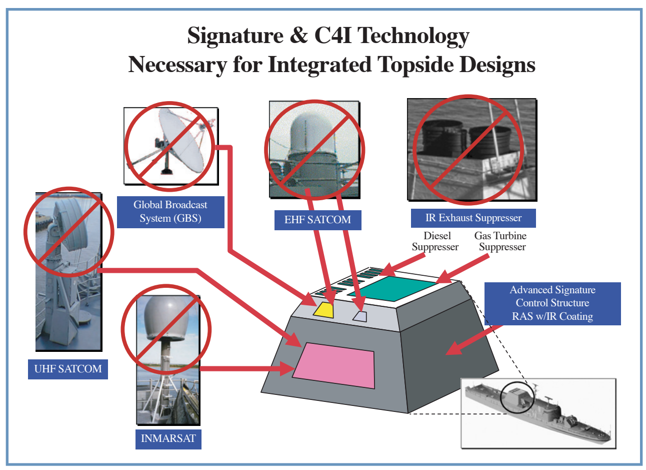


Figure 1. LMS concept.

The signature performance requirements for each of the major LMS components were established based on signature budgets developed by the Naval Sea Systems Command for future combatants. The signature budgets define RCS goals for major Hull, Mechanical and Electrical (HM&E) systems and for major C4I systems, and IR goals for the stack and plume, non-stack and plume surfaces, and secondary hot spots. Table 1 shows how the signature budgets apply to the LMS components.

Table 1. LMS signature budget application.

	Exhaust Suppresser	Exhaust Shroud	SATCOM Antennas
HM&E RCS	4	4	
C4I RCS			4
Stack & Plume IR	4		
Non-Stack & Plume IR		4	
Secondary Hot-Spot IR			4

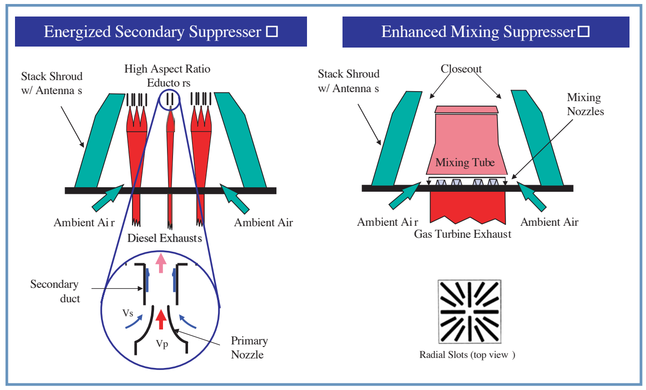


Figure 2. Suppresser concepts.

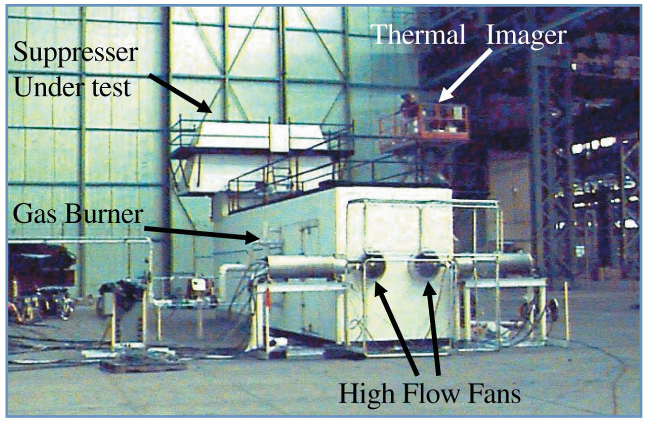


Figure 3. Hot-flow test rig located in Memphis, TN.

Exhaust Suppresser Concepts

Engine exhaust systems are significant contributors to the IR signature on modern naval ships. The two elements of exhaust systems that need treatment are the hot uptake components and the exhaust plume itself. The challenge in exhaust suppresser development is to eliminate the view of any hot or even warm parts from the view of the threat sensor, reduce the radiant intensity of the exhaust plume, and minimize the ship design impact of the suppresser implementation.

Cross-sectional sketches of the two exhaust suppresser concepts developed for the LMS are illustrated in Figure 2. The left side of the figure depicts the energized secondary suppresser (ESS), which uses flow control technology to maintain cool surfaces along the visible eductor walls, shown as the secondary duct in the enlargement. The ESS design induces significant quantities of ambient air for plume cooling, and employs high aspect ratio (long and thin) nozzles to increase mixing of the hot exhaust with the cooling air.

The right side of Figure 2 portrays the Enhanced Mixing Suppresser (EMS). The EMS uses advanced nozzle concepts to intensify the mixing of hot exhaust and induced ambient air and thus reduce the plume signature. The exhaust is separated into 16 high aspect ratio nozzles arranged in a radial pattern, as illustrated in the top view sketch. The EMS eductor mixing tube is significantly shorter than legacy suppresser systems. The hot mixing tube is hidden from the line of sight of low flying sensors by the surrounding structure, and a thermally controlled close-out surface prevents secondary heating due to plume radiation. The ESS and the EMS are housed in a low RCS composite shroud described in the next section.

These new suppresser concepts offer significant improvements in RCS and IR signature control, physical size, and topside weight over existing suppresser designs. The concepts were developed through a series of scale model cold-flow tests at the Naval Surface Warfare Center, Carderock Division (NSWCCD) and the Naval Post Graduate School, Monterey, CA, and with hot-flow tests at the Hot-Flow Test Rig at NSWCCD's Memphis, TN, site (Figure 3). Cold-flow tests provided important information about the system performance in terms of the mass flow rates, flow momentum expansion, and the fluid flow behavior for short ejector designs. Hot-flow testing was necessary to provide details of the suppresser thermal performance and to establish methods to stabilize and control the flow in the secondary ducts in the presence of over-the-deck cross wind conditions.

One of several technical challenges in the design of the suppressers was to account for the fact that, after the hot exhaust exits the primary duct, the thermal boundary profile expands at a greater rate than the momentum boundary profile. This attribute is illustrated in Figure 4, and is expressed by the Prandtl Number given by:

$$\Pr = \frac{\mu C_p}{\kappa}$$

where for the hot exhaust:

μ = absolute viscosity
C_p = specific heat at constant pressure
κ = coefficient of thermal expansion

The Prandtl Number represents the ratio of the rates at which the momentum and thermal boundary profiles expand. The Prandlt value is < 1.0 for hot exhausts. While this fact was an important first step in establishing the basic concept for the suppresser design, the actual value of the thermal expansion angle is the determining factor in how

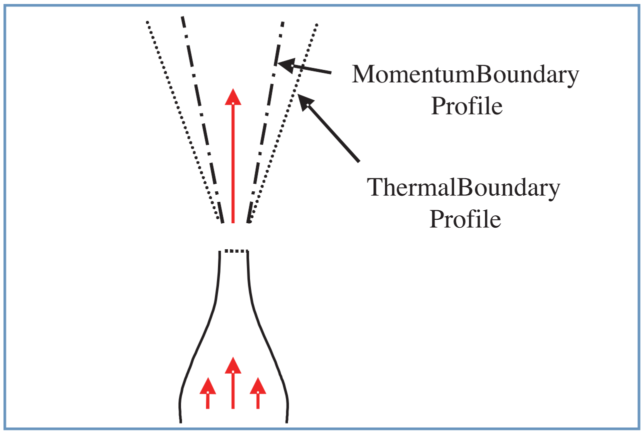


Figure 4. Thermal spreading.

well the suppresser performs. This is because the design must ensure that there is no contact of even warm exhaust with the surface parts that can be viewed from the threat sensor.

Approximations of the expansion angles were developed using Abramovich's[1] formula for the two-dimensional spreading angle:

$$\alpha = \tan^{-1}\left(C\left[\frac{1-m}{1+m}\right]\right)$$

where

$$m = \frac{u_2}{u_1}$$

and

u_1 = exhaust velocity
u_2 = co-flowing velocity
C = experimentally determined coefficient.

Experimental data from the literature was used to establish values of C for the momentum and the thermal boundaries and the subsequently calculated expansion angles were used to establish the basic suppresser geometries. However, due to the asymptotic nature of the thermal profile, the literature reports significant variations in what the actual thermal expansion angle will be for a hot plume. Therefore, the actual thermal performance can only be determined with hot- flow tests.

Shroud Design

To meet the RCS and IR signature goals established for the LMS, the shroud around the exhaust suppressers is constructed of advanced signature control composite materials. The LMS project investigated three Radar-Absorbing Structure (RAS) concepts for the shroud, as shown in Figure 5. In addition to analytic design and coupon testing of the RAS options, medium scale RAS pyramids were built by the Northrop Grumman Ship Systems (NGSS) Full Service Center (FSC) and tested in the Naval Air Warfare Center (NAWC) RCS indoor range, as shown in Figure 6.

The layered dielectric RAS was the only one that met the performance requirements established for the LMS shroud structure, but the cost of this option was higher than desired. A lower-cost alternative approach to manufacture dielectric layers for the RAS was developed at the NSWCCD materials laboratory. Using these lower-cost layers, a shroud structural concept was developed that incorporates the layered dielectric absorber into a structural sandwich composed of e-glass, foam-core, and balsa-core materials. The construction of this structural sandwich borrows heavily from prior structural composite efforts to provide a system that is robust and suitable for the shipboard environment.

A newly-developed IR reflective paint is used on the outside of the LMS shroud. The paint incorporates IR reflective pigments that are manufactured using a process developed in a recent Navy Small Business Innovation Research (SBIR) program executed by Sigma Labs and

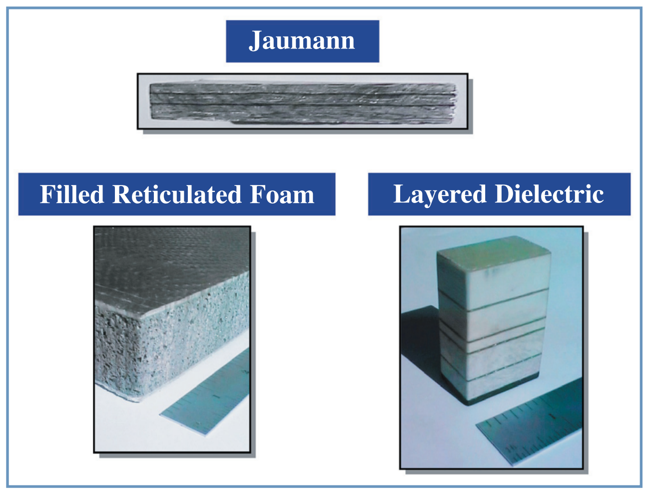


Figure 5. RAS options.

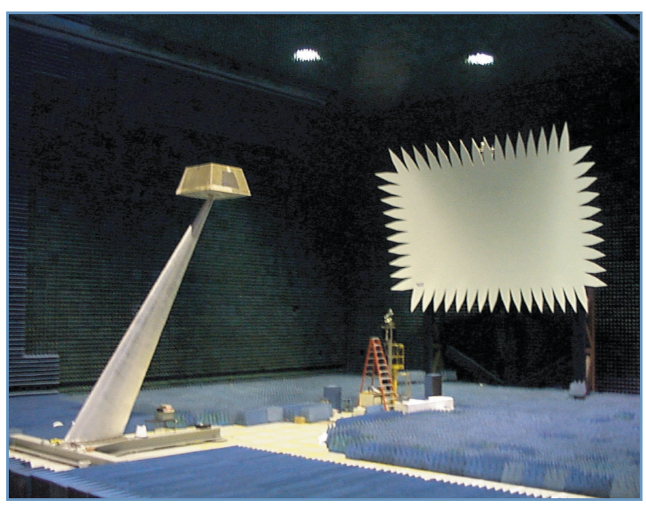


Figure 6. RAS pyramid tests at NAWC, Pt. Mugu, CA.

managed by NSWCCD. The pigments are incorporated in a binder similar to the ones used in current Navy paint systems.

Antenna Concepts

The SATCOM antennas in use by the Navy have RCS signatures that are significantly above the C4I RCS goals established for the LMS and needed for new ships. Two new antenna concepts were developed for the LMS under the leadership of the SPAWAR Systems Center, San Diego, CA. The first is a dual function antenna, developed by Ball Aerospace, that uses 10 Vitreous™ ultra-high frequency (UHF) elements stacked on top of 244 L-band elements. The antenna elements are embedded into a composite radome structure that is built as an integral part of the LMS shroud structure. A sub-array consisting of one UHF element and 32 L-band elements was built and tested as part of the development process and is shown in Figure 7.

The second antenna concept, developed by the Boeing Company, consists of separate transmit and receive arrays to handle EHF, MILSTSAR, and Global Broadcast System (GBS) functions in the same array set. The receive array contains 4000 elements, and the transmit array contains 512 elements. These arrays are mounted conformally with the surface of the LMS composite structure. A 256-element sub-array of the EHF/GBS receive antenna used as a proof of concept is shown in Figure 8. Signature control for the LMS antennas is achieved by using the planar phased arrays and by incorporating frequency selective design features into the antenna architectures. The antenna designs also incorporate appropriate electrical transition features between the antennas themselves and the RAS of the LMS shroud.

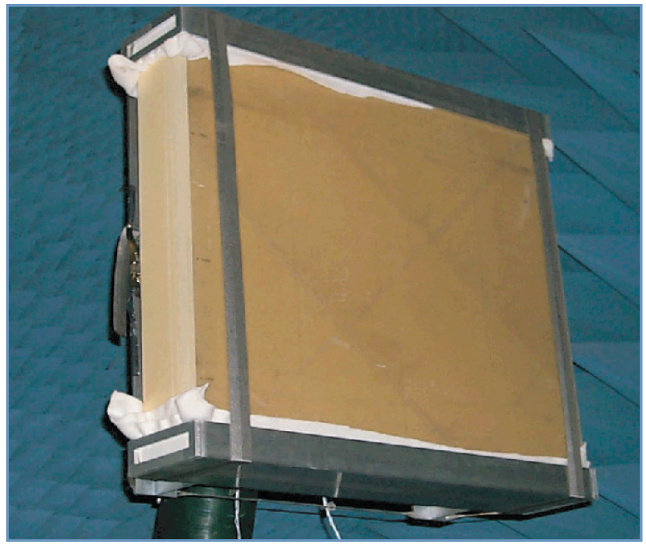


Figure 7. UHL-band sub-array in Ball Aerospace test range

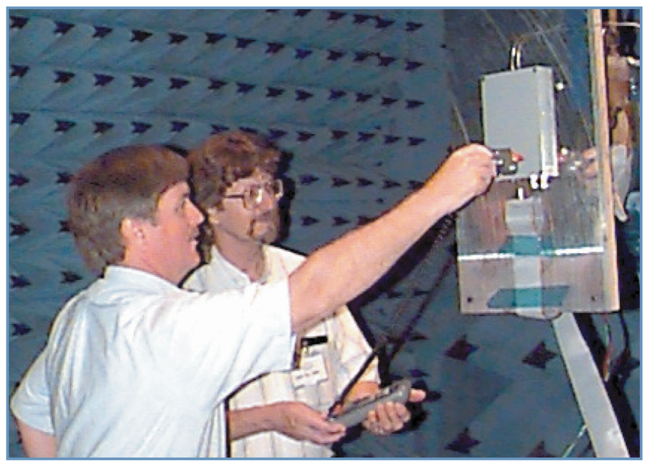


Figure 8. EHF/GBS sub-array in Boeing test range.

LMS Testing

The LMS suppressers, shroud, and antennas were assembled as a unit and mounted on a rotator for land-based RCS tests at the NGSS Near Field Radar Reflectivity Range (NFR3) as shown in Figure 9. The RCS tests not only determined the total LMS signature, but also the signature contribution of each of the LMS component parts. The LMS was then installed on an ex-ASHEVILLE–Class patrol gunboat operated by NSWCCD for “at-sea” tests (Figure 10).

The at-sea tests allowed evaluation of the performance of the EMS and ESS exhaust system concepts on gas turbine and diesel power plants, respectively, while operating in realistic conditions. The at-sea tests also allowed evaluation of the shroud IR signatures when operating in a shipboard environment. Future testing will further evaluate the performance of the LMS Antennas. The land- based and at-sea tests provide data needed for follow-on design of ship applications of the LMS technologies.

Figure 9. LMS RCS Testing.

™Vitreous is a trademark of Ball Aerospace

Figure 10. Ex-ASHEVILLE Class patrol gunboat with LMS installed.

Summary

The need for stealth and for a robust C4I capability in modern warships creates the challenge to develop clean topside architectures that incorporate signature control shapes and materials, treatment for IR signature sources, and low-observable antennas. The LMS ATD provides solutions to many of the outstanding technical problems associated with implementation of these architectures. In particular, the LMS provides concepts for two advanced, exhaust suppresser systems, a radar-absorbing deckhouse structure with IR signature control paint and two advanced antenna array systems. The technology was developed by a team of industry and Navy researchers to meet specific signature goals for ship subsystems. The development of these technologies started with the computational analysis of potential solutions, proceeded to scale model or coupon tests of the solutions, and culminated in a full-scale at-sea demonstration of the evolved concepts.

Acknowledgements

The LMS demonstration could not have been achieved without the guidance and support of the ONR project officer (Mr. James Gagorik), and the NAVSEA and SPAWAR Execution Managers (Mr. Neil Baron and Mr. Richard Woods respectively). In addition the team work and professionalism of the major Navy and industrial participants were critical to the projects success. They were Anteon Corporation; Ball Aerospace and Communications Group; Boeing Phantom Works; Naval Post Graduate School; Northrop Grumman Litton Ship Systems; MAR, Incorporated; and Space and Naval Warfare Systems Command Systems Center, San Diego.

Reference

1. Abramovich, G.N., *The theory of turbulent jets*, M.I.T. Press, Cambridge, MA (1963).

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Design and Integration of the LPD 17–Class Advanced Degaussing System

Dana W. Hesse

The degaussing system being incorporated into the SAN ANTONIO (LPD 17)–Class amphibious assault ships is unlike any ever designed for a U.S. Navy steel-hull surface ship class. Early in the design phase, the expeditionary warfare community expressed a desire for greater protection for LPD 17–Class from magnetic influence bottom mines because of mission requirements that emphasize operations in littoral regions. This paper addresses the evolution of the degaussing system from an unsophisticated stand-alone electrical system to a state-of-the-art, fully-integrated, computer-controlled electronic countermeasures system that reduces susceptibility to magnetic mines while being affordable and maintainable.

Introduction

Ever since the widespread use of magnetic-influence sea mines by the Germans in World War II, it has been standard practice for navies to build their ships with organic self-protection "degaussing" systems to minimize the ships' magnetic signatures.[1] Technologies and procedures developed during the 1940s and 1950s for magnetic signature control of steel-hull surface ships (SHSS) have changed little in the subsequent decades. Even the ARLEIGH BURKE (DDG 51)–Class destroyers being built today have a degaussing system architecture very similar to those that Admiral Burke himself commanded during the war.

Shortly after the Gulf War, the Navy formally shifted its stated likelihood of future conflicts away from the "blue water" Cold War mid-ocean confrontations with the Soviets, toward the "green water" littorals near the familiar trouble spots like the Persian Gulf, Taiwan, Korea, and the Adriatic. All areas of mine warfare were studied for improvement, including mine hunting and minesweeping, particularly by the AVENGER (MCM 1) and OSPREY (MHC 51)–Class mine warfare ships, and by helicopter/sled minesweeping systems. Many improvements have been made in the U.S. Navy's dedicated mine warfare capability since the Gulf War. However, it was determined that there was still a need for improved mine countermeasures as part of the organic self-protection and signature management systems of all SHSS classes.

In the mid 1990s, the Naval Sea Systems Command (NAVSEA) began design of the LPD 17–Class of ships. This class of 12 ships was to replace an aging Fleet of 41 LST 1179, LKA 113, LSD 36, LPD 1, and LPD 7–Class amphibious warfare ships. The LPD 17–Class is to be the premier, high-profile, multimission amphibious ship class of the first half of the 21st century, and has a very high military value given the multiple ships each LPD 17 replaces. By definition, amphibious warfare ships perform combat missions in the shallower littorals and, as such, are more likely to encounter an enemy minefield than the cruisers and destroyers which can fulfill most of their missions at a safer standoff distance many miles from enemy shores.

Rather than take the traditional stovepipe approach to this opportunity for new technology insertion, NSWCCD was strongly encouraged by the LPD 17 program office (PMS 317) to fully integrate the degaussing system products with the rest of the systems being specified for the ship. There were significant cultural differences between the Division's degaussing system designers and the myriad of other systems being integrated on the ship. However, after the initial hurdles were overcome, it became obvious to all that this was the right approach.

As a result, the degaussing system has graduated from being a "dumb" stand-alone electrical system to a fully-integrated, fully-networked electronic countermeasures system, developed in parallel and in close coordination with sister systems. An immediate payoff was that a lower off-board magnetic signature could be achieved with shorter system calibration time. Total ownership cost (TOC) minimization has been and continues to be a primary design goal of the project, as reflected in the high level of built-in-test (BIT) and automated self-monitoring features.

Background: Mine Warfare Ships versus Steel-Hull Surface Ships

This paper emphasizes the integrated nature of the LPD 17 "Type ADG" advanced degaussing system. However, some background in degaussing system terminology and concepts is in order first.

Mine Warfare Ships

Typically, mine warfare ship classes are designed to have a very low magnetic signature. They are made of non-magnetic construction materials such as stainless steel, wood, fiber glass, and glass-reinforced plastic (GRP). In the U.S. Fleet, MCM 1–Class minesweeper hulls are made of wood with a fiberglass overcoat, and MHC 51–Class mine hunter hulls are made entirely of GRP. Most equipment installed in these ships typically is nonferrous or partially ferrous. Even so, there are many equipment items, engine parts, motors, generators, lockers, etc, that are ferrous enough to have a magnetic signature and require compensation. Over 100 items on a MCM 1–Class ship have been identified to be magnetically significant, of which 40 are deemed to be important.

To compensate for the magnetic signatures of these items, a large number of degaussing loops are installed in orthogonal directions around the spaces containing the items. There are typically 82 loops on MCM 1–Class minesweepers. Each space containing large magnetic items (e.g., engines, gas turbines, generators) typically has several degaussing loops surrounding it in all three geometric planes (vertical, longitudinal, athwartship) to compensate for the three-axis magnetic source produced by the items. Degaussing loops that provide vertical compensation are called "M-loops," those for longitudinal compensation are called "L-loops," and those for athwartship compensation are called "A-loops." This fully orthogonal approach is called a "MLA" design for brevity.

Each degaussing loop is made of small multiple-conductor cables of low current capacity, and is connected to its own power amplifier in the degaussing system equipment rack. The magnetic field generation capability of each loop is multiplied by connecting the many conductors of the same cable head-to-tail in a series fashion such that 100 to 200 ampere-turns (A-T) of effect can be achieved with a power amplifier rated at only 4 amperes.

The total current output from each amplifier is set at calibration time to be the sum of three components: permanent, induced, and eddy. The permanent component relates to compensation of the permanent ferromagnetic signature of the source item(s), which is assumed to be a constant value. The induced component relates to compensation of the induced ferromagnetic signature of the source item(s), which is in direct proportion to the external magnetic field of the Earth impinging on the ship, further broken down into XYZ components. The eddy component relates to the time-rate-of-change of the inducing magnetic field as the ship rolls, pitches, and changes heading while underway, causing eddy-currents to be generated in any conducting ferromagnetic or nonmagnetic body.

The external magnetic field of the Earth is measured by a three-axis magnetometer on the ship's mast, where it is far away from the magnetic sources of the ship. Each degaussing loop's amplifier has control settings in it that identify the primary axis of compensation and the relative amplitudes and phase angles of the three components that make up the total output current.

Steel-Hull Surface Ships

The design of degaussing systems for SHSS historically has been very different than for minesweepers. A steel hull and structure surrounds the internal items and effectively shields them; therefore, degaussing loops are installed to compensate for the hull structure itself as opposed to individual magnetic items. The total number of loops is relatively small, the area enclosed by each loop typically is very large, and the magnetic field generation capability of each loop is a minimum of 1000 ampere-turns. Most importantly, all loops of the same axis are electrically connected together in series and driven by one large capacity power supply. This, in effect, reduces the number of independent control variables from 82 for a MCM 1–Class ship, down to 3 or 4 for most SHSS classes.

A single loop's magnetic compensation calibration cannot be adjusted with a simple dial adjustment as on a minesweeper. Instead, a large electrical connection box must be accessed, and the series order of the connection of conductors must be changed. This is a very arduous and time-consuming task and is so difficult and prone to error that, typically, a ship's force does not even attempt it; an expert technician from a Fleet Magnetic Silencing Facility (MSF) will do the job. Figure 1 is a block diagram of a typical DDG 51–Class degaussing system, showing the four large power supplies and the individual degaussing loops of one axis wired together as one load.

The other major difference between SHSS and minesweepers is in the area of longitudinal magnetization compensation. Virtually all present day SHSS classes employ a "two-axis" design by installing "F-loops" (forecastle) and "Q-loops" (quarterdeck) in the horizontal plane of the ship (Figure 2a) and wiring them together with opposite polarities. This antiquated technique attempts to generate compensating longitudinal magnetic flux under the ship. In other words, F and Q loops (FQ method) are geometrically the same as M loops, and only attempt to compensate longitudinal flux under the ship by wiring connection polarities. Thus, the two-axis system is comprised of loops that by themselves can only generate vertical or athwartship fields.

The FQ method historically has been preferred because of its lower shipbuilding cost and lower operating power requirement over a true three-axis MLA design. However, this approach was not sufficient for LPD 17's planned operational mission requirements and signature limits when operating in littoral regions against a modern mine threat. A degaussing system that looked more like a minesweeper's than a traditional steel-hull combatant's was in order (Figure 2b).

Since the ship is a three-axis magnetic source, the best way to compensate it is with a true three-axis degaussing system. An isometric view of the LPD 17–Class degaussing loops is shown in Figure 3. Dramatic improvements in signature reduction can be achieved by replacing the FQ coil system with a properly installed and calibrated L coil system, and by maximizing the available degrees of freedom in calculating a real-time degaussing solution by controlling individual power amplifiers on each degaussing loop. The differences between a traditional and advanced degaussing system design are summarized in Table 1.

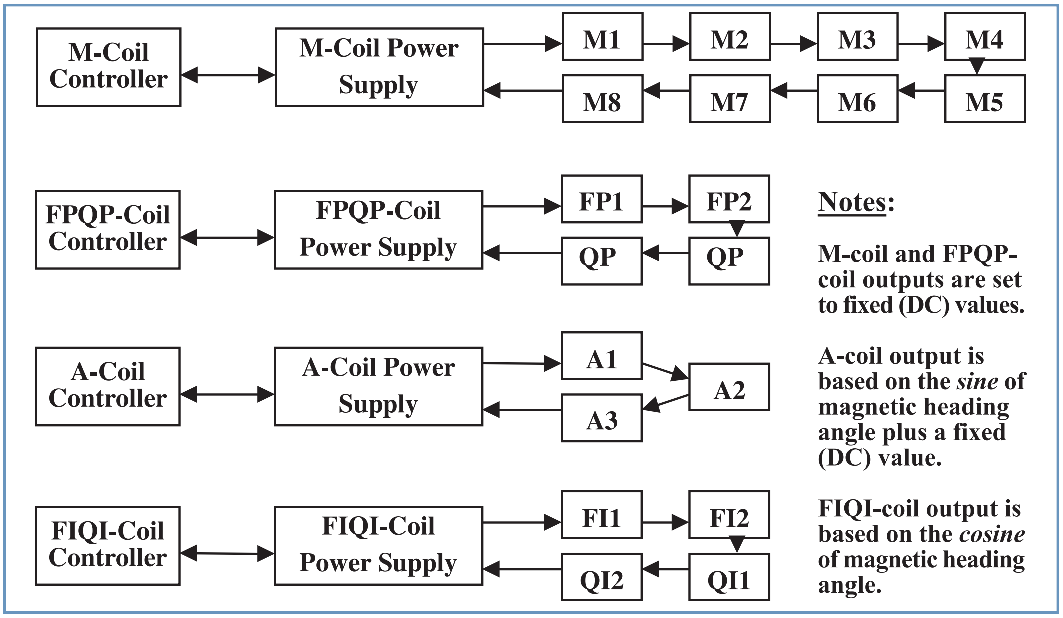

Figure 1. DDG 51–Class degaussing system.

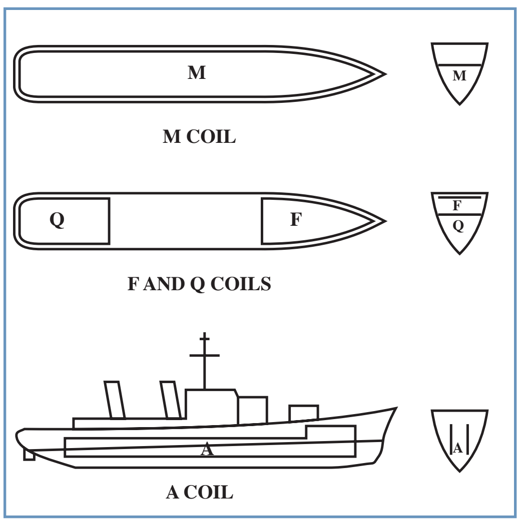

Figure 2a. MFQA degaussing loop geometries.

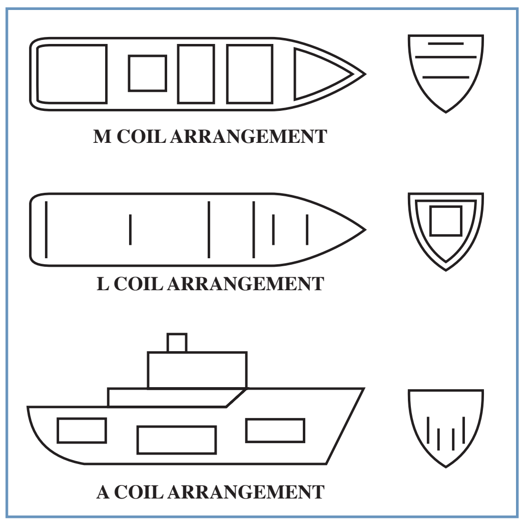

Figure 2b. MLA degaussing loop geometries.

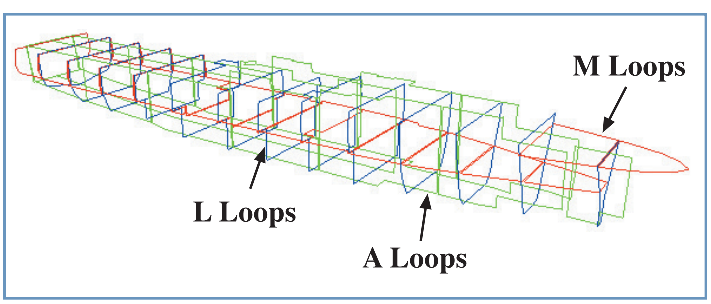

Figure 3. Isometric view of LPD 17 MLA degaussing loop system.

Software and Hardware Development of the Type ADG System in the LPD 17 Teaming Environment

From 1994 to 1999, the Division was tasked under the ONR funded Advanced Degaussing Technology Program to work with NAVSEA and PMS 317 to develop the detailed ship specification language necessary to implement advanced degaussing for the LPD 17 procurement. No longer a trivial cut-and-paste from the NAVSEA General Specification for the Design of Ships, this effort required much self-education about the other parts of the ship specification and the systems being developed by other organizations.

Table 1. Major differences between traditional and advanced degaussing systems.

Quality	Traditional Degaussing System	Advanced Degaussing System
Number of loops	Smaller (<20 typical)	Larger (20+ typical)
Number of power amplifiers	Few (1-4)	Many (one per loop)
Average enclosed area per loop	Larger	Smaller
Ship axes that are adequately compensated	Vertical, athwartship	Vertical, athwartship, longitudinal
Ship motion inputs	Heading only (analog)	Roll, pitch, heading (10 to 50 Hz digital)
Source of Earth's magnetic field lookup for ship's present position	Very crude paper charts, accurate to 10% to 15%	Software mathematical models, accurate to 1% to 2%
Eddy-current compensation	Not possible	Possible
Controller type	Analog	Digital
Intra-system communications	Analog	Digital
Recalibration/adjustment methods	Cumbersome reconnection of large-gage wires in junction boxes	Simple updates to software configuration
Construction cost	Lower	Higher (more cable & tank penetrations)
Power consumption	Lower	Higher
Maintainability	Fewer components with minimal BIT features	More components but with many remotely accessible BIT and fault isolation features

For example, the following questions needed to be answered. What were the preferred computer system hardware, operating software, programming language, and application program interfaces? What would the capabilities and specifications of the Shipboard Wide Area Network (SWAN) be? In the end, a specification package was generated that not only contained traditional items like locations and cable types of degaussing loops, but also detailed hardware, software, and interface specifications for the components of the new Type ADG architecture. Table 2 contains the particulars of the LPD 17–Type ADG degaussing system specification.

A unique situation was established whereby the Division was responsible to ensure that the overall degaussing system was developed, tested, and delivered according to the Navy's needs; now, the Division also will supply the Navy-developed critical technology to the shipbuilder for integration. A high-quality, bug-free, well-documented and timely software product as Government Furnished Information (GFI) must be delivered to the shipbuilder and maintained over the 40-year life cycle of the ship.

Even prior to the award of the LPD 17 contract in 1997, the Division had contracted with Vitro Corp. (now BAE Systems) of Silver Spring, MD, to develop and support the Type ADG GFI software product. Knowing that military-grade software development and support would be required under MIL-STD-498, this experienced contractor was brought on board early in the process to help formulate requirements, define processes, and eventually code, test, and deliver the final GFI product to the winning shipbuilder team.

Table 2. LPD 17 degaussing system features.

Feature/Parameter	Specification
Number of degaussing loops	42 (15 M loops, 13 L loops, 14 A loops); total cable length ~90,000 ft
Number of Bipolar Power Amplifier Units (BPAUs)	63 (some loops will have multiple BPAUs connected to them due to excessive resistance of the loop cable conductor series connections)
Input voltage	440 Vac Type I shipboard power
Rated output current	±17.0 amperes (±18.7 amperes during overload condition)
Rated output voltage	±350 volts
Rated output power (continuous)	6000 watts
Output current accuracy	(1% of rated current during normal conditions; <2% during transients)
Maximum weight	160 kg (350 lb)
Dimensions	600 mm wide x 380 mm deep x 1100 mm high (23.6 x 15 x 43.3 in.)
Operational temperature/humidity	0° to 50° C; 95% noncondensing
Shock/vibration/EMI/noise	Grade A shock; MIL-STD-167/1; MIL-STD-461D; MIL-STD-740-1 “B”
Mounting	Bulkhead-mounted near the degaussing loop junction box

In May 1996, the LPD 17 shipbuilding contract was awarded to an alliance of Avondale Industries, Inc. (Now part of Northrup Grumman, Corp.), Bath Iron Works (BIW) Corp., and Raytheon Systems Co. (RSC). Contract execution was delayed until April 1997, after which the new team of government and industry partners began work on the design and manufacture of the Type ADG system for LPD 17. Thus, the Magnetic Signature Control Subsystem (MSCS) Integrated Product Team (IPT) was chartered in August 1997, as part of the Integrated Shipboard Electronics Team (ISET) at Raytheon (formerly Hughes Electronics in San Diego, CA).

Integration of the Type ADG Degaussing System into the Total LPD 17 Environment

Figure 4 shows the MSCS system as presently configured (with partner subsystems identified). There are a total of 63 Bi-Polar Amplifier Units (BPAU)s located throughout the ship, each driving part or all of the particular degaussing loop load. There are 42 degaussing loops specified for the ship, and 12 of them had so much resistance that the load needed to be split among two or more BPAUs.

It is remarkable to note that there is no physical connection between any MSCS component and any other. All communication and control is done via the SWAN, even among BPAUs, which “share” a degaussing loop load. Such sharing is done strictly through identical software commands, as there is no electrical connection between BPAUs. Each BPAU is powered by local 440 Vac power in the zone in which it is installed, and has dual-fiber network interface cards that are installed into the BPAU’s Pentium II single-board computer. All communications follow standard protocols and Application Program Interfaces (APIs) that have been published by the SWAN IPT.

All communication with partner subsystems likewise is accomplished over the SWAN.

- Shipboard Status Monitoring Subsystem (SSMS), which receives multilevel status outputs from MSCS and sends status request messages to it.
- Machinery Control Subsystem (MCS), which performs a similar function as SSMS and also makes audible alerts in case of trouble.
- Navigation Data Distribution Subsystem (NDDS), which provides high data rate (50-Hz) ship attitude and position data to MSCS from the Navigation Sensor System Interface (NAVSSI);
- Ship Control Subsystem (SCS) bridge workstation, which provides backup navigational data in case of failure of NDDS.

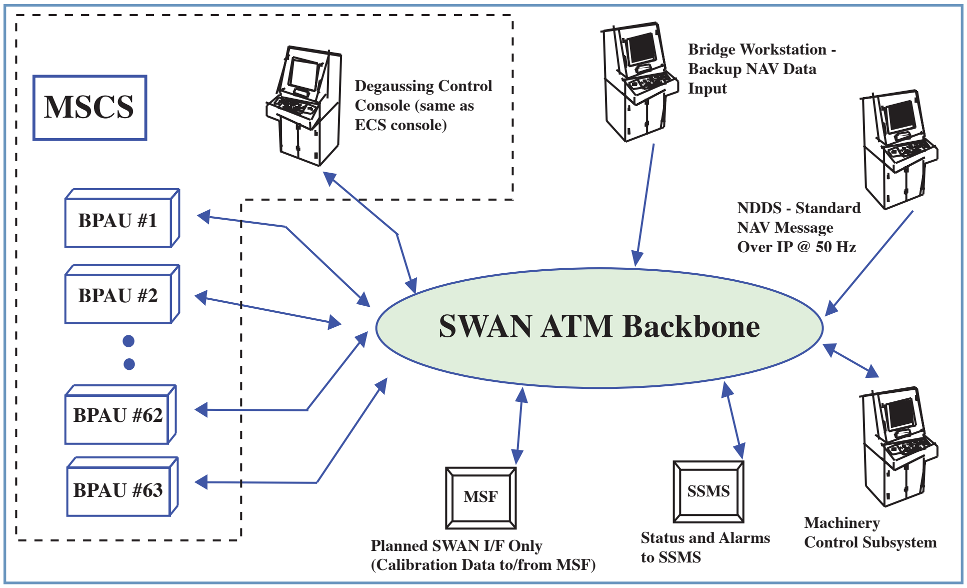

Figure 4. LPD 17 Type ADG degaussing system. (Figure courtesy of Raytheon Systems Co. All rights reserved.)

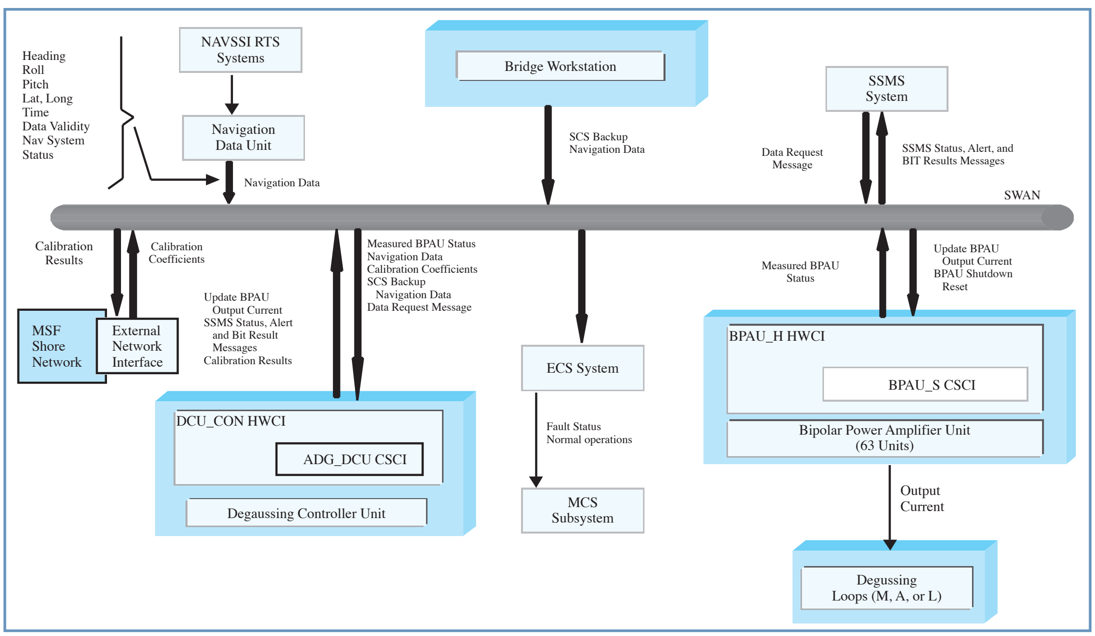

Figure 5. LPD 17 Type ADG degaussing system communications. (Figure courtesy Raytheon Systems Co. All rights reserved.)

Figure 5 shows a more detailed message flow diagram between the subsystems that comprise MSCS. The level of status and fault reporting communications that is being delivered is unprecedented for a degaussing system. From the DCU, an operator will be able to operate, test/diagnose, and fault isolate down to the subassembly level within each of the 63 BPAUs. An on-line technical manual will be accessible from the DCU as well. From anywhere on the ship, anyone with the right permissions can launch an SSMS display and inquire into the degaussing system status hierarchically down to the internal BPAU subassemblies. The transit time saved by a Sailor is critical with a ship the size of LPD 17.

Automation Enhancements

Under manual degaussing methods, a crude paper chart was used to estimate the local Earth's magnetic field and program the degaussing controller. This method could have a peak error of up to 11,000 nanotesla and relies solely on the diligence of ship's force to dial in the correct values every day as the ship transits from one part of the Earth to another. With LPD 17, the software continuously makes new predictions of the local Earth's magnetic field to an accuracy of several hundred nanotesla and requires no human intervention. The result is a more accurate magnetic compensation with less human interaction.

Automation has been used to improve the degaussing range crossing function as well. Most ships when leaving or entering their homeport will cross over the degaussing range that is embedded in the main shipping channel. If they wish, they can have their off board signature checked by the technicians on shore and can report their degaussing status and current amplitudes via voice radio circuits. The degaussing range thus keeps paper-based records of all the ships home ported there, and relies on clear voice communication and accuracy in their note-taking. With LPD 17, the operator of the degaussing system will have a very simple software user interface to operate during the ranging event, and the Type ADG software will generate a text file automatically that captures all relevant internal information. Once cleared for release by the ship, this file can be transmitted either by e-mail or by naval message to the shore facility. Much more information on the internal status of the onboard system will thus be conveyed to the degaussing range with fewer errors and less human interaction. (A futuristic goal is to have the Type ADG software monitor the lat/long position of the ship continually, to be able to decide if the ship is approaching one of the known degaussing ranges, and to execute all degaussing range crossing operations autonomously without any human interaction or even human knowledge that this special data capture event took place.)

In general, the design of the LPD 17 system software allows the operator in one space to "drill down" through several layers of hierarchical status and error messages on a particular BPAU power supply located elsewhere on the ship. Thus, a particular spare part within a BPAU that is indicating a fault could conceivably be retrieved from a storeroom prior to accessing the faulty BPAU, saving overall repair man-hours. This is not possible with standard degaussing equipment. Only a summary fault indication is received at the controller, and it is left to the sailor to follow manual fault isolation and repair procedures on the faulty equipment at the remote location.

Current Status and Future Plans

As the team works out the integration issues between the MSCS components, it will add communications with partner subsystems. Land-based integration testing should last through 2002, and shipboard integration testing will take place in Avondale in the 2002-2003 timeframe.

As each ship is built, it will be sent for magnetic treatment at a Fleet MSF just like all new construction ships. The new degaussing system will be calibrated and put into operation. External SWAN network access into the degaussing system will be provided so that a ship moored at a deperming facility will have a direct link to the MSF network, and the MSF deperming technician can single-handedly operate both the onboard degaussing system and the off board magnetic sensor data collection and treatment systems. This will save many man-hours during the initial calibration of the ship. As secure wireless networking technology evolves, shore-based MSF operators similarly will be able to operate and/or diagnose an underway ship's degaussing system with minimal actions required by the crew.

Summary

For generations, shipboard degaussing systems have been a collection of unsophisticated electrical equipment that was marginally adequate in protecting the ship from magnetic-influence mines. The Division and its contractors, working as a coherent team, have created a fully-integrated, computer-based system for LPD 17 that will give the ship a marked improvement in protection from the threat of enemy sea mines in an affordable and supportable manner.

Acknowledgments

The author would like to acknowledge Donald E. Pugsley who is a senior Government participant on the Government-contractor MSCS IPT. His contributions in the areas of computer networking and software have been invaluable. Also, Frank P. Koval and Warren F. Stannard are the team leaders at BAE Systems responsible for the development of the Government-furnished software and documentation to the LPD 17 shipbuilding alliance. The high quality of the GFI products delivered to the Alliance is a direct result of the degaussing software team at BAE Systems. Timothy B. Houser and Alan T. Light are the MSCS team leaders at Raytheon Systems Co., and are responsible for the installation of the system on LPD 17. Their management of the IPT has fostered an environment in which all team members work seamlessly regardless of organization or site.

References

1. Hartmann, G.K., and S.C. Truver, Weapons That Wait, (Updated Edition), Annapolis: Naval Institute Press (1991).

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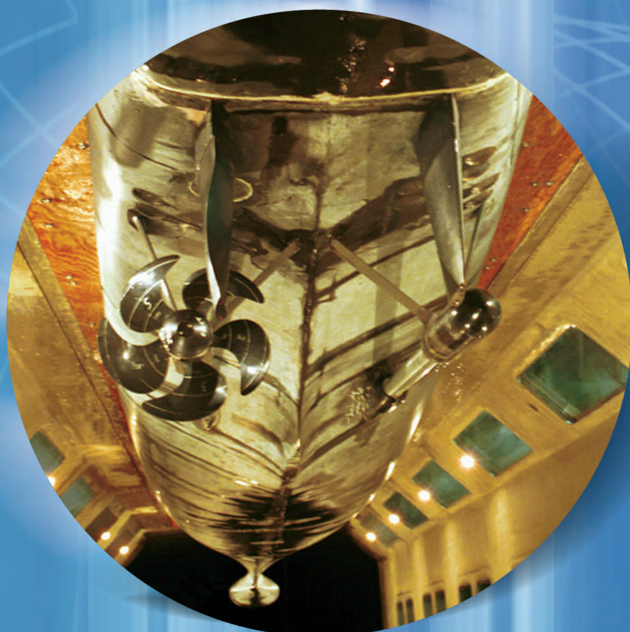


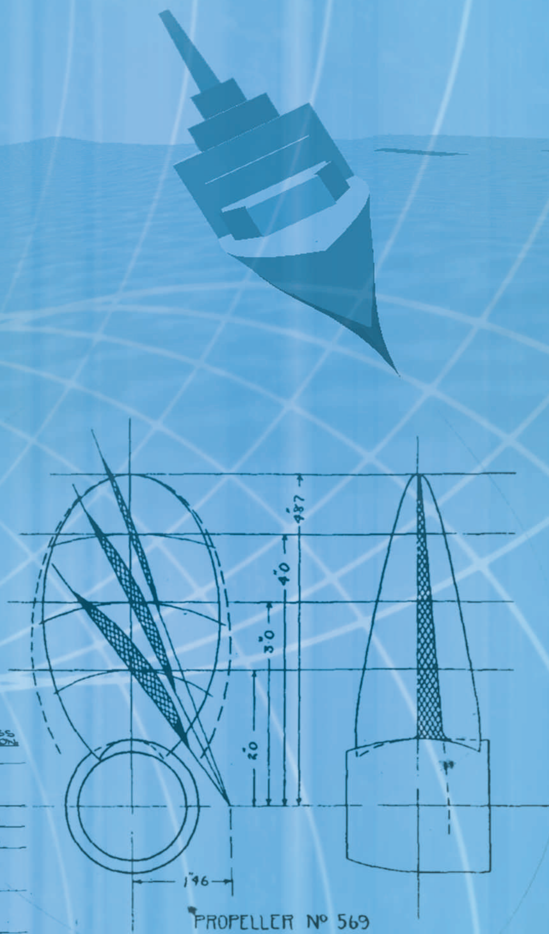
Hull Forms and Propulsors

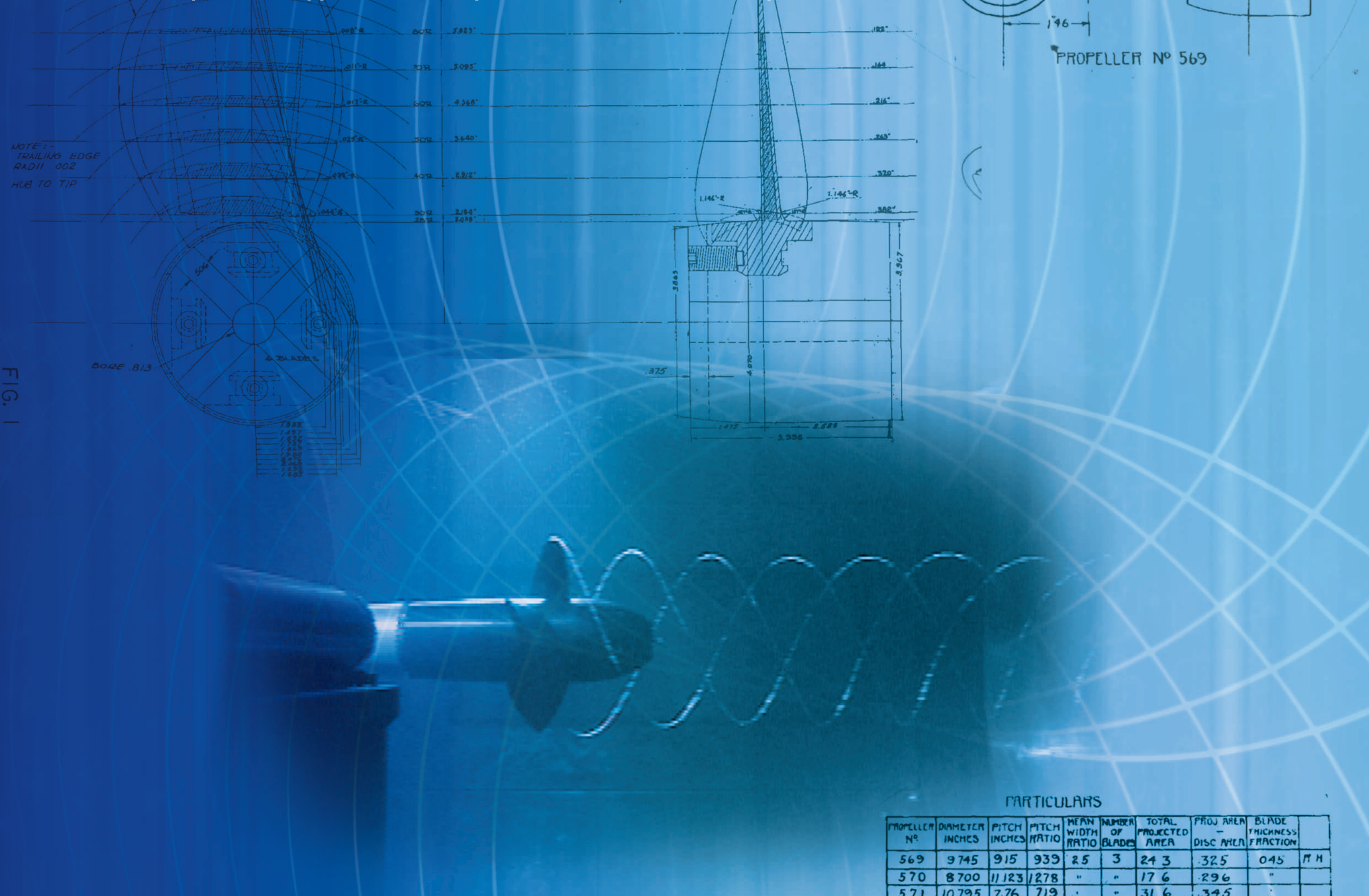
Overview Article Follows

TECHNICAL DIGEST

HULL FORMS & PROPULSORS

This core program area provides the Navy's only technical capability for surface and undersea vehicle hull forms and propulsors. It supports all naval vehicles (surface ships, submarines, unmanned vehicles, and craft) by developing the technologies for systems and procedures which define the external shape of the vehicle, control systems and control surfaces, and its propulsor interaction with the hull and its environment. These systems are necessary to ensure that the performance of each platform meets mission requirements for controllability, mobility, seakeeping and propeller noise. These characteristics to a large part determine the safety, efficiency and affordability of the platform operation, and contribute to its signature characteristics. Extensive and highly specialized model testing facilities are required to support the development and validation of analytical tools.





Hull Forms and Propulsors: An Overview

Michael J. Davis and Joseph J. Gorski

Navy requirements for new missions; greater efficiency; lower signatures; and lower cost ships, submarines, and other vehicles have perpetuated the need for new and improved hull forms and propulsors. NSWCCD's engineers and scientists apply their expertise in hull form and propulsor technology, computational fluid dynamics (CFD) and simulation technologies, and the Division's world-renowned facilities to support these requirements. The cost, efficiency, and flexibility of CFD and simulation technologies are extremely attractive to the design community, when compared to relatively expensive and time-consuming scale models and scale/full-size tests. On the other hand, CFD and other simulation tools vary widely in capability and accuracy, thus requiring verification, validation, and/or calibration. Division personnel have extensive experience with the development and use of these tools as well as with model and full-scale trials using today's advanced technologies. The wealth of data acquired from these efforts, coupled with the Division's unique facilities provides an ideal environment to improve current tools and ship systems and to support new hull form and propulsor designs.

Introduction

Early U.S. Navy shipwrights often built wood models to visualize how a hull would look, and detailed wooden structural models to aid the shipwrights as they built the ship. Benjamin Franklin conducted rudimentary ship model resistance tests with a simple gravity tow model basin. Admiral David W. Taylor was instrumental in institutionalizing a scientific approach to ship and aircraft model testing for the Navy. The Carderock Division's comprehensive hydromechanics testing facilities (Figure 1) owe their origin to his vision and influence.

The Division's facilities, whose origins are found in the Experimental Model Basin constructed at the Washington Navy Yard in 1898, have been used to conduct experiments to improve the naval architect's range of knowledge and to support individual ship designs. The Division has provided hydromechanics research; development; and design support for many ship, submarine, and craft hull forms and their propulsors; examples are shown in Figures 2 and 3.

Though not obvious to the untrained observer, ship and submarine hulls and propulsors (especially those of Navy vessels) have changed significantly over the past 50 years. Evolution in the hull and propulsors arena is contin-

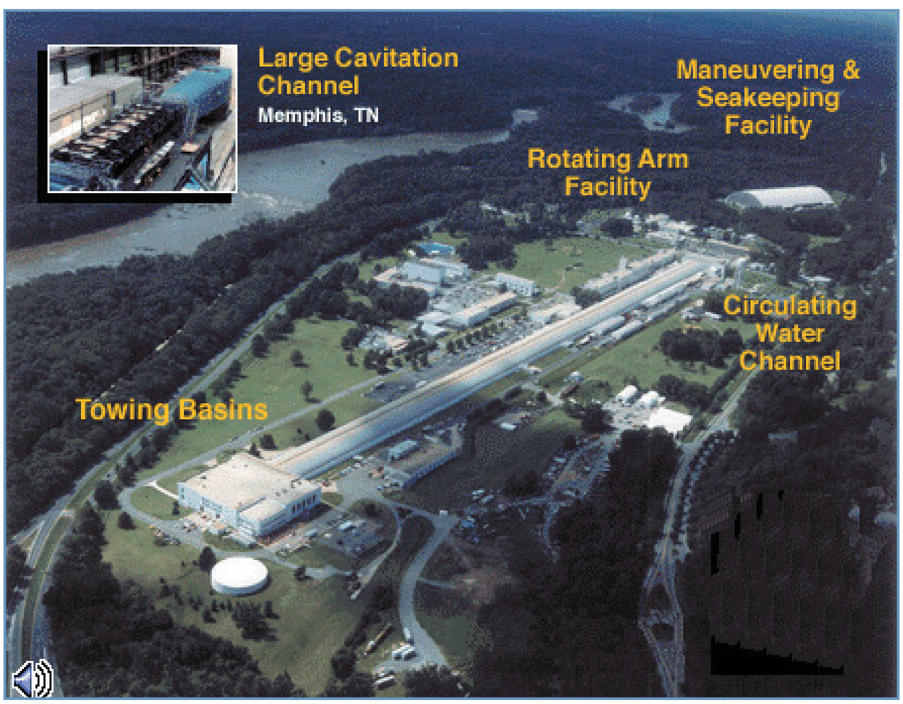


Figure 1. Hydromechanics facilities at the Carderock Division.

ual, as Division technology enables improvements. Future changes will occur with changing mission requirements that evolve from new operational arenas (e.g., littoral regions), new weapon threats, and advances in sensors. These evolving mission requirements may require radical changes to hull forms and propulsors. Current Navy concept designs such as tumble-home hull forms and integrated propulsor/hull designs, and waterjets, which are the propulsor of choice for the high speed ferry community, are examples of such potential significant changes. These mission oriented design variations will benefit from new design support technology under development at the NSWC Carderock Division.

The Division has been at the forefront of the development and application of computational fluid dynamics (CFD) for naval hydrodynamics. With improvements in computer technology and, subsequently, more accurate and timely flow predictions, a new paradigm for design and analysis of Naval vehicles has emerged over the last decade. Still, the combination of experiments and computation (neither of which can provide a complete answer alone) is the best approach to develop new and out-of-the-box designs. Computations provide a complete "picture" of a flow field, which can help in understanding the physics involved and any on-going interactions. However, CFD methods are not always accurate because of modeling deficiencies and computer limitations. Consequently, experiments must determine detailed measurements in critical areas and provide validation and verification of the computations and the final design.

Figure 2. Some hull forms for which the Carderock Division provided hydromechanics research, development, and design support.

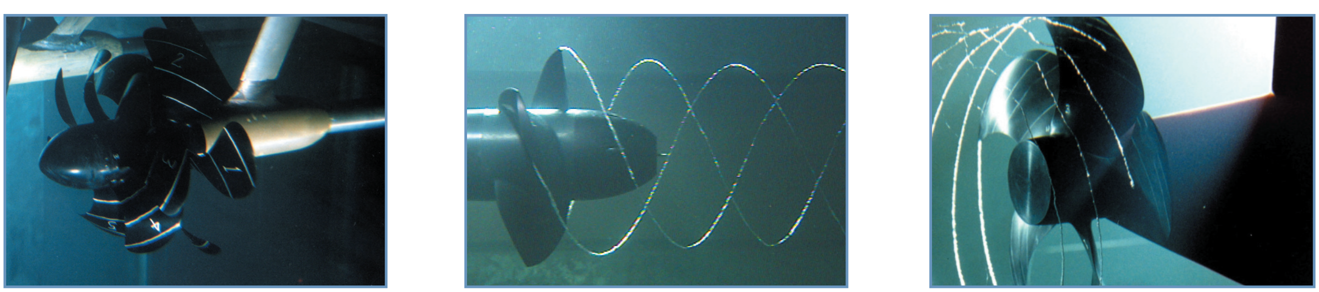


Figure 3. Some propulsors designed by the Carderock Division.

CFD, Simulation, and Model Testing

Simulations for the naval architecture design community, as well as other design communities that work with complex systems, allow design options to be evaluated without the need for physical model tests or large-scale demonstrators. This is desirable from a cost, time, and risk standpoint, and many efforts are underway to reach this goal. The Navy's hydromechanics community is striving to use CFD and other simulations to support the design of new hull forms and propulsors. The state-of-the-art and accuracy of these models varies widely, however. Ideally, a simulation could give predictions with only vehicle geometry input and a time history of environmental conditions, ordered speed, and control surface settings. At their current stage of development, some CFD models assume calm water, constant speed, and fixed-control surface settings. Some of the current motion simulation models require coefficients, generally determined only from model experiments, to examine maneuvering characteristics. These computational tools, though still under development, have been used to support the design of future ships and submarines, as reported by the *Advanced Submarine Sail*, *Extreme Ship Motions*, and *CFD Submarine Maneuvering* papers in this section of the Digest.

The least costly method that provides the desired accuracy generally determines the approach chosen to support a design or investigate an alternative. If available, a CFD or other simulation code that will provide the accuracy required by the designer will be used. Often, however, suitable codes are not available or are in the verification/validation stage. Depending on their capabilities, available codes may be used in conjunction with experimental results. For specific designs or alternatives, a physical model tested in the Division's facilities, in conjunction with applicable CFD and simulation models, frequently offers the necessary information to the designer in less time, for less money, and with greater accuracy than any available simulation code used alone.

Verification, Validation, and Calibration

A modeling process requires accurate CFD and simulation results. Consequently, recent efforts have focused on the verification and validation of computational tools. Verification and validation estimates the accuracy of the numerical process compared to the actual physical process being modeled. Verification ensures that the equations are solved correctly by the computational method; it is often accomplished with analytic benchmarks. Validation assesses the uncertainty of modeling by using benchmark experimental data and estimating the sign and magnitude of the modeling error when conditions permit. The experimental benchmark data must be of high quality and acquired under well-controlled conditions to ensure that the model is accurate and is properly validated.

It is difficult to obtain true values for the physical process that can then be used to compare with predicted or measured values. The easy answer would be to measure the true physical value on the full-scale vehicle. In practice, the predicted values are most often for a vessel that has not yet been built. Also, it is difficult to make accurate full-scale measurements that account for all of the environmental forces acting on the ship or submarine; i.e., current, wind, and waves. Generally, the nature of these forces varies with time and spatial location. The Division's hydromechanics test facilities were designed to address the problem of predicting the performance of vehicles not yet built, and controlling and measuring the environmental conditions acting on the test vehicle. However, examination of data in some of the categories shows variability in model scale data even under controlled conditions. The user of the data must be able to determine when variability can be reduced with additional effort or a different approach. In some cases, variability may be acceptable or unavoidable due to the nature of the phenomena being studied.

Verification and validation requires that conditions be the same for each case being compared. Characteristics such as wave and wind direction, which can be precisely produced and controlled in a numerical simulation, are in reality quite random in nature. Therefore, it can be difficult to compare computed and full-scale or model-scale results unless extremely good measurements have been made of the environmental forces acting on the vehicle. The ability to make these measurements and decisions comes only from hands-on experience under the guidance of personnel with specific expertise.

Often, a simulation will correctly predict the trends in motions or forces resulting from a hull form or propulsor design change but will not give the absolute value of the motion or force. In many cases, model-scale data can be used to calibrate the simulation prediction and verify the trends. Then, the simulation can be used over a range of similar hull forms or in conjunction with model testing to reduce the number of test conditions that must be examined. Again, the experience and judgment of the user is critical to determine if the simulation process is accurate enough for the required use and if the simulation is being configured and applied correctly.

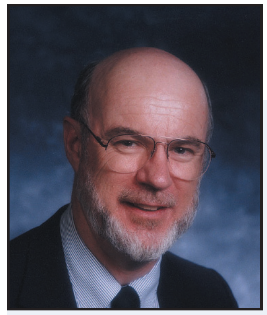
Summary

The U.S. Navy and Maritime communities have a continuing need for hydromechanics research and development to support improvements in ship and vehicle performance and total operating cost, and to meet changing mission requirements. Changes in mission requirements may require radical changes to hull forms and propulsors.

There are challenges in model- and full-scale testing and in CFD and simulation development, calibration, verification, and validation. Knowledge and experience is necessary to control and judge the accuracy of the benchmarks being used for comparison and to understand what is needed to improve the accuracy of the CFD or simulation process. Numerical simulations with the capabilities and accuracy the Navy requires to support design work will require significant additional development, verification, and validation. The accuracy required for validation may require new model test or full-scale trial approaches, which in some cases may have been considered too expensive in the past. The experienced work force at the Carderock Division, combined with its comprehensive hydromechanics facilities, provide the optimal environment for these efforts.

Technical Papers

The six technical papers that follow provide examples of the Division's technology applied to current and future propulsors, hull forms, appendages, and an autonomous remotely-controlled vehicle. The first paper on the twisted rudder design shows the application of analytical and experimental methods to reduce rudder erosion caused by the propellers' slipstreams impinging on the rudders. The second and third papers demonstrate the application of CFD to current design studies of submarine maneuvering prediction and an advanced submarine sail. The fourth paper shows the application and validation of a ship motion simulation program developed to predict extreme ship motions. The fifth paper, reports on a quiet propeller for fisheries research, which demonstrates one of our many cooperative programs with other government agencies and the Maritime industry. The final paper discusses the autonomous mobile periscope system and shows the system design, integration, and testing of a remotely piloted unmanned underwater vehicle developed to provide a low cost training target for submarine periscope hunting aircraft crews.



__Michael J. Davis__ earned a B.S.E. degree in naval architecture and marine engineering from the University of Michigan. He joined the High Performance Craft Dynamics Branch in 1972, specializing in the development of computerized data acquisition systems and seakeeping analyses. He was the project manager responsible for the initiation and development of the Division's support of TRIDENT Trainers containing ship motion simulations. He served as head of the Special Ship and Ocean Systems Dynamics Branch and currently is a naval architect in the Seakeeping Department working on special projects for the Hydromechanics Directorate.

__Dr. Joseph J. Gorski__ earned a B.S. degree in engineering science (Honors Program) and an M.S. degree in aerospace engineering from the Pennsylvania State University. He received a Ph.D. degree in mechanical engineering from the University of Maryland. Dr. Gorski is employed in the Propulsion and Fluid Systems Department of the Hydromechanics Directorate and is the team leader for the CFD Group. The CFD Group comprises approximately 10 Ph.D./M.S. level engineers and scientists who perform a wide variety of computational work ranging from traditional hydromechanics (surface ship, submarine, and propeller calculations) to ship air wakes, air compressors, and environmentally related flow problems including combustion. Dr. Gorski applies Reynolds-averaged Navier-Stokes solvers to geometries of naval interest to help evaluate, understand, and improve the fluid dynamics behavior of various designs.

Twisted Rudders

Young T. Shen, Scott Gowing, and Kenneth D. Remmers

Rudder cavitation is an expensive maintenance problem and a ship-silencing issue for DDG 51–Class ships. Dry-dock inspections show severe erosion damage in a consistent pattern on the outboard surfaces of the twin rudders, and photo-viewing trials revealed cavitation collapsing in the same area on the rudder surfaces. To counter this problem, the concept of a twisted rudder is used to adapt the rudder to the propeller swirl and reduce or eliminate the erosive cavitation. Hull flow measurements in the tow tank, coupled with computational fluid dynamics calculations, provide the input for the rudder design, and model tests in the Navy's Large Cavitation Channel confirm the cavitation benefit of using twisted rudders. From these tests, a pair of twisted rudders have been designed, constructed, and installed on the DDG 84. Full-scale cavitation tests were performed in the summer of 2001. The design philosophy and model test results are presented in this paper.

Introduction

Reduction of maintenance costs and decreased ship downtime are important goals in today's Navy. Expensive paints and intense labor are required to repair the rudder cavitation erosion associated with DDG 51–Class ships. Figure 1 shows typical damage seen on many DDG 51–Class ships in dry dock. Photo-viewing trials on the DDG 52 showed surface cavitation collapsing on the rudder in the same area as the erosion. In addition to maintenance issues, cavitation increases drag, hull vibration, and radiated noise, compromising the ship's fuel and acoustic performance. The Navy initiated a project to develop computational capabilities to predict propeller/rudder interaction and to develop a new rudder design method to reduce rudder cavitation.

Figure 1. Rudder cavitation erosion.

Design Philosophy

It is common practice in shipbuilding to place the rudders in the propeller slipstream. This takes advantage of the accelerated flow to enhance the rudder side force and ship maneuvering, especially at low speeds. This approach can cause problems because the cross-flow velocities induced by the propeller swirl skew the flow hitting the rudder's leading edge. The flow field in the propeller slipstream is complex; therefore, its influence was not considered in the typical rudder design procedure, and the rudder was designed as if the incoming flow was uniform. In this sense, rudder design practice has been virtually unchanged since the 1940s.

The propeller swirl causes large in-flow angles that vary along the rudder span and produce local areas of high suction that lead to cavitation. Surface cavitation can be reduced or eliminated by reducing or eliminating the in-flow angles. Rotating the rudder cross sections along the span to offset the incoming flow angles induced by the propeller rotation does this. The method produces a rudder with a twisted shape along the span, hence the name "twisted rudder."[1]

Numerical methods were used to determine the flow field characteristics at the rudder's leading edge and thus determine the correct twist distribution. As a starting point, wake surveys from tow tank tests of the DDG 51 model were put into a computational fluid dynamics (CFD) propeller code to calculate velocities at the propeller plane. Another code calculated the velocities in the propeller slipstream. These computed in-flow velocity distributions were fed into a lifting surface program to calculate the velocity and pressure distributions on the rudder surfaces. The calculated minimum pressure coefficients were compared for port and starboard rudder deflections by varying the distribution of twist along the rudder span. An optimum twist distribution was determined that made the minimum pressures along the span the same for 10 degrees of deflection in either direction. This design allows the greatest range of rudder movement before the onset of cavitation.

Experimental Verification and Testing

Based on the design, twisted rudder models were fabricated and tested on a DDG 51 ship hull model in the Navy's Large Cavitation Channel (LCC) in Tennessee. As shown in Figure 2, the 11-m-long DDG 51 model was attached to the ceiling of the 12.4-m-long, 3.05-m x 3.05-m test section. Measurements included rudder side forces, drag, surface pressures, cavitation inception angles and speeds, and noise levels. A two-component laser Doppler velocimeter (LDV) measured the stream-wise and cross-flow components in the propeller slipstream just ahead of the rudder to compare with the calculations. The twisted and non-twisted models were tested back-to-back for direct comparison using the same test setup and procedures.

Figure 2. LCC test setup for DDG 84 port rudder.

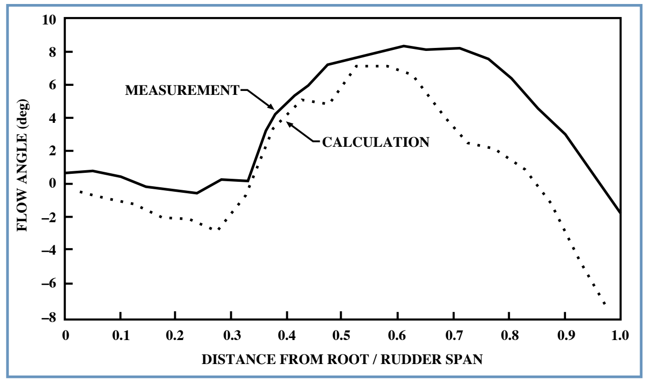


Figure 3. Swirl induced by the propeller.

Flow Velocity Measurements and Twisted Angle Distribution

Figure 3 compares the distributions of in-flow angles derived from the LDV data with the theoretical calculations. As much as 8 degrees of flow angle was measured between the 50% to 70% range of the rudder span.

Rudder Forces and Pressures

It was important that the twisted rudder yield the same turning performance as the original design to provide similar ship maneuverability, and also to provide similar drag characteristics. Figure 4 compares the rudder side force and drag at 20 knots. The rudder effectiveness is measured as the change in rudder side force with change in rudder angle,

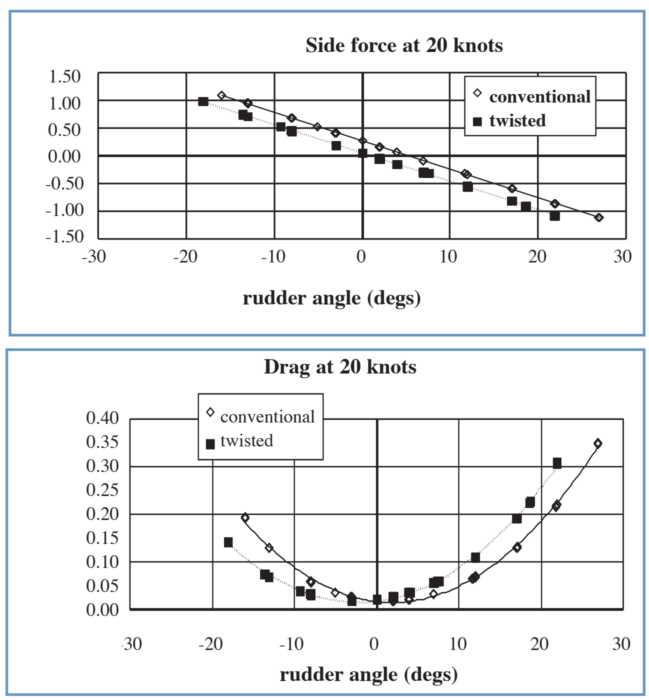


Figure 4. Rudder lift and drag versus rudder deflection (ATD propeller).

and the twisted and non-twisted rudders have the same effectiveness. The twisted rudder has negligible lift at 0 degrees because the cross flow is correctly compensated by the twist, whereas the straight rudder has a net side force that is countered by the opposing rudder on the real ship. Twisted rudders will provide the same ship maneuvering capability because the slope of the lift curve determines the rudder effectiveness. The shape of the drag curves of these two rudders is similar with almost the same minimum drag coefficients, and again, the shift in these two curves is a consequence of the twisted vs. non-twisted designs.

The pressure distributions on the rudder surfaces compared well with the numerical predictions.[2] These data confirmed the effect of reduction of the in-flow angle on the minimum pressure areas.

Cavitation Performance

Figure 5 compares the cavitation on the conventional and the twisted rudders at 25 and 31 knots going straight ahead ($\delta = 0^{\circ}$). The conventional rudder has a large cavity on the outboard surface at 25 knots, and at 31 knots, this rudder experiences severe cavitation with collapsing bubble clouds. The cavity pattern closely resembles the full-scale erosion pattern shown in dry-dock (Figure 1). No surface cavitation is noted on the twisted rudder for either of these conditions.

Figure 6 shows the cavitation patterns on the rudders with rudder angles used in turning ($\delta = 8^{\circ}$). Severe surface cavitation occurs on the outboard surface of the conventional rudder, but no surface cavitation is seen on the twisted rudder, even at the larger angle. Test results in the LCC confirm the significant reduction in surface cavitation by using a twisted rudder instead of a conventional rudder.

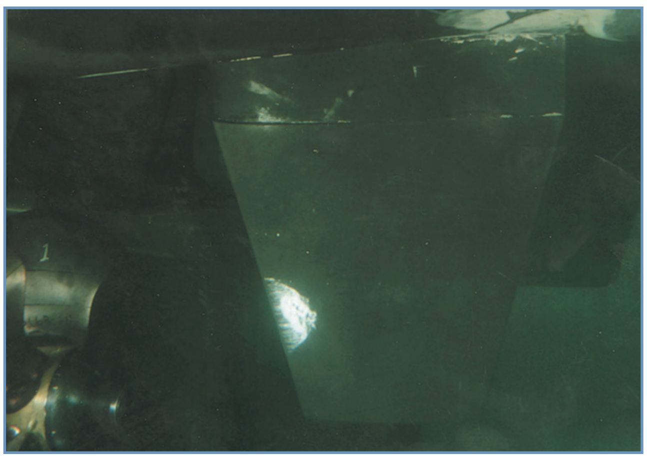


Figure 5a. Conventional rudder, 0°, 25 kts

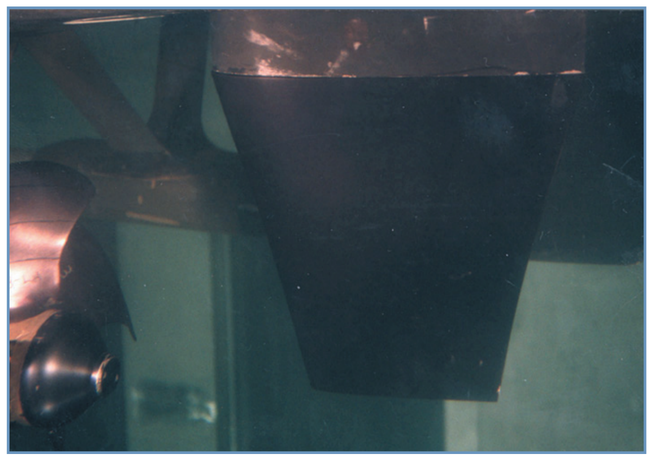


Figure 5b. Twisted rudder, 0°, 25 kts

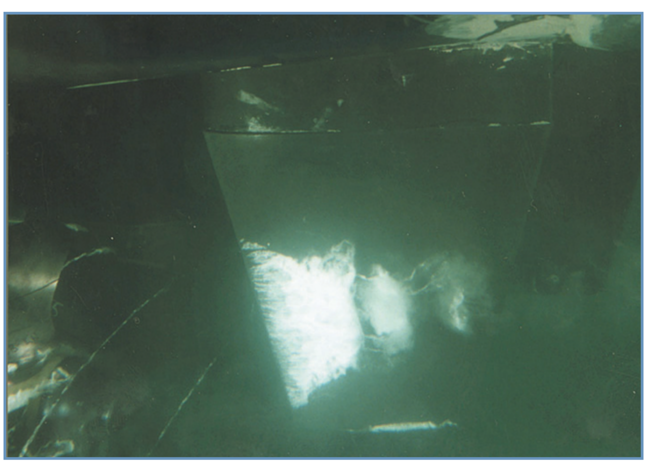


Figure 5c. Conventional rudder, 0°, 31 kts

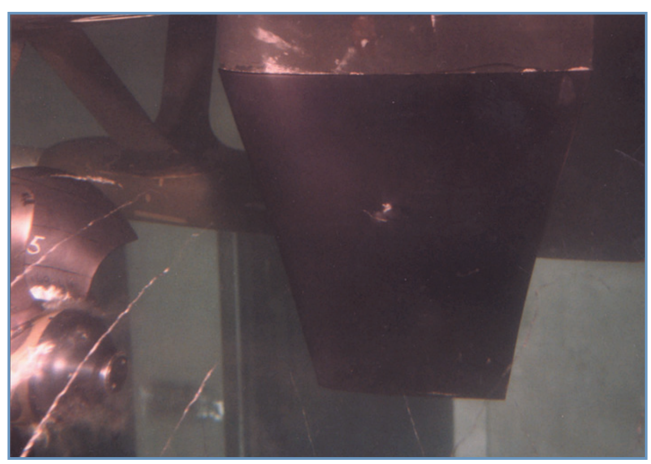


Figure 5d. Twisted rudder, 0°, 31 kts

Figure 5. Cavitation pattern in straight course at 25 and 31 knots (LCC).

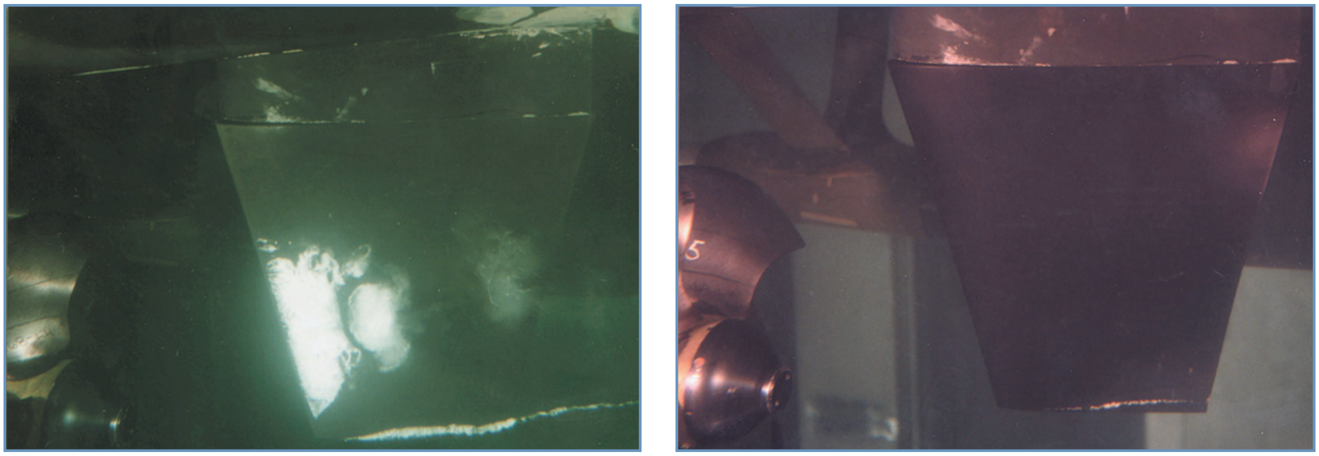


Figure 6a. Conventional rudder, 8°, 25 kts

Figure 6b. Twisted rudder, 8°, 25 kts

Figure 6. Cavitation pattern at 25 knots with rudder deflected (LCC).

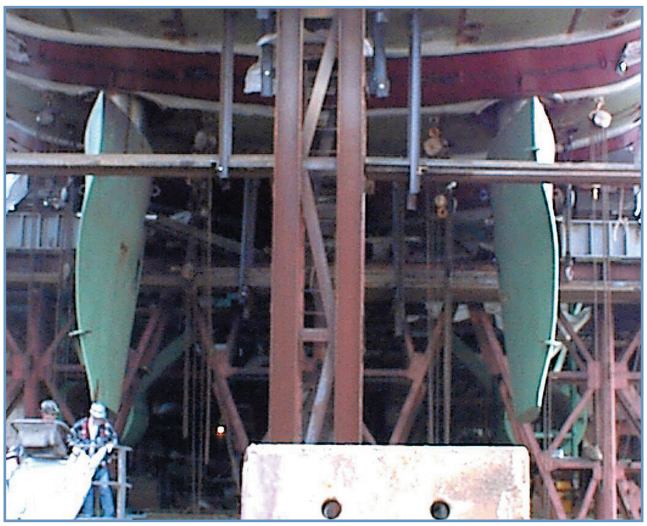


Photo Courtesy of Ingalls Shipbuilding of Pascagoula, MS

Figure 7. DDG 84 twisted rudders

Construction and Trial Validation of Full-Scale Twisted Rudders

A pair of full-scale twisted rudders was constructed for the DDG 84 at Litton Ingalls Shipbuilding (Figure 7). Full-scale trials were completed June 2001. The trial tests included photo-viewing, acoustic and vibration measurements, and powering measurements. Based on the results of these tests, the twisted rudder appears to be a success.

Summary

A new approach to rudder design has been developed that adapts the rudder to the propeller slipstream in a way that minimizes cavitation. This approach combines tow tank measurements with CFD programs to produce a rudder design uniquely adapted to any existing or future ship design. Model tests of this approach confirmed its predictions and allowed a quick transition of the design to a full-scale ship, the DDG 84 constructed at Litton Ingalls Shipbuilding. The potential for reduced maintenance costs adds up to real savings over the life of the ship, while the benefit of reduced noise signature could make the ship harder for enemies to detect.

Acknowledgements

The encouragement and support by Mr. Jerry O'Shaughnessy of NAVSEA PMS 400, Pat Crowe of NAVSEA 05, and James Gagonik of ONR are greatly appreciated.

References

1. Shen, Y.T., et al, *A twisted rudder for reduced cavitation,* Journal of Ship Research, Vol. 41, No. 4 (Dec 1997).

2. Shen, Y.T., et al, *Effects of ship hull and propeller on rudder cavitation,* Journal of Ship Research, Vol. 41, No. 3 (Sep 1997).

Dr. Young T. Shen *received his B.S. degree from National Taiwan University, his M.S. from the University of Minnesota, and his Ph.D. from the University of Michigan. He received additional academic training at the California Institute of Technology as a Post Doctor Research Fellow. Dr. Shen has worked at the Naval Surface Warfare Center, Carderock Division since 1973. He has extensive experience in fluid mechanics and hydrodynamics, especially in the areas of hydrofoils, model testing, and cavitation research. He has published numerous refereed papers in the Journal of Ship Research, SNAME Journal of Marine Technology, ASME Journal of Fluids Engineering, and the Journal of Hydronautics, and he holds several patents.*

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Computational Fluid Dynamics for Submarine Maneuvering Prediction and Analysis

Henry J. Haussling

An ability to understand and predict submarine maneuvering characteristics is critical for improved Navy submarine performance. Advances in Computational Fluid Dynamics (CFD) have led to the development of fundamental physics-based computational tools for submarine maneuvering prediction and analysis. These tools are being used in conjunction with model testing to accelerate progress in submarine design. This paper describes the current state-of-the-art of CFD for submarine maneuvering as well as some of the remaining challenges.

Introduction

Modern submarines must meet complicated and increasingly stringent performance requirements to achieve their intended mission capabilities. One set of requirements involves maneuvering characteristics, which are critical for safe and effective operation. Maneuvering prediction refers to the determination of the trajectory a submarine will follow once its propulsor and control surface settings are specified. Accurate prediction is a must before submarine designs are finalized. An effective method to determine the effectiveness of submarine designs is to test scale models in model basins. Test procedures, which can involve towed and radio-controlled models (Figure 1), have been improved over the years and will continue to play a significant role in the design process. Inaccuracies in extrapolating from model scale to full scale are being mitigated by tests of Large-Scale Vehicle (LSV) models at Lake Pend Oreille, Idaho. However, model tests are expensive and can be performed for a limited number of candidate hull forms. Therefore, analytical tools are being used to predict performance as a supplement to the model tests.

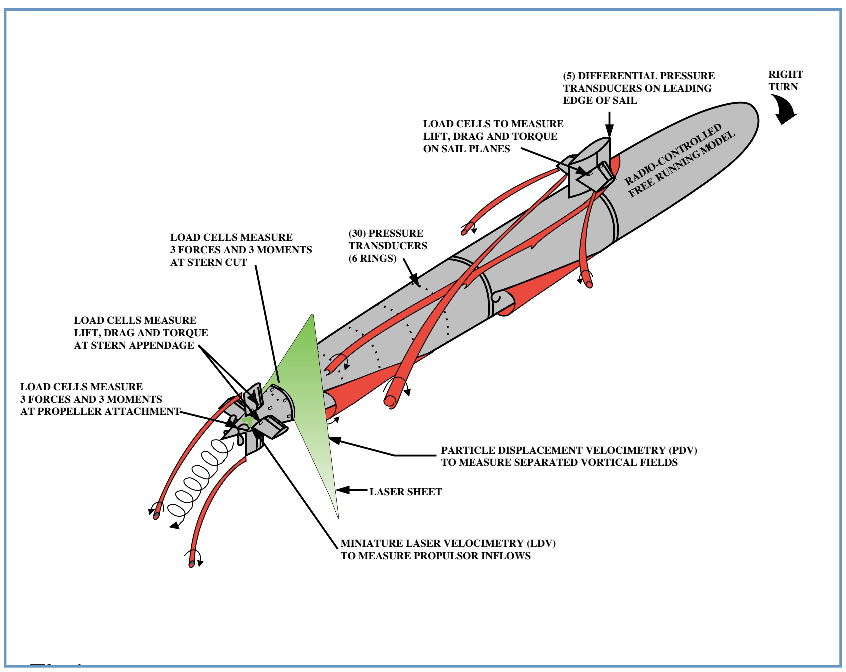

Figure 1. Radio-controlled model showing selected instrumentation and vortices.

Background

One analytical tool used regularly at NSWCCD to predict maneuvering is referred to as the coefficient-based model. With propulsor and control surface settings as input, this tool solves a set of equations governing body motion to predict a submarine trajectory. The equations involve coefficients, which approximate the hydrodynamic characteristics of the submarine, and which generally must be determined experimentally for each new design. While use of the coefficient-based model does reduce the extent of model testing, its dependence on experimental factors limits its ability to explore a wide variety of design options.

Researchers have focused attention on the solution of the equations governing the flow of water as the submarine pushes through it to achieve a more general analytical predictive capability for submarine maneuvering. In theory, solutions of such equations yield the hydrodynamic forces on the boat, which then can be used to compute the trajectory. The solutions contain flow details, which provide information to better understand and predict submarine performance. Unfortunately, the equations are quite complex and mathematical solutions cannot be written down in their exact form. However, computer technology has made it possible to derive accurate numerical solutions to the equations. This numerical approach is referred to as Computational Fluid Dynamics (CFD). The continuous differential equations that represent the hydrodynamic velocities and pressure everywhere, are replaced by a large set of algebraic equations that govern the water flow at a set of grid points near the hull. The distribution of these grid points must be dense enough to yield force predictions with accuracy sufficient for trajectory computation.

Even this numerical solution of the full equations of hydrodynamics is a prodigious task and is beyond the capability of present computer technology. However, considerable progress has been made by simplifying the equations through elimination of those aspects of the physics which play a negligible role. For example, the equations governing inviscid flow (frictional effects neglected) are much simpler than the full equations, and their numerical solution can be achieved quickly. When point singularities called discrete vortices are added to the equations, some of the more important viscous effects are incorporated without unduly increasing the solution effort. The multivortex code that results is a tool that supplements the coefficient-based model and is in regular use for maneuvering prediction.

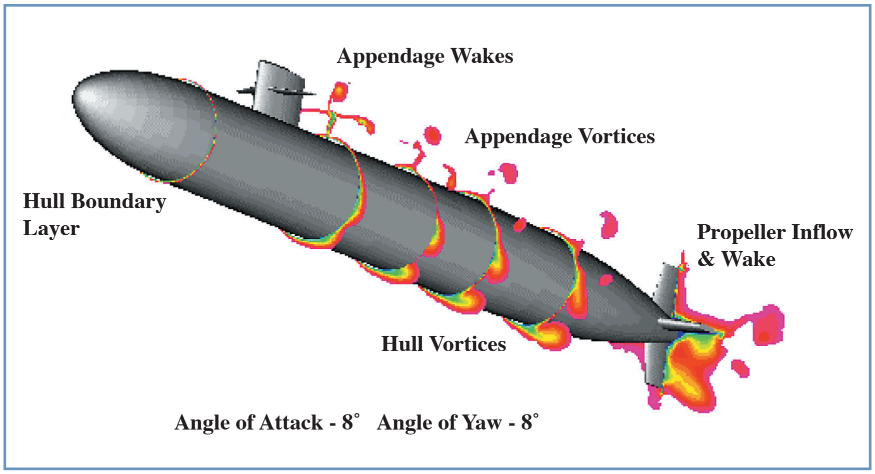

Figure 2. Near-hull steady flow field (axial velocity contours) computed by the UNCLE RANS code showing flow features that must be resolved to obtain hydrodynamic force estimates accurate enough for dependable maneuvering trajectory predictions.

Reynolds-Averaged Navier-Stokes Codes

Recent research has focused on the solution of less approximate versions of the hydrodynamics equations to extend predictive capabilities beyond those of the coefficient-based model and multivortex code. Much of this work deals with the Navier-Stokes equations, which scientists believe can fully describe the flow of water. However, flows such as those surrounding submarines, are turbulent. They are highly complex and contain all scales of motion - from boat length to molecular scale. It is not yet feasible to resolve the smallest scales with the grids of computational fluid dynamics. Therefore, researchers have developed another set of equations by combining the Navier-Stokes equations with turbulence models to treat the larger-scale motions yet still include the effects of the small-scale motions. This system is known as the Reynolds-averaged

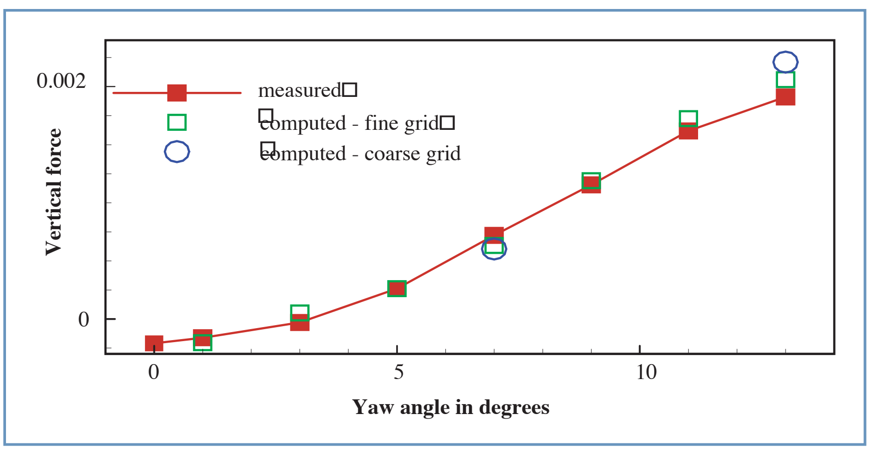

Figure 3. Vertical force versus yaw angle on a turning submarine computed with the IFLOW RANS code compared with measured data.

Navier-Stokes (RANS) equations. Computer codes that provide solutions to these equations are known as RANS codes. Advanced computer memory and speed and the development of improved turbulence models makes it feasible to use these codes in the CFD process with grid densities that can yield accurate force prediction.

Researchers from NSWCCD, with support from the Office of Naval Research (ONR), have been involved in the development of Navier-Stokes and RANS code technology since the late 1960s. As the methodology has matured, the work has evolved from solely basic research to include practical applications. Current efforts involve the verification and validation of two RANS codes: IFLOW,[1] developed at NSWCCD; and UNCLE,[2] developed at the Engineering Research Center for Computational Field Simulation at Mississippi State University (Figure 2). The depth of CFD knowledge and experience at NSWCCD facilitates testing and the ultimate application of these tools.

The early versions of RANS codes were limited in capability and required extensive computer time and real time to solve. Progress has been rapid, and new versions take advantage of the latest multiple-processor supercomputers of the DOD High Performance Computing Network and the Navy Submarine Hydrodynamics/Hydroacoustics Technology Center. A submarine maneuvering prediction that took weeks to produce in 1997, now can be obtained in as little as 2 days.

Software verification is made through input parameter studies. Validation is underway through comparison of predicted results with measured data (Figure 3). In particular, the ability of the software to compute forces precise enough to use for maneuvering predictions is checked. Results are demonstrated to the maneuvering community to encourage transition. User feedback is provided to ensure continued code improvement.

Further Challenges

One remaining hurdle for CFD maneuvering prediction is to include the capability to move control surfaces. Changing geometries require that the grid points move as the submarine maneuvers. The challenge is to include grid point movement in a generic manner so man-hours are not wasted including additional input. Recent developmental work on the UNCLE code focuses on creating that capability and on the addition of six-degree-of-freedom equations to compute the movement of the boat in response to the instant forces. A version of the code with a moving sailplane option is being tested (Figure 4). A version with moving stern appendages should be available in the near future.

Additional challenges include improving the technology to accelerate the grid generation and flow solution efforts. Grid generation is often a major bottleneck because it may take many hours of expert labor, depending on the complexity of the geometry. The replacement of current flow solvers with solvers that can accept relatively easier-to-generate unstructured grids, will substantially reduce the time required to generate the structured grids. The time required to generate the flow solution will also be reduced by the transition to unstructured grids, which allow more efficient grid point placement than do structured grids.

Verification and validation, being facilitated by experiments at NSWCCD and supported by ONR, will provide high quality maneuvering data for a radio-controlled model developed specifically for this purpose. The model differs enough from a real submarine that its geometry is unclassified, yet is close enough to provide a meaningful test of maneuvering tools. Experimental data will be made available to test the maneuvering tools.

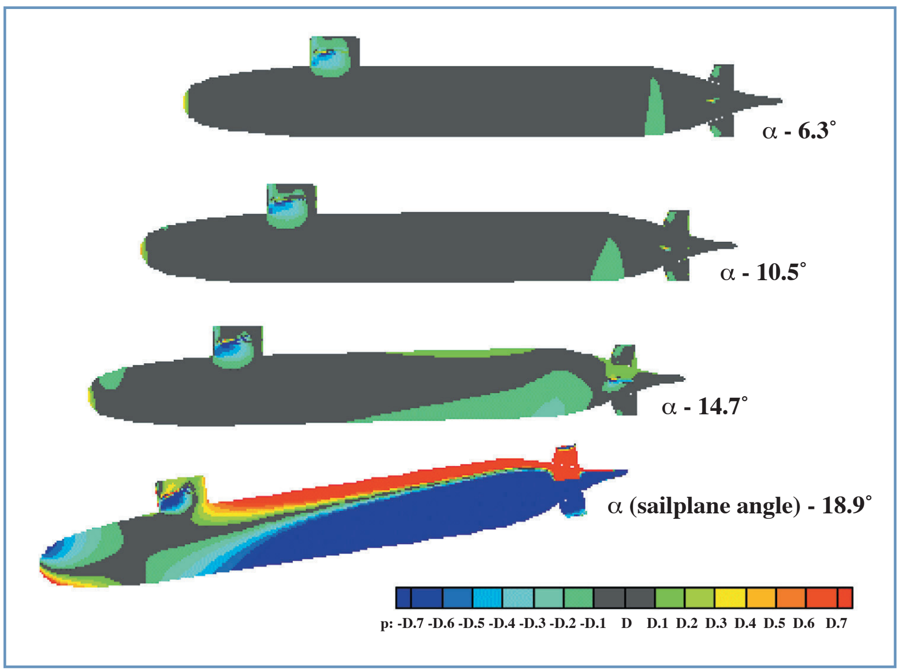

Figure 4. Sailplane effectiveness computed by UNCLE showing the hydrodynamic pressure on the hull as the sailplanes rotate and the boat begins to dive.

Summary

While verification and validation are not yet completed, the RANS codes have already proved useful for submarine maneuvering analysis. They are being used to supplement the coefficient-based model and multivortex code, and have been used in submarine design (see *Advanced Submarine Sail* paper in this section of the Digest). The RANS solutions can be studied to better understand the shortcomings of and to improve the more approximate methods. The CFD solutions cover the complete flow field and thus provide important information for propulsor design and signature prediction. The UNCLE code was built with surface ships in mind, as well as submarines, and thus has an option to include the effects of the water surface. This option has been used to provide a better understanding of the effects of the water surface on radio-controlled model tests and will be used to analyze maneuvering performance in littoral waters.

An array of complementary experimental and analytical tools is in use at NSWCCD for submarine maneuvering prediction and analysis. The addition of leading-edge CFD methods in the form of RANS codes significantly increases capabilities. Their use, along with the other tools, is contributing to improved submarine performance. As they achieve their full capability for maneuvering prediction, they will allow rapid evaluation of a large number of design alternatives and will lead to more innovative submarine designs, all of which results in significantly improved performance.

__Dr. Henry J. Haussling__ received his B.S. degree in mathematics in 1967 from the Massachusetts Institute of Technology and his Ph.D. in meteorology in 1974 from the University of Maryland. Upon joining the Numerical Fluid Dynamics Branch at the Carderock Division in 1968, he commenced work on the numerical solution of the Navier-Stokes equations and contributed some of the early publications in this field. Throughout the 1970s he also carried out research on the numerical solution of ship wave problems and contributed to the development of methods for treating nonlinear free-surface phenomena. He was appointed Head of the Numerical Fluid Dynamics Branch in 1979 and served in that capacity until 1989. From 1986 through 1990 he led a team of researchers on the Numerical Analysis of Naval Fluid Dynamics Accelerated Research initiative sponsored at first by NAVSEA and then by ONR. This work resulted in the development of one of the most advanced and usable codes for the solution of the Reynolds-averaged Navier-Stokes equations. Dr. Haussling was detailed in 1989 to the Advanced Submarine Computational Fluid Dynamics Group to participate in the Carderock Division's highly successful effort in the DARPA "SUBOFF" project. Dr. Haussling's recent work as a physicist in the Hydromechanics Branch includes viscous free-surface problems and the inclusion of propeller models in Reynolds-averaged Navier-Stokes solvers.

References

1. Sung, C.H., et al., *Validation of incompressible flow computation of forces and moments on axisymmetric bodies undergoing constant radius turning.* Proceedings of the 21st Symposium on Naval Hydrodynamics (1997).

2. Taylor, L.K., et al., *Large-scale simulations for maneuvering submarines and propulsors.* AIAA Paper 98-2930, 29th AIAA Plasmadynamics and Lasers Conference (1998).

Advanced Submarine Sail

Magaret C. Stout and Daniel F. Dozier

An advanced submarine sail is being developed as a candidate to replace the VIRGINIA–Class baseline sail. The advanced sail increases submarine mission capabilities by providing significant growth in volume and surface area for future payloads and sensors, which supports the continued evolution of the VIRGINIA–Class to meet current and future threats via technology insertion. This new generation of submarine sails is truly radical for the U.S. Navy, and only a limited knowledge base exists. The sail is a predominant feature of a submarine and affects many platform characteristics. Hence, the development of design tools to assess the sail's impact on the submarine's performance measures, require many technical disciplines. This paper describes the extent to which the advanced sail design process relies on Computational Fluid Dynamics (CFD) codes to estimate the impact these unique and larger shapes have on particular hydrodynamic aspects, including sail pressures, ship drag, propulsor inflow, and maneuvering. CFD results are compared with measurements on both small- and large-scale models. The effort required to build the 1/4-scale sail is also detailed.

Background

A submarine sail provides a hydrodynamic fairing around many mission critical systems that require proximity to the air-water interface. Systems currently housed within submarine sails include periscopes, mast-mounted sensors and antennas, snorkel equipment, sonar arrays, bridge access hatch, navigation aids, and other equipment. For many years, ideas have been put forth on how to change the basic sail shape or size, including sail removal, to improve some aspect of the submarine's performance. Many studies have been performed, but were generally limited to exploring a single or just a few attributes. These studies were successful in some ways, but failed to generate sufficient interest in further development.

Conventional submarine sail shapes and sizes have been relatively unchanged since their introduction in the late 1940's. The design philosophy was to select a low-drag parent shape, and to enclose the necessary equipment within the smallest volume. These constraints led to basic airfoil shapes, which have been used by the U.S. Navy for the past 50 years.

With the focus of submarine operations shifting to littoral missions, there has been an increased desire for new systems to improve littoral warfare effectiveness, and designs that will allow flexibility for mission-specific reconfiguration and rapid insertion of new technologies. With the recent emphasis on off-board payloads and sensors, close proximity to the air-water interface has become increasingly desirable. Candidate systems under consideration include: countermeasure enhancements, high data rate antennas, UUVs/UAVs, littoral warfare weapons, advanced bouyant cable antennas, and Special Operations Forces (SOF) stowage, among others. Far term possibilities could include directed-energy or electromagnetic gun systems. Figure 1 shows a notional arrangement of future sail payloads.

A new low-drag sail shape would be necessary to accommodate the new systems. This new form would need to be a doubly curved, canopy-like shape encompassing all existing legacy sail systems, and with room for future payloads. Because of its low form drag, an Advanced Sail can contain much more volume than a standard sail, with little increase in total drag of the submarine. Figure 2 shows pro-

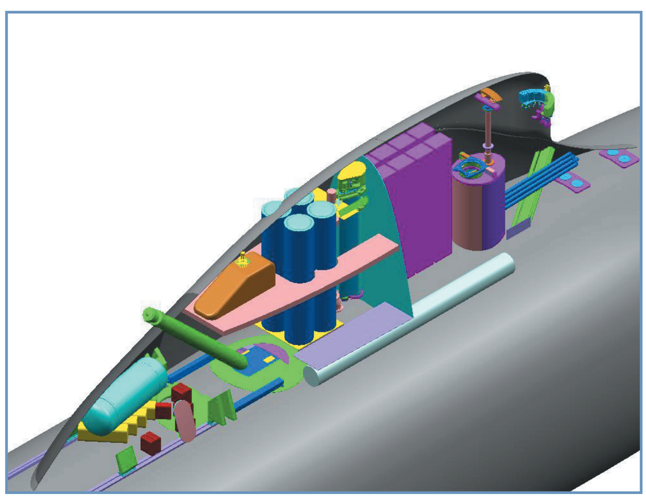

Figure 1: Notional sail payload suite

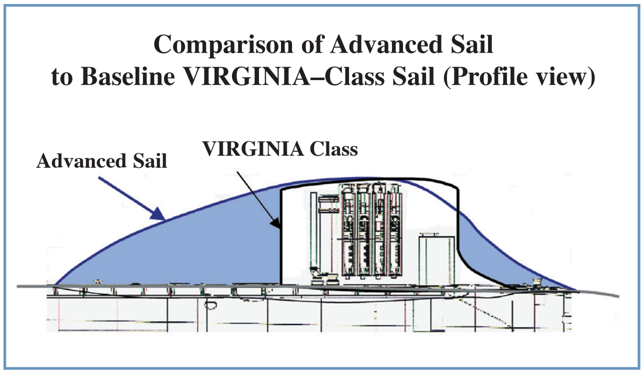

Figure 2: Comparison of Advanced Sail to Baseline VIRGINIA–Class sail

file views of the current VIRGINIA–Class sail and a possible Advanced Sail. Because the sail is such a prominent feature of the submarine, its design and construction impact a large number of ship characteristics, including signatures (radiated noise from sail and propulsor, target strength, radar cross section), maneuvering, powering, surfaced operations, structures and materials, and resistance to ship impacts. Figure 3 shows the leading Advanced Sail candidate at various stages from early computations to eventual full-scale implementation.

Computation-Based Design Process

To reduce schedule and cost, it was necessary to assess sail shape variations by relying heavily on Computational Fluid Dynamics (CFD) and other validated computational tools available. A team was established in 1997, under the sponsorship of the Advanced Submarine R&D Office (NAVSEA (SEA 93R)), to address these complex sail design issues. This demonstration/validation (DEM/VAL) project had the capability to generate a consistent computational and experimental database on Advanced Sail designs that would not have been possible under usual S&T funding limitations or acquisition program schedule constraints. As work progressed on the impact of an Advanced Sail, it was discovered that most were relatively insensitive to small changes in sail shape parameters (leading edge slope, side slope, trailing edge sharpness), as long as some basic design tenets were followed. However, it was demonstrated that details of the sail design had a large impact on propulsor inflow. Assessment of propulsor inflow has historically been done by experimental testing, which is time and cost intensive. While final assessments of propulsor inflow and resultant noise will probably always be determined using physical tests, it was necessary to develop new or validate existing computational tools to allow design tradeoffs in a timely and cost-effective manner. This was particularly urgent because it was expected that actual full-scale implementation of an Advanced Sail would involve compromises to shape that would not have been anticipated, and added costs to experimentally evaluate each possible shape change would prohibit full-scale implementation.

Figure 3: Advanced Sail at various stages from early computations through eventual full-scale implementation

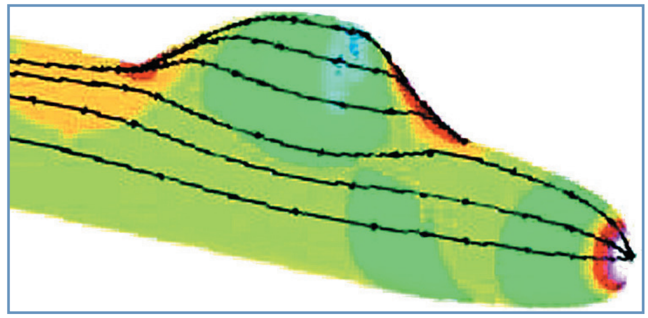

Figure 3a: CFD predictions of pressure distribution and streamlines

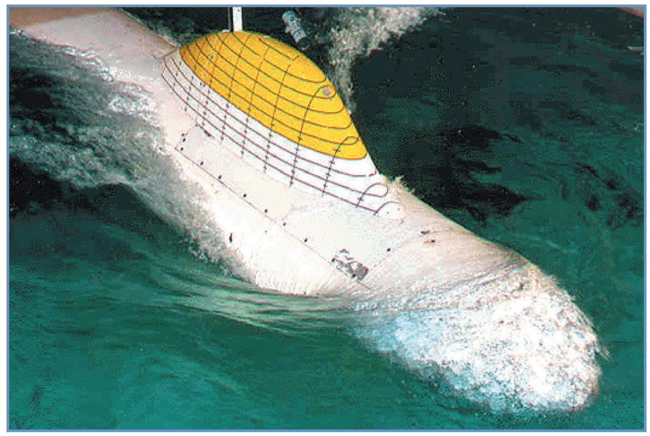

Figure 3b: 1/16.6-scale experiment in NSWCCD towing tank

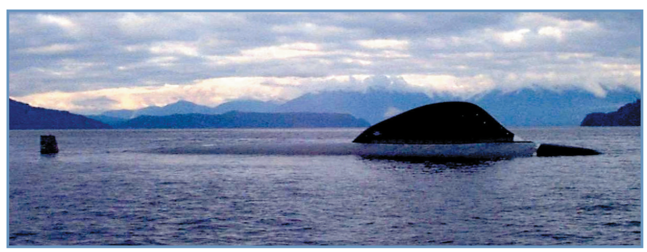

Figure 3c: 1/4-scale Advanced Sail evaluation at NSWCCD Acoustic Research Detachment in Bayview, ID

Figure 3d: Artist rendering of full-scale installation, circa 2010

Computational Tool Demonstration/Validation

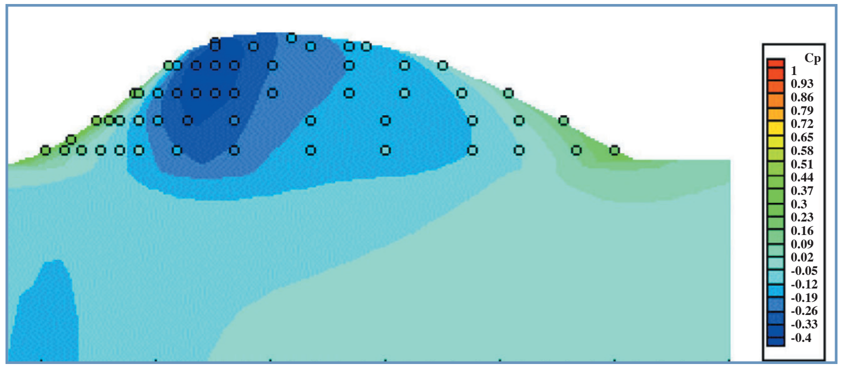

Figure 4: Measured surface pressures from AFF (colors in circles) compared with computed pressure field (CFD).

The approach taken was to make predictions using computational methods, and then compare them to accepted measurements. The sail shapes and hull form tested needed to be as consistent as possible, to eliminate sources of error among the various methods. The phrase "model the model" was a basic methodology used where possible throughout the project.

This process occurred in two stages. In the first stage, measurements were made for a particular sail shape on the VIRGINIA–Class hull form and compared to available prediction methods and modeling practices. Where discrepancies were found, the predictive tools were examined and improved until acceptable computations could be made.

In the second stage, the predictive tools, used in the same manner that had produced acceptable agreement with the existing data set, were used to guide a new Advanced Sail design iteration designated "Advanced Sail 1998" or AS98. To obtain a consistent validation database, the sail shape and hull form selections were driven by the largest scale model that could be tested, the Navy's Large-Scale Vehicle (LSV1). The LSV1 is a 1/4-scale autonomously controlled model of Seawolf (SSN 21), and is operated at the NSWC-CD Acoustic Research Detachment in Bayview, Idaho. Despite the heavy use of LSV1 in the SEAWOLF– and VIRGINIA–Class propulsor programs, very few small-scale measurements had previously been made of the LSV1 hull form.

Detailed laser measurements were made of the existing LSV1 hull to ensure that the computational and small-scale models agreed with the LSV1 geometry. Due to differences in hull form between VIRGINIA– and SEAWOLF–Class submarines, a slight variation to sail geometry was required for the VIRGINIA–Class Advanced Sail to fit on LSV1, and this shape was designated "AS98*". The CFD grids and 1/20-scale model then were configured based on this information.

Sail Pressures and Forces

For two hydrodynamic areas, sufficient validation of the CFD predictions had been achieved in the first stage of testing on the VIRGINIA–Class hull form to warrant eliminating the measurements from the LSV hull form database. The first of these was sail pressures. They had been calculated and subsequently measured in three separate tests; (1/35-scale in the 8'x10' Transonic Wind Tunnel, 1/16-scale in air in the Anechoic Flow Facility, and 1/16-scale in water in the Large Cavitation Channel (LCC)) for an Advanced Sail on the VIRGINIA–Class hull form with good agreement. Figure 4 shows the results from the Anechoic Flow Facility (AFF) as colored circles plotted against the CFD prediction.

The second area was sail forces during maneuvers. These were calculated and compared with two separate sets of small-scale tests involving sail loads at angles of attack. The agreement between calculations and measurements of these sail forces on the VIRGINIA–Class hull form was sufficient for the Navy to proceed to LSV1 testing with no additional maneuvering tests necessary to determine submerged operating envelope. The result was a project savings of approximately $1M. LSV1 maneuvering data then were obtained for comparison with the pretest computations.

Sail Impact on Propulsor Inflow

Accurate prediction of the angular location of circumferential non-uniformities in the propulsor inflow is critical to determine the impact on unsteady propeller forces and associated noise. While early computations yielded good information on sail pressures and forces, they did not accurately predict the location or character of vortices in the propulsor inflow for the VIRGINIA–Class hull form. The early calculations were made using the RANS code DTNS, with the Baldwin-Lomax turbulence model. DTNS was developed at NSWCCD.

Use of a two-equation turbulence model (k-ε) and the RANS code UNCLE (developed at Mississippi State University) resulted in a computed flow field that more closely resembled the measured wake in character. However the vortex pair from the Advanced Sail was still not in the right angular location. Changes made to the computational grid showed little difference. Using the q-ω turbulence model, the calculated angular location and strength of the vortex were much closer to the actual measurements. These series of computations are shown along with the measured result in Figure 5.

The conclusion drawn from these results was that a two-equation turbulence model was highly desirable, and that the q-ω model yielded the best representation of the propulsor flow field. This method has been used in subsequent design iterations for the Advanced Sail program, as well as other submarine programs.

Predictions were made of the new sail shape, which compared well with the 1/20-scale model measurements.

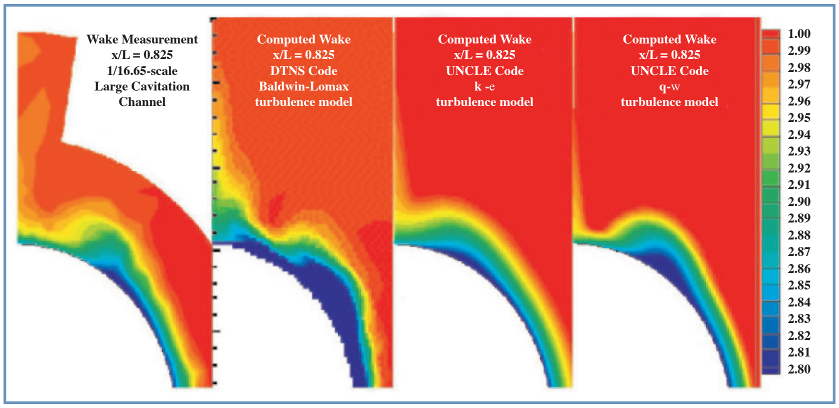

Figure 5: Measured flowfield (axial velocity) compared to the CFD solutions.

Advanced Sail were proposed and assessed in August and September 1998. As previously reported, predictions made during these iterations consistently compare well with results of small-scale testing.

With the success of the toolset (code and criteria) used in the NAVSEA (SEA 93R) project, the final hydrodynamic design of the Advanced Sail to be inserted on an early hull of the VIRGINIA–Class is being developed using CFD. Turnaround times for design evaluations have dropped even further from earlier metrics. The intent is that the design will be generated based largely on CFD, with confirmatory model testing to be performed before making the final commitment to install the Advanced Sail on the VIRGINIA–Class. This CFD based design process has resulted in very quick assessment of design ideas and has allowed a high level of collaboration between all design team members, including individuals from NAVSEA, Electric Boat Corporation, Newport News Shipbuilding, NSWCCD, the Applied Research Labs at Penn State University and the University of Texas, and NUWC.

Preliminary analysis of the LSV1 measurements indicates that the 1/4-scale flow field and the resulting unsteady forces match the small-scale and computational results.

Sail Impact on Resistance and Powering

Using CFD, predictions of the change in drag were made that agreed to some extent with measurements of the 1/16-scale VIRGINIA–Class model. It was determined that CFD could be used to determine changes from a parent shape, but not to assess absolute changes between shapes that were significantly different. However, it was possible to determine gross trends between significantly different shapes.

Frictional drag was computed for the LSV1 baseline sail configuration and the LSV1 fitted with AS98*. Figure 6 shows the agreement between the computational result and the measurement of a 1/20-scale model in the LCC. The speed change measured on LSV agreed with the pre-test predictions as well.

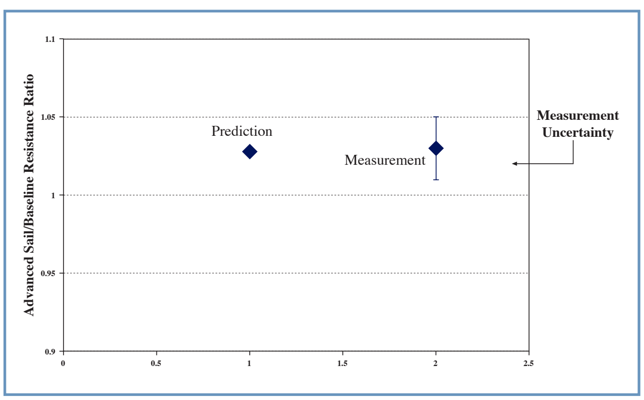

Figure 6: Measured ship resistance with Advanced Sail compared to CFD prediction.

Subsequent Use of CFD as a Design Tool

The turnaround time for computations has been reduced from a matter of months to a few days based on the positive experience using the UNCLE code with the q-ω turbulence model, and the availability of parallel processing computing resources. Four significant modifications to the

1/4-Scale Model Construction Effort

The 1/4-scale testing on LSV1 primarily evaluated hydrodynamic and hydroacoustic phenomena attributed to the Advanced Sail shape. The need to build such a large model, combined with the complexity of the Advanced Sail geometry, presented an opportunity to gain valuable information about the construction of a full-featured composite sail. Based partially on confidence gained during the 1/4-scale construction effort, it has been determined that the VIRGINIA–Class Advanced Sail will be constructed from composite materials to reduce weight impact and minimize costs.

The design and fabrication of the LSV1 Advanced Sail required its own integrated product team (IPT) including NSWCCD, Electric Boat Corporation, Newport News Shipbuilding, Material Sciences Corporation, Analysis and Technology, and Seemann Composites Co. The 23-ft-long, 1/4-scale Advanced Sail was fabricated by Seemann Composites of Gulfport, Mississippi, using their patented Seemann Composite Resin Infusion Molding Process (SCRIMP). The female mold for the structure was made, in rough form, at Seemann Composites and machined to final shape at NSWCCD using an electronic IGES file from Electric Boat Corporation.

The composite sail was mounted to a steel bedplate that, in turn, was bolted to LSV's hull to reduce installation time. NSWCCD constructed the bedplate according to Newport News Shipbuilding drawings, and based on detailed laser measurements taken of the LSV1. The attachment of the composite sail to the bedplate was indicative of a full-scale attachment method. Other features of the sail were also representative of full-scale such as the drain holes and stiffener design.

The construction of this model and its subsequent testing on LSV1 has been extremely successful. It demonstrated the cost-effectiveness of the composite structure; which is expected to be a quarter of the projected cost of a steel sail. Also, it has greatly increased the Navy's confidence and experience in employing advanced composite materials for such a structure. Figure 7 shows the installation of the 1/4-scale Advanced Sail on LSV1.

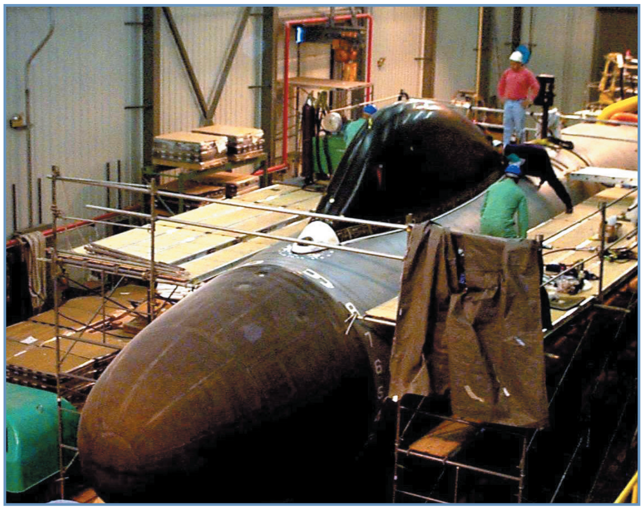

Figure 7: Installation of 1/4 Scale Advanced Sail on Navy's Large Scale Vehicle.

Summary

The Advanced Sail can enhance the littoral mission effectiveness of VIRGINIA–Class submarines with improvements in submarine performance. A major benefit has been the assessment of the available CFD and other predictive tools against a consistent database, for the flow characteristics observed with advanced sails. Through this design and analysis process, confidence has been gained that CFD captures the gross flow attributes measured at small (1/20 to 1/16) and large (1/4) scales. Because of this increased confidence, we can now use CFD to accomplish screening, in lieu of model testing. While progress has been made in the validation process, there are still unknown effects that will need further model testing. Model tests will continue before major changes are made to full-scale hardware. However, significant time and cost reductions in product development have been demonstrated and will continue to be realized as we rely on CFD rather than model tests to explore the design space and reduce model testing to a more confirmatory role.

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Modeling and Simulation of Extreme Ship Motions in Waves: Capsizing, Broaching, and Surf-riding

William L. Thomas III and John G. Hoyt III

A capsized ship can be a catastrophic event, unless it occurs in a model test. Innovative frigate/destroyer hull designs that incorporate novel characteristics, such as wave-piercing bows and tumblehome, cannot be evaluated for adequate stability using traditional quasi-static calm water righting energy-wind energy relationships. All existing stability criteria, even that of Design Data Sheet DDS-079-1, are empirical in nature, and rely on factors of safety to account for seaway dynamics. The factors of safety are derived from experience gained with 50 years of safe operation of conventional ship designs. Unfortunately, quasi-static methodologies to assess stability cannot account for capsizing in the realm where it most often occurs - at high speeds in stern quartering seas.

Recent advances in computational capability, coupled with innovative model testing techniques, make it possible to model the extreme non-linear behavior of a ship, and include capsizing, broaching, and surfriding in waves. Thus, new ship designs can be evaluated more realistically in terms of dynamic stability behavior and capsize vulnerability.

This paper describes the status of the computational capability and model testing techniques employed in the process of dynamic stability code validation.

Introduction

Innovative hull designs that bring the U.S. Navy into the 21st Century call into question the adequacy of stability assessment procedures that have not changed appreciably over the past 35 to 40 years. The existing criteria[1] served as a basis for the U.S. Navy Design Data Sheet DDS-079-1.[2] The criteria are empirically based on simple calm water righting energy and wind energy relationships derived from ship data in the era of the 1930's and 1940's. While the criteria has worked successfully to provide a level of safety such that no U.S. Navy ships have capsized since 1994, ship designs of 50 years ago were very different from future combatants that may include significant features, such as wave-piercing bows and tumblehome. These novel features can have a significant dynamic capsize risk in higher sea states if improperly designed. With the passage of time, the progression of differences between modern combatant hull forms and their World War II vintage predecessors virtually guarantees that the empiricism in the DDS-79-1 calm water energy relationships will become obsolete.[3] Thus, it is necessary to take a fresh look at the way stability assessments are performed.

A joint research effort on ship stability began in 1989 under the sponsorship of the Cooperative Research Navies (CRNAV) under the auspices of the Maritime Research Institute Netherlands (MARIN) to address shortcomings in stability criteria using a physics-based approach. The Dynamic Stability Working Group was established in CRNAV and included six navies (from Australia, Canada, France, Netherlands, United Kingdom, and United States), the U.S. Coast Guard, and MARIN. CRNAV focused on the dynamic stability assessment of intact and damaged ships using numerical simulations and model experiments.[4]

Capsize assessments strongly rely on numerical models to simulate events that would be hazardous to life and limb at full scale. The obvious need to use a validated prediction tool, coupled with the elimination of full-scale capsize tests, leaves model testing as the choice to validate material (Figure 1).

Numerical Simulations

FREDYN, developed by the CRNAV Dynamic Stability Working Group, is the prediction tool of choice for capsize

Figure 1. Capsize model test in NSWCCD Maneuvering and Seakeeping Basin.

assessments. FREDYN is a quasi-nonlinear code that models a free-running intact or damaged vessel in six degrees of freedom using an autopilot to control heading. The hull form geometry is modeled from the keel to the edge of the main deck, and the equations of motion are solved in the time domain. The architecture of FREDYN is based on the De Kat and Pauling model and, in essence, superimposes the relevant force contributions in the equations of motion, including Froude-Krylov forces, wave diffraction and radiation forces, viscous forces, hull resistance, propeller force, rudder and skeg forces, wind forces, and forces due to internal fluids and flooding.[4,5]

While higher order ship motion codes are under development, they are years away from implementation and validation for naval vessels. The intensive computational requirements of RANS codes make them impractical at this point for use in capsize assessments because of the excessive time required to perform the many simulations needed to assess capsize risk.

A more practical approach to minimize computational effort is a physics-based approach, which correctly models the most important forces relevant to capsizing, broaching, and surfriding. Research has shown that capsize phenomena are driven primarily by Froude-Krylov forces as a first order effect.[5] In FREDYN, the Froude-Krylov forces are evaluated up to the instantaneous free surface and include hydrostatic effects. Linear theory is used in the time domain to estimate the diffraction and radiation forces. Viscous effects comprise roll damping due to hull and bilge keels, wave-induced drag due to orbital velocities, and calm water maneuvering forces. Viscous drag due to cross-flow velocities is estimated empirically, using section-dependent drag coefficients derived from segmented model test results. Propeller and rudder interaction is modeled also, including the effect of orbital velocities.[4] This approach allows FREDYN to efficiently and accurately determine the onset of capsize in severe seaway conditions. FREDYN can simulate the following non-linear events.

- Loss of transverse stability on the wave crest
- Parametric rolling
- Surfriding
- Broaching
- Dynamic rolling
- Combinations of the above.

FREDYN is the only dynamic stability and seakeeping prediction program in use by the U.S. Navy, which is in compliance with International Standards Organization (ISO) 9001 standards. ISO compliance is backed by a formal quality assurance effort. The FREDYN Quality Assurance Plan implemented by MARIN and CRNAV ensures the following.

- Proper documentation of theory
- Computer code is consistent with theory
- Computer code is properly implemented
- Validation material is collected and compared with FREDYN predictions
- Version control of FREDYN is maintained.

Updates to FREDYN are not issued until the code is run against test cases in low amplitude (non-capsizing) seaways, where transfer functions are computed and checked against model test data. If results are satisfactory, FREDYN simulations are compared against model test results in capsize, broaching, and surfriding situations. When satisfactory comparisons are found, new theory manuals, user manuals, and documentation of the above quality assurance efforts are delivered to CRNAV members.

NSWCCD takes a step further in FREDYN quality assurance by independently verifying code changes as well as performing validation against model test data. A comparison between FREDYN roll predictions with model test data for the pre-contract DDG-51 model is shown in Figure 2.

Transfer functions are calculated by FREDYN and compared against NSWCCD model test results (Figure 3). The comparisons are very good, especially in the case of roll where the FREDYN prediction is superior to the Navy's frequency domain strip theory program known as Ship Motion Program (SMP).

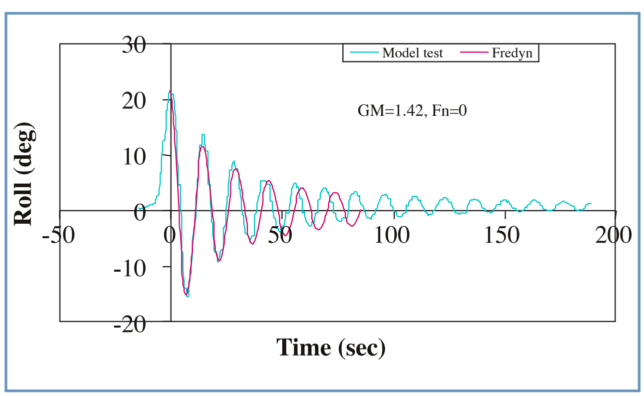

Figure 2. Model 5514 roll decay comparison

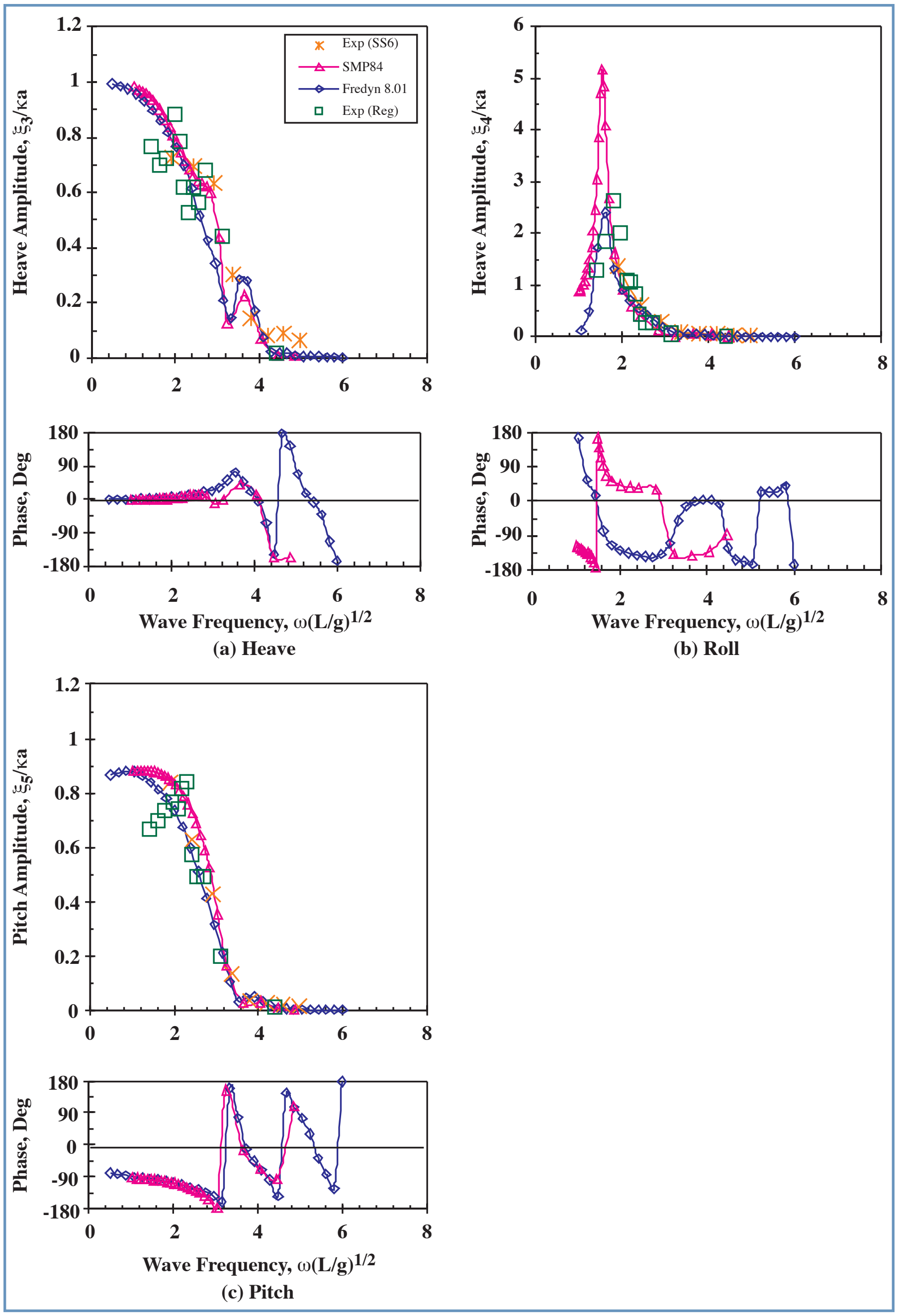

Figure 3. Comparison of FREDYN transfer functions with model test data for the CG-47 in Sea State 6, ship speed of 10 knots with waves 30 degrees off the stern.

The final step in the validation process is to compare FREDYN simulations with model test data in capsize and broaching situations (Figure 4). While the comparison is not perfect, the essential behavior is represented well enough for engineering calculations. FREDYN has been used to evaluate prototype DD (X) designs, which feature wave-piercing bows and tumblehome. It has identified substantial dynamic stability issues in terms of capsize and broaching risks which were later confirmed in model tests, but not identified using the DDS-079-1 wind heel/righting arm stability criteria.

Model Tests

The validation of dynamic stability simulation tools, such as FREDYN, require experimental data, which include capsizing, broaching, and surfriding events. Experimental data are essential to validate capsize predictions of novel hull forms that are beyond the range of present day experience. A large test basin is required with the capability to generate moderate and steep waves at all headings over the complete speed range of the model. The key to a successful test program is the ability to allow non-linear events to occur within the span of one pass in the test basin because "memory effects," which are often critical in capsizing and broaching, are lost at the end of each run. The model must be brought up to a steady speed on heading and free from the influence of startup transients before data is recorded. Since the critical conditions for capsizing, broaching, and surfriding often occur at the higher speeds (0.28<Fn<0.40) in stern quartering seas, the effective run length becomes limited to approximately one-third of the basin. For example, tests in irregular waves are not favored because many passes are required for each heading and speed in search of a capsize. Worse yet, the loss of "memory effects" at the end of every pass often fails to allow the critical non-linearities to manifest themselves in the same manner as would be experienced in the open ocean.

The approach preferred by NSWCCD, CRNAV, and others is an experiment in regular waves, which include the following.[6,7]

- High speed runs in following seas through beam seas of suitable run length to allow capsizing, broaching and surfriding.
- Large amplitude regular waves having steepness (H/λ) of 1/20, 1/15, 1/10, where H is the wave height and λ is the wavelength.
- Wavelength to ship length ratios (λ/L) between 0.75 and 2.5.

A typical test matrix is displayed in Table 1.

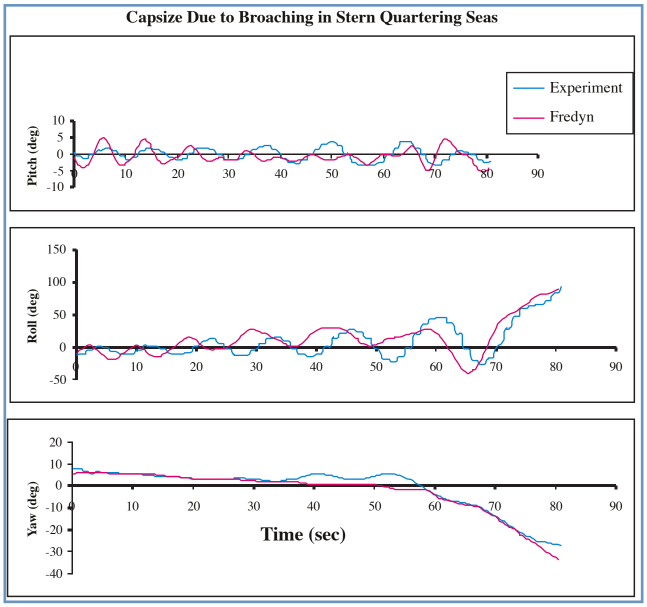

Figure 4. Comparison of experimental results and FREDYN simulation in regular waves for a naval frigate at Fn = 0.3.

Model size usually is determined by the capability of the wave maker to produce the large, steep waves required by the test matrix. The typical capsize model is 3 to 4 meters in length and is self-propelled and radio-controlled, as displayed in Figure 5. An autopilot is required with known controller settings to allow the rudder behavior to be modeled in the simulations for validation. This is especially important during broaching events, which can change dramatically with different autopilot coefficients. Manual steering is inconsistent and does not adapt readily to autopilot settings.

Capsize model tests take place in the NSWCCD Maneuvering and Seakeeping Basin (MASK). The MASK is an indoor basin with an overall length of 110 meters, a width of 73 meters and a depth of 6.1 meters, except for a 10.7-meter-wide trench parallel to the long side of the basin. The MASK is spanned by a 115-meter bridge supported on a rail system that permits the bridge to traverse half of the width of the basin and rotate up to 45 degrees, which allows tests to be conducted at all headings relative to the waves. Pneumatic wave makers are located along two adjacent sides of the basin. A towing carriage is hung from the bridge. The maximum speed of the carriage is 7.7 m/sec.

Capsize model tests often are carried out in several load configurations. One load condition typically is the "worst case," representing marginal compliance with the DDS-079-1 wind heel/righting arm intact stability criteria. A second load condition might represent compliance with both the intact and damage stability criteria of DDS-079-1. Full load, end of service, and light ship conditions are occasionally tested also.

The experimental techniques described in this paper are designed to aggressively challenge hull forms to identify vulnerabilities to capsizing, broaching, and surfriding. It is not sufficient to know that a particular hull form might capsize. The identification of specific capsizing, broaching, and surfriding behaviors is of equal importance. Innovative ship designs almost inevitably contain features that go beyond past experience and challenge the limits of numerical

Table 1. Typical capsize test matrix in regular waves.

Frigate Model Marginal Stability Condition

GM = .68m

λ/L	h/λ	Fn	χ (deg) 0	15	30	45	60	75	90
0.75	1/15	0.1							
		0.2				X			
		0.3		X	X	X	X		
		0.4		X	X	X	X		
	1/10	0.1							
		0.2							
		0.3		X	X	X	X		
		0.4	X	X	X	X	X	X	X
1.00	1/20	0.1							
		0.2		X					
		0.3		X					
		0.4	X	X	X	X			
	1/15	0.1		X	X	X			X
		0.2		X	X	X			
		0.3		X	X	X			
		0.4		X	X	X			
	1/10	0.1							
		0.2		X	X	X	X		
		0.3		X	X	X	X		
		0.4	X	X	X	X	X	X	X
1.25	1/20	0.1							
		0.2		X	X	X	X		
		0.3							
		0.4							
	1/15	0.1		X	X	X			
		0.2		X	X	X	X		
		0.3		X	X	X	X		
		0.4		X	X	X			
	1/10	0.1							
		0.2		X	X	X	X		
		0.3		X	X	X	X		
		0.4	X	X	X	X	X	X	X
1.50	1/20	0.1				X			
		0.2							
		0.3							
		0.4		X	X	X			
	1/15.5	0.1		X	X	X			X
		0.2		X	X	X			
		0.3		X	X	X			
		0.4	X	X	X	X	X	X	X
	1/10	0.1							X
		0.2							
		0.3		X	X	X			
		0.4	X	X	X	X	X	X	X
2.00	1/20	0.1							X
		0.2							
		0.3							
		0.4							
	1/15	0.1		X	X	X			X
		0.2		X	X	X			
		0.3		X	X	X			
		0.4	X	X	X	X	X	X	X
2.50	1/20	0.1		X	X	X			X
		0.2							
		0.3							
		0.4							
	1/15	0.1							
		0.2		X	X	X			
		0.3	X						
		0.4							

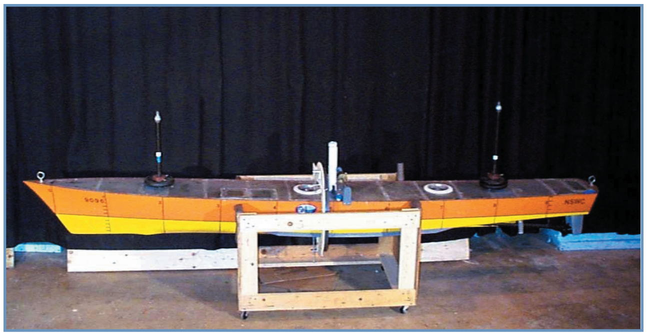

Figure 5. HAMILTON–Class Coast Guard Cutter model (1/36 scale of 378-ft cutter) used in 1997 CRNAV capsize experiments.

simulations. Therefore, the applicability of the numerical tools must first be confirmed against capsize model experiments.

Assessment of Capsize Risk

Satisfactory comparisons between model experiments in regular waves and numerical simulations tools such as FREDYN, pave the way to assess capsize risk in seaways representing the operational environment experienced by a ship. For a particular seaway, capsize operability can be assessed in a manner similar to a *Seakeeping Operability Envelope*[8] using capsize as the limiting motion. The capsize risk can be displayed as a polar plot for a particular sea condition. An example is provided for a destroyer in Sea State 8 in Figure 6. The polar plot depicts ship heading relative to the waves with head seas at the top of the plot and following seas at the bottom. Ship speed is depicted by concentric circles starting at the speed of zero knots in the center of the plot and increasing in 5-knot increments.

In this figure, time domain simulations using FREDYN were performed in Sea State 8 at 15-degree heading increments and 5-knot speed increments over the speed range of the vessel. Each simulation lasted 30 minutes and was repeated using 25 different wave realizations to ensure that the characterization of the capsize behavior was statistically meaningful. The capsize risk depicted in this figure is based on the number of capsizes divided by the number of simulations for each speed and heading in the polar plot. Thus, for a particular seaway, the probability of capsize can be described[9,10]

$$P[C_D|V_S,\beta,(H_{1/3},T_o)]=N_C/N_S \qquad (1)$$

where

$P[C_D]$ = probability of capsize during duration, D
V_S = nominal ship speed
β = heading
$H_{1/3}$ = significant wave height
T_P T_o = most probable wave period given the wave height
N_C = number of capsizes
N_S = number of simulations.

Summary

Modeling and simulation techniques have opened the door to stability assessments based on ship dynamics, in particular capsizing, broaching, and surfriding. The capability to perform simulations addresses only part of the assessment process. Innovative hull designs always seem to extend beyond the existing range of experience. Thus, simulations must first be verified against model experiments. Once this verification and validation process is completed successfully, numerous simulations must be performed in the projected operational wave environments for the new hull design. These computational techniques, backed by model tests for validation, provide the tools to model and assess capsize risk of novel hull forms, ensuring that the record of safe operation enjoyed by the U.S. Navy since 1944 remains unblemished.

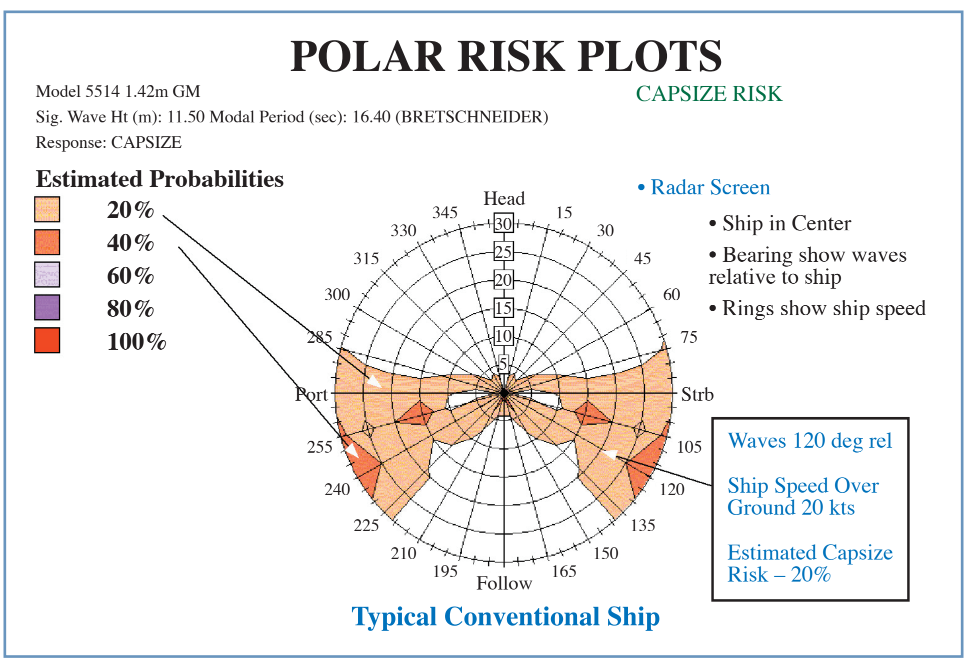

Figure 6. Typical destroyer capsize risk in Sea State 8.

Acknowledgements

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References

1. Sarchin, T. H., and L. L. Goldberg, "Stability and Buoyancy Criteria for U. S. Naval Surface Ships," *SNAME Transactions*, New York, Vol. 70 (1962).

2. "*Stability and Buoyancy of U.S. Naval Surface Ships*," Design Data Sheet- DDS-079-1 Naval Ship Engineering Center (currently Naval Sea Systems Command), Washington, DC (Aug 1975).

3. Alman, P. R., et al, "Dynamic Capsize Vulnerability: Reducing the Hidden Operational Risk," SNAME *Transactions*, New York, Vol. 107 (1999).

4. De Kat, J. O., et al, "Intact Ship Survivability in Extreme Waves: New Criteria from a Research and Navy Perspective," 5th International Conference on Stability of Ships and Ocean vehicles, STAB 94. Melbourne, FL (1994).

5. De Kat, J. O., and J. R. Paulling, "The Simulation of Ship Motions and Capsizing in Severe Seas," *SNAME Transactions*, New York, Vol. 97 (1989).

6. De Kat, J. O., and W. L. Thomas III, "Extreme Rolling, Broaching and Capsizing Model Tests and Simulations of a Steered Ship in Waves," 22nd Symposium on Naval Hydrodynamics, Office of Naval Research, National Academy of Sciences, Washington, DC (Aug 1998).

7. Umeda, N., et al "Stability Assessment for Intact Ships in the Light of Model Experiments," *Journal of Marine Science and Technology*, Vol. 4 (1999).

8. Comstock, E. N., et al "Seakeeping in Ship Operations," SNAME STAR Symposium, San Diego, CA (1980).

9. McTaggart, K. A., "Ship Capsize Risk in a Seaway Using Time Domain Simulations and Fitted Gumbel Distributions," 18th International Conference on Offshore Mechanics and Arctic Engineering-ONMAE99, St. John's Newfoundland (July 1999).

10. McTaggart, K., and J. O. De Kat, "Capsize Risk of Intact Frigates in Irregular Seas," *SNAME Transactions*, Vol. 108 (2000).

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Quiet Propeller for a Fisheries Research Vessel

Thad J. Michael, Stuart D. Jessup, and Michael B. Wilson

A propeller was designed and tested for the National Oceanic and Atmospheric Administration fisheries research vessel FRV-40. The ship is propelled by a single propeller operating in the wake of a skeg. The radiated-noise goal required that the propeller operate cavitation free at a speed of at least 11 knots. A five-bladed, fixed-pitch propeller was designed to meet the requirement. The design was completed using lifting-line and lifting-surface computer programs. The design propeller incorporates tip unloading, large diameter, and long chord lengths to achieve the required performance. Cavitation tests performed in the Navy's Large Cavitation Channel showed that the design was a success.

Propeller cavitation tests in NSWCCD's Large Cavitation Channel (LCC), Memphis Tenn.

Introduction

The FRV-40 is a new fisheries research vessel designed for the National Oceanic and Atmospheric Administration (NOAA). The principal dimensions of the FRV-40 are listed in Table 1.

Table 1. NOAA FRV-40 principal characteristics.

Length on waterline	200.1 ft	(60.3 m)
Beam, midships	49.2 ft	(15.0 m)
Draft, midships	17.7 ft	(5.4 m)
Displacement	2379 LT	(2417 tons)

Since the ship will survey marine life that may be attracted or repelled by noise, the propeller was to be cavitation free up to 11 knots. The propeller must also meet American Bureau of Shipping (ABS) requirements for ice class C0. The Naval Surface Warfare Center, Carderock Division (NSWCCD) was tasked to design a propeller to meet the vessel's requirement of low hydroacoustic noise.

Design Requirements

The primary requirement for this propeller design was cavitation-free operation up to 11 knots. Additional goals were to maximize efficiency and to minimize cavitation for all other operating conditions, including a 14-knot full-power condition and a 4-knot towing condition with a 35,900 lb (160 kN) tow load. The thrust required in the 4-knot towing condition approaches the thrust required at 85% power in the free-running condition. A more extreme 4-knot towing condition, defined by the maximum deliverable engine torque, was not involved directly in the propeller design requirements, but was of interest in the experimental cavitation evaluation of the propeller performance.

Tip vortex cavitation was expected to be the first type of cavitation to incept. The substantial wake deficit produced by the stern at the top of the propeller disk made this a challenging goal (Figure 1). Prior studies indicated that a large diameter propeller would be required to meet the cavitation requirement, although a twin shaft arrangement would be preferable. The hull lines had been faired to accommodate a single propeller with a diameter larger than would typically be expected for this size ship.

Preliminary Design

Parametric Calculations

Preliminary calculations were performed to quantify the trade-off between the design parameters such as diameter, rpm, and blade area, with performance goals of cavita-

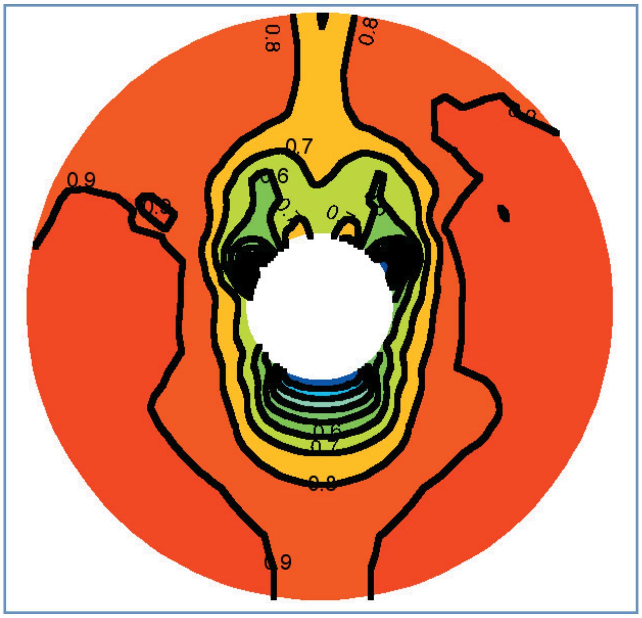

Figure 1. FRV-40 nominal wake, axial velocity contours.

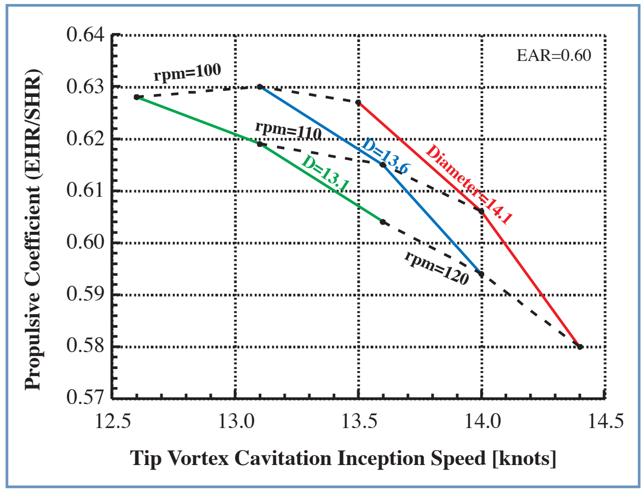

Figure 2. Parametric variation of diameter and rpm.

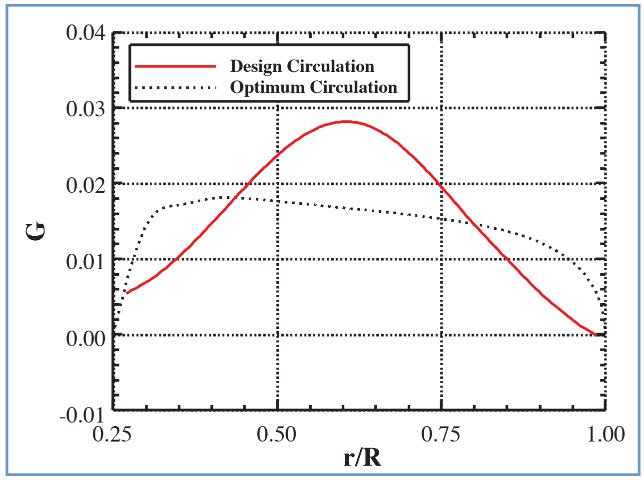

Figure 3. Radial loading distribution.

tion and efficiency. The design speed was chosen to be 11 knots because it was the most critical speed for propeller performance. The following guidelines were adopted to achieve the best efficiency and still maintain a tip vortex cavitation inception speed above 11 knots.

- The tip was greatly unloaded.
- The largest diameter possible was selected, 14.1 ft (4.297 m), with reasonable tip clearance.
- The rpm was kept as low as possible while meeting the cavitation requirement.
- Long chord lengths were used at the tip.
- A tip bulb was added.

In this combination, the tip vortex cavitation inception speed was increased while efficiency loss was minimized.

Lifting line calculations were made using the MIT-PLL computer code.[1] A procedure was added to the code to evaluate tip vortex inception speed based on the propeller geometry, loading, ship wake, and resistance. Propeller performance was calculated over a range of diameters, rotation speeds, and area ratios for a number of circulation and chord distributions, with five and seven blades. The efficiency and tip vortex cavitation inception speed for a range of diameters and rpm is shown in Figure 2. While a seven-blade design was predicted to be advantageous for tip vortex cavitation inception, five blades were acceptable, more conventional, and preferable for manufacturing.

To delay tip vortex cavitation inception, the propeller tip was strongly unloaded, as shown in Figure 3. The tip produces minimal lift, but requires torque to overcome drag. With very little pressure differential across the tip, the tip vortex is minimized, but the efficiency is reduced.

Based on the parametric calculations, a 14.1-ft-diameter propeller operating at 100 rpm at 11 knots was selected for design refinement. An empirically predicted tip vortex cavitation inception speed of 13.9 knots was achieved after further improvements were made to the blade geometry. A 3-knot margin was desired to ensure the full-scale requirement would be met.

Investigation of Controllable Pitch versus Fixed Pitch

Once the general parameters required for the 11-knot design condition were well established, the advantages of a controllable-pitch propeller were investigated. Open water curves were calculated for a preliminary design propeller with pitch variations from -5 to +5 degrees. The curves were used in conjunction with the ship resistance data for full power and towing to determine what efficiency improvements could be expected.

Figure 4 shows the open water curves for pitch adjustments of -5, 0, and +5 degrees from the 11-knot design pitch. For the 4-knot towing condition and the 14- knot free condition, the operating points were plotted and the corresponding efficiency was read from the open water curve.

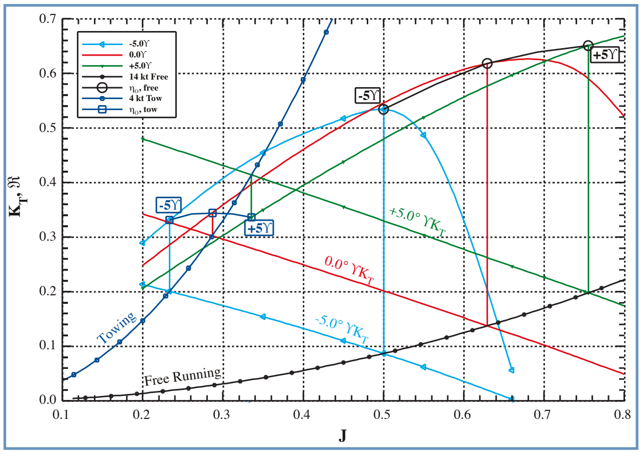

Figure 4. Investigation of controllable-pitch propeller performance.

Figure 4 shows that changing the pitch would have no efficiency benefit in the towing condition, as indicated by the flat curve with the open square symbols. Adjusting the pitch to +5 degrees at 14 knots would provide an efficiency improvement of 4%, as indicated by the curve with the open circle symbols. Angles greater than +5 degrees were investigated, but the efficiency showed no further improvement. The efficiency improvement shown here would be somewhat reduced by the larger hub of a controllable-pitch propeller. The design operational profile for the FRV-40 indicated that the 14-knot free running condition was not a limiting condition for fuel consumption. The complications of a controllable-pitch propeller outweighed the advantages in efficiency; therefore, a fixed-pitch propeller was selected.

Detailed Geometry Definition

The final propeller geometry was designed using a lifting surface code, PBD-10.[2] Detailed geometry was created using NCBLADE[3] to generate B-spline surfaces. The B-spline surfaces have the advantage of being completely defined at all points, eliminating possible errors in interpolation or interpretation by anyone receiving the data. Within the code, an anti-singing trailing edge was added over most of the span. The trailing edge radius was increased near the root to provide a smooth transition between the rounded trailing edge at the root and the anti-singing trailing edge over most of the blade. A tip bulb having an elliptical shape with a 2:1 aspect ratio[4] was added to delay the inception of tip vortex cavitation. The pressure distribution on the blade surface was calculated with the panel code PSF-10[5] and is shown in Figure 5. A conventional T/3 fillet was added between the root of the blade and the hub. The T/3 fillet has a radius equal to one-third of the blade root thickness at that point, with a minimum full-scale radius of 1 in. (25.4 mm). The final propeller is shown in Figure 6. Table 2 lists the major propeller geometric characteristics.

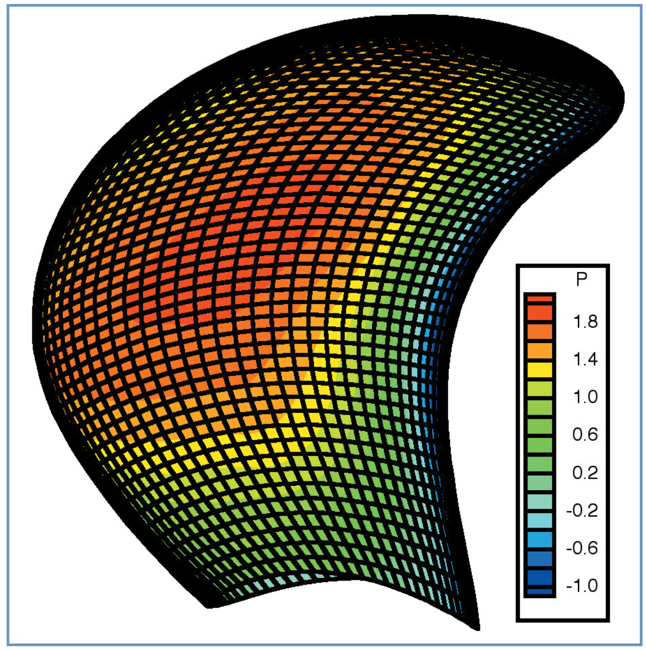

Figure 5. Pressure distribution (C_P) on suction side blade surface.

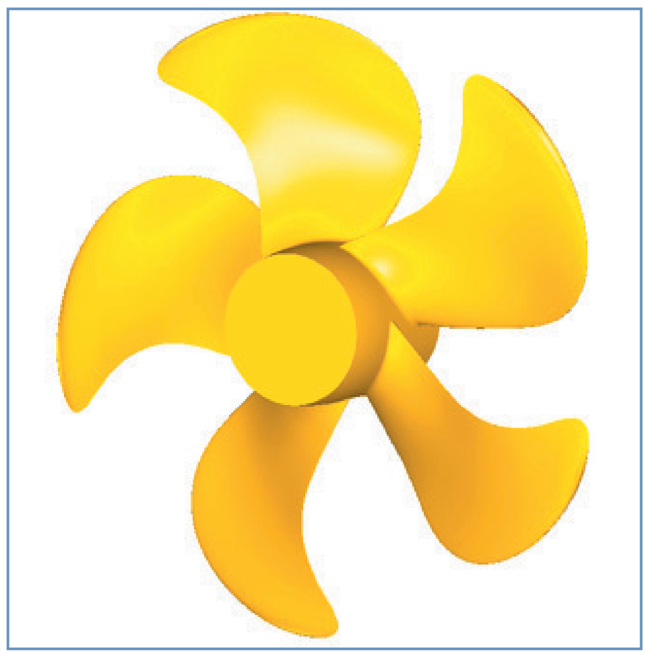

Figure 6. Computer image of FRV-40 propeller.

Table 2. Propeller principal characteristics.

Number of Blades: 5
Diameter: 14.1 ft (4.297 m)
Design RPM: 100 at 11 knots
Expanded Area Ratio: 0.637
Right-Hand Rotation
Thickness Section: NACA 66 (DTMB Modified)
Camber Section: 3-D from a=0.8 mean line

Cavitation Test

Facility and Arrangement

Cavitation observation tests were carried out in the Large Cavitation Channel (LCC) located in Memphis, Tennessee.[6] Figure 7 is a profile sketch of the FRV-40 model in the LCC facility. The FRV-40 wooden model hull length of 15.13 ft (4.61 m) used in towing basin tests for resistance and powering[7] was used in the cavitation experiments also. Appendages mounted on the hull for these tests included the actuated flap-type rudder, the final design sonar centerboard, and the baseline skeg configuration. The small bilge keels were not included. A fiberglass fairing piece was installed behind the wide transom stern region to prevent flow separation and any localized unsteady recirculating flows.

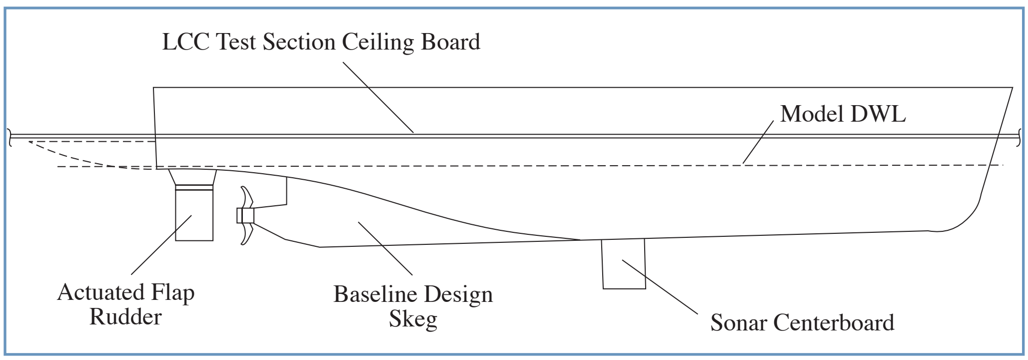

Figure 7. Model FRV hull mounted in the LCC (sectional view).

Model propeller thrust and torque were measured with a Kempf and Remmers transmission dynamometer. The variable-frequency waterproof electric motor was installed inside the model hull and connected to the dynamometer and propeller shaft.

Measurement Uncertainties

Estimates are given here for the relative uncertainty levels of the basic independent measurement variables, and for a best-available estimate of the inherent error of measurement of the index of visual cavitation inception.

From Blanton,[8] the LCC tunnel pressure can be determined with a total uncertainty of about ±0.1 psi (0.7 kPa) or about ±1% of the lowest pressure used here. The LCC tunnel velocity has a total uncertainty of about ±0.8% for the lowest speed used here, and water density can be determined within ±0.1%.

Propeller shaft rotational speed can be measured within ±1 rpm or about ±0.1%. Model propeller thrust and torque can be determined within about ±1.5%. Gas content determined as percent of saturation at atmospheric conditions can be measured to within about 5%.

With the methods and notation of Coleman and Steele,[9] the normalized uncertainty of the cavitation number (based strictly on the separately analyzed total uncertainties of the independent measurement variables of tunnel speed, pressure, and density) is only ±1.3%. This completely ignores the well known highly variable character of the appearance of incipient vortex cavitation. We need a realistic order of magnitude estimate of the dominant component of error in calling cavitation inception. From an unpublished investigation of visually called propeller tip vortex cavitation inception determined from many repeat measurements (sample size of about 50) a worst-case normalized precision limit of 0.28 was obtained. If this uncertainty estimate is regarded as a representative example, it can be treated here as a bias estimate for the present propeller case. Then, together with the uncertainty estimate noted above, a bounding estimate for the combined total normalized uncertainty for visual calls of cavitation inception number is 0.28. Physically, it makes sense to apply this only as a one-sided error estimate. Thus, within roughly a 95% confidence interval, the estimate of the incipient cavitation number is the measured value multiplied by 1.28.

Procedure and Testing

For this test program, the conditions at each operating point were set using the torque identity method because of problems with the thrust measurement channel of the dynamometer. This involved maintaining the desired torque coefficient and advance coefficient based on the wake factor obtained in towing basin propulsion experiments.[7] Tunnel pressure was adjusted to obtain the desired cavitation number for each separate condition. Care was taken to correct the tunnel pressure measurement for the longitudinal location of the model propeller plane within the test section. Hull model blockage of the LCC cross-section area was 6.24%.

The cavitation performance results for the FRV-40 design propeller, represented by propeller Model 5343, can be summarized as follows.

- The design propeller produces no blade cavitation of any kind at the 11-knot quiet operations condition. This includes the absence of any tip vortex cavitation, as confirmed by testing at the Reynolds-Number scaled value for that condition.

- At the extreme 4-knot tow load case, corresponding to the maximum deliverable engine torque, there was fully developed suction side tip vortex cavitation occurring around the full angular extent of the disc and thin patches of leading-edge sheet cavitation on some of the blades. Some of the cavitating tip vortices were intermittently detached from the blade tip from which they originated. The sheet cavity termination regions showed no signs of cloud cavitation or unstable collapse patterns. These cavitation patterns were judged to be benign and should not give rise to blade surface erosion problems. For this tow case, the Reynolds-Number scaled full-scale ship speed for the disappearance of tip vortex cavitation is estimated to be 1.8 knots. Figure 8 shows this condition.

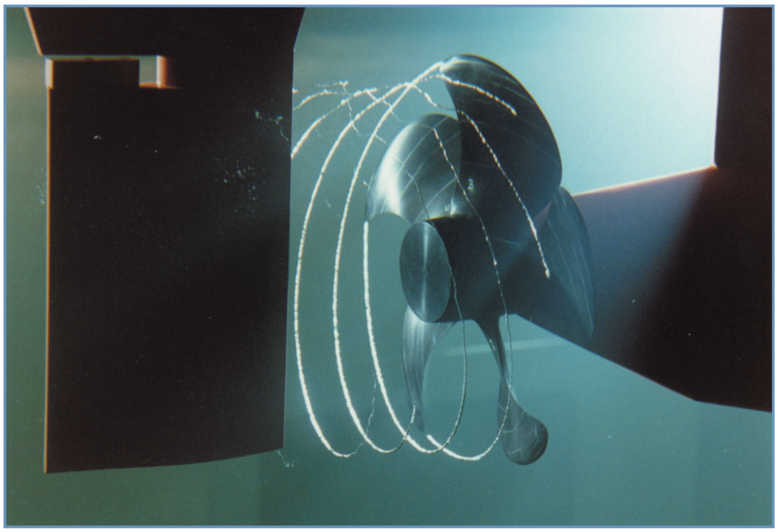

Figure 8. FRV-40 model propeller cavitation at the tow case of maximum engine torque.

- For the free-running ship, an experimental tip vortex cavitation inception ship speed of 12.7 knots was measured in the LCC. However, there is an uncertainty level that must be applied to this result. If the estimated model cavitation index uncertainty ratio is applied at full scale, the final worst-case prediction value for no cavitation operation at full scale is 11.2 knots. This provides a predicted inception speed with a margin 1.5 knots lower than the nominal scaled value.

Summary

A quiet ice-class propeller was successfully designed for the NOAA FRV-40 fisheries research vessel. Tip vortex cavitation has been mitigated with a large diameter propeller and unloaded propeller tips. The propeller rpm has been kept as low as possible to minimize non-cavitating noise. The propeller meets ABS ice-class C0 requirements.

Experimental data indicate the propeller will operate cavitation-free at ship speeds up to at least 11.2 knots. This predicted cavitation inception speed, with a margin of 1.5 knots below the observed inception speed, was obtained by applying the estimated uncertainty ratio for inception cavitation index determined at model scale. Cavitation has been minimized in the 4-knot towing condition.

Acknowledgements

The authors wish to thank Carl Setterstrom of MARAD for his assistance in this work and John Hotaling of NOAA for sponsoring the project.

References

1. Coney, W. B., “A Method for the Design of a Class of Optimum Marine Propulsors,” Doctoral Dissertation, MIT Department of Ocean Engineering (1989).

2. Greeley, D. S., and J. E. Kerwin, “Numerical Methods for Propeller Design and Analysis in Steady Flow,” *SNAME Transactions*, Vol. 90 (1982).

3. Neely, S. K., “Application of NURBS Surfaces for Propeller Geometry,” *Proceedings of the Twenty-Fifth American Towing Tank Conference* (1998).

4. Souders, W. G., and G. P. Platzer, “Tip Vortex Cavitation Characteristics and Delay of Inception on a Three-Dimensional Hydrofoil,” NSWCCD Report DTNSRDC-81/007 (Apr 1981).

5. Lee, J. T., “A Potential Based Panel Method for the Analysis of Marine Propellers in Steady Flow,” Doctoral Dissertation, MIT Department of Ocean Engineering (1987).

6. Wilson, M.B., and R.J. Etter, “Hydrodynamic and Hydroacoustic Characteristics of the New David Taylor Model Basin Large Cavitation Channel,” *Proc. Second Symposium on Propeller and Cavitation, Hangzhou, China* (1992).

7. Forgach, K.M., “Resistance and Design Propeller Powering Experiments With Model 5522-1 Representing the NOAA Fisheries Research Vessel FRV 40,” NSWCCD Report NSWCCD-50-TR-1999/035 (Feb 1999).

8. Blanton, J.N., “Uncertainty Estimate of Test Section Pressure and Velocity in the Large Cavitation Channel,” 31st Joint Propulsion Conference and Exhibit AIAA Paper 95-3079, San Diego CA (July 1995).

9. Coleman, H. W., and W. G. Steele, *Experimentation and Uncertainty Analysis for Engineers*, John Wiley and Sons, New York (1989).

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Autonomous Mobile Periscope System

Stephen P. Ebner, Richard Knutson, and Hung Phi Vo

As new periscope detection tools become available, a training requirement has evolved for an inexpensive, readily available periscope detection target. The Autonomous Mobile Periscope System (AMPS) was developed to meet this need by presenting the above-water portion of a full-scale submarine attack periscope. Cost for AMPS from concept to at-sea operations was an order of magnitude less than other first-copy autonomous underwater vehicles of this complexity. The relatively low cost is due to extensive 3-D dynamic simulation analysis, scale-model evaluation prior to full-scale development, and a small design team.

Introduction

The difficulty of acoustic detection of nearly silent diesel submarines has made periscope detection a high priority for the U.S. Navy. As new periscope detection tools continually become available, training is required for air, sea, and land based antisubmarine warfare (ASW) crews. The need for an inexpensive, readily available periscope detection target was identified because the U.S. does not have a diesel submarine, and the nuclear submarine force is not available for this type of training. The Autonomous Mobile Periscope System (AMPS) (Figure 1) was developed to meet this need by presenting the above water portion of a submarine attack periscope. AMPS is an autonomous unmanned underwater vehicle that can perform preprogrammed runs with and without the periscope exposed. AMPS basic operational characteristics are outlined in Table 1.

The effort encompassed all design aspects of the system from concept to full-scale acceptance testing. However, due to an extremely limited budget and a development schedule of approximately 3 years, the extensive development time and costs were not acceptable. Therefore, 3-D dynamic simulations were performed during preliminary design development to analyze the hydrodynamic design, the signal processing design, the motion control design, and the servo control design.

A scale-model basin evaluation was conducted upon completion of the preliminary full-scale design effort to verify hydrodynamics, signal processing, and motion control predicted by the dynamic simulation. Successful completion of the basin evaluation and good correlation with

Table 1. AMPS operational characteristics.

Parameter	Characteristic
Endurance (full charge)	
- mast exposed at all times	3.9 hr at 5 knots
- mast exposed 1/3, submerged 2/3	6 hr at 5 knots
Operational sea state	3
Speed range	3.5 to 5 knots
Mast exposure	5 ft
Maximum pitch & roll	<10 deg 90% of the time
Operating depths at vehicle centerline	
- periscope exposed	6 ft
- submerged	25 ft
- survive	600 ft
Tracking`	Acoustic and/or GPS

predicted performance led to full-scale mechanical and electrical design, fabrication, functional checks, static tests in the deep water basin, operational tests in the Chesapeake Bay, and acceptance tests at the Pacific Missile Range Facility (PMRF) in Kauai, Hawaii.

The AMPS Vehicle

Vehicle physical characteristics are given in Table 2; geometry is shown in Figure 1. The vehicle is divided into five main modular sections: the bow (nose fairing and bow can), battery, keel/mast, electronics, and aft (forward tail and tail cone) sections (Figure 2). The keel/mast, aft sections, and nose fairing are flooded with watertight housings for the propulsor motor, servo motors, and the tracking pinger located within these sections. All other sections are watertight.

Table 2. AMPS vehicle design characteristics.

Parameter	Characteristic
Hull length	26.5 ft
Hull diameter	24 in.
Mast height	10 ft
Weight in air	3600 lb
Net buoyancy in seawater	80 lb
Propulsor power required	4 Hp
Power source	16 24-V NiCd batteries

For attitude control, AMPS incorporates independently operated bow planes for roll, pitch, and depth control; stern planes for depth and pitch control; and rudder for heading control. The keel and mast are erected after launch and folded prior to vehicle retrieval. During operations, the vehicle will operate at either periscope depth with the upper 5 ft of the mast exposed or at submerged depth with the mast folded. Sixteen 24-volt nickel-cadmium (NiCd) batteries power the vehicle. Under nominal operating conditions, vehicle endurance is approximately 6 hr at 5 knots.

AMPS uses a Global Positioning System (GPS) and a heading sensor to navigate to preprogrammed waypoints where a maneuver is performed (i.e., dive, turn, rise, end run). The preprogrammed run is downloaded to the vehicle using a hardwire link prior to deployment. During operation, a series of status commands (start, idle, end run, transit) can be transmitted to the vehicle via a radio frequency (RF) link that is integrated into the mast. The vehicle also transmits real-time engineering data to the operator using the RF link. AMPS also incorporates a tracking pinger to track the vehicle when operating on an underwater acoustic range.

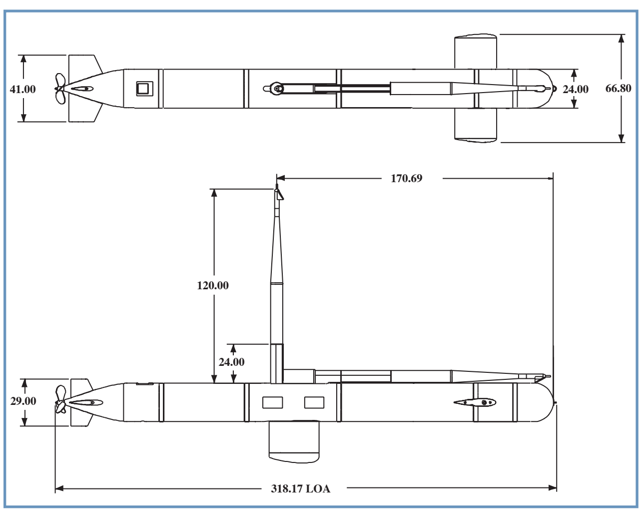

Figure 1. Plan and side view of the AMPS vehicle. (All dimensions are in inches).

Development

Concept development established basic performance goals and performed sufficient analysis to determine general physical parameters. Preliminary design carried the concept to a level of detail sufficient to specify vehicle components and arrangements. During preliminary design, working-level drawings were produced, design analyses were conducted, baseline motion control software was developed, and signal-level simulation and bench testing of control hardware and software were performed.

Preliminary development required extensive dynamic simulation of the vehicle and its response to various sea-state conditions. Vehicle simulations were performed using FORTRAN programs developed by the Marine and Aviation Department. The vehicle model includes the effects of the surface piercing mast. Multiple run iterations were completed to check response to changes of the parameters given in Table 3. Specifications and criteria were developed for the vehicle hydrodynamics, signal processing, motion control, and servo control. A dynamic

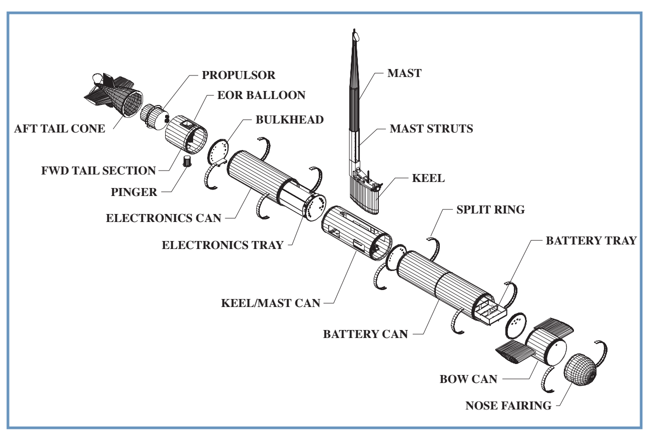

Figure 2. Exploded view of AMPS.

heave rate compensator also was developed and checked with the simulation. The compensator is effectively a band-pass filter, which allows the vehicle to follow the long period swells while not responding to local wind-driven waves. By doing this, the vehicle will expose the mast target consistently when operating near the surface in Hawaii where large swells often are present.

A 0.29-scale model was evaluated in calm water and waves in the Deep Water Towing Basin. The model incorporated the full-scale inertial measurement unit (IMU) and control architecture with closed-loop depth, roll, and pitch control. Heading and speed were operated manually. Test results verified the hydrodynamic design, control sensors, and motion control, and had good correlation with the dynamic simulation results. Control system performance was successful in all tested sea conditions.

The full-scale design finalized the vehicle's mechanical, electronic, and software designs as well as handling, shore-side interface, and ship and shore support systems. Full-scale performance was demonstrated throughout the design and fabrication process through laboratory checks and proof tests. Prior to at-sea evaluations, 37.5 hr of static in-water endurance tests were completed in the Deep Water Towing Basin dry-dock. During this test, propeller speed was set to simulate loading corresponding to 5 knots, and the control surfaces were commanded to move continually in a sinusoidal motion. The mast was deployed and retrieved every 5 minutes throughout the test with mast drag approximated. Preliminary operational tests then were conducted in the Chesapeake Bay. All aspects of vehicle performance were tested except radio range, underwater acoustic tracking, submerged operations, and in-situ handling with the support boat.

AMPS acceptance tests were started during the full-scale development with a series of proof tests designed to validate performance per specified requirements. However, final acceptance required full operations at PMRF. Checkout runs and tests initially were conducted outside the acoustic ranges to check vehicle performance and train local personnel in handling, operating, and maintaining the vehicle. Final acceptance tests were successfully conducted on the acoustic ranges at PMRF (Figures 3, 4, and 5). NSWCCD will continue to provide support for AMPS operations until PMRF personnel are fully familiar with operational and maintenance procedures.

Table 3. AMPS dynamic simulation parameters.

Hydrodynamic	Signal Processing	Motion Control	Servo Control
Geometric design	Sensor range	Architecture	Drive friction
Mast water surface penetration	Sensor accuracy	Feedback parameters	Drive inertia
Drag	Signal analog filter design	Feedback gains	Angular rate requirement
Stability	A-D conversion (digitizing, resolution)	Motion error integration	Torque requirement (static/dynamic)
Control authority	Derivation of state variables (roll, pitch, heave rate, heave)	Limiters	Frequency bandwidth requirement
Trim	Digital bias filter gains	Dynamic heave compensation	Mechanical backlash
Maneuverability	Signal phase shift	Closed-loop seaway response (frequency/time domain)	
Open-loop seaway response (frequency/time domain)	Signal noise	Heading control	
		Dive transients	

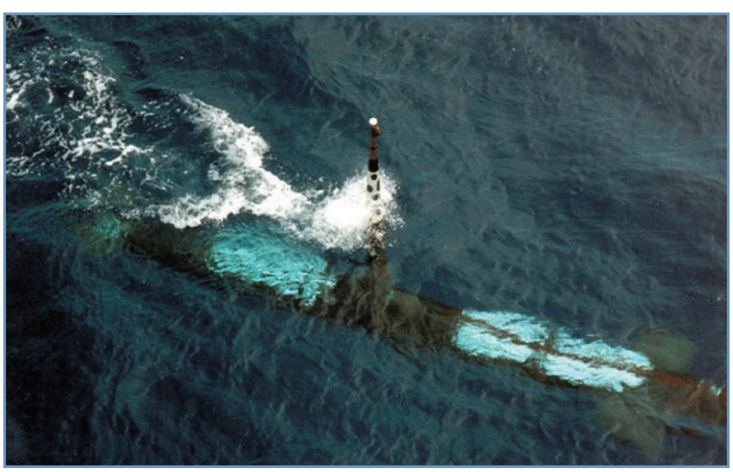

Figure 3. AMPS Acceptance test operations.

Figure 4. Acceptance test handling operations using the Weapons Recovery Boat.

Figure 5. Acceptance tests off Kauai, Hawaii.

Cost

Cost for AMPS from concept through acceptance tests at PMRF was $2.5 million, approximately an order of magnitude less than other first-copy autonomous underwater vehicles of this complexity. The relatively low cost is due to extensive 3-D dynamic simulation analysis for design development, comprehensive testing, and a small team of very dedicated engineers.

Summary

AMPS was developed for PMRF use as a low cost solution to provide U.S. Navy ASW crews with radar and visual periscope detection training. Successful acceptance tests and continued operations of AMPS after a 3-year development effort and minimal budget attests to the time and cost savings that can be achieved with extensive simulation and proper design and testing.

AMPS operational and support systems have performed very well in a variety of sea conditions. Initial reviews from Fleet ASW crews that exercised with AMPS indicate that it presents well as a submarine periscope.

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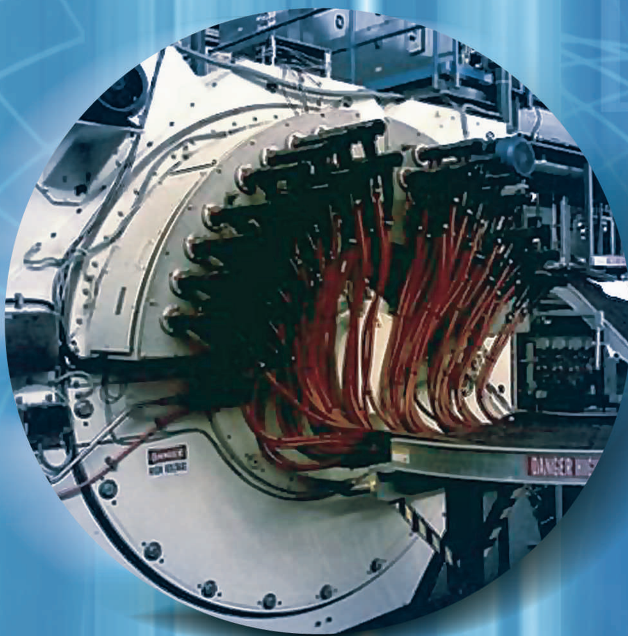
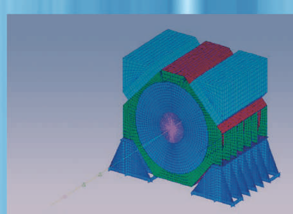
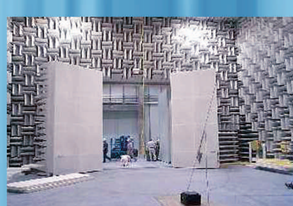


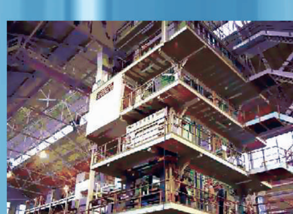
Systems Components

Machinery Systems and Components

Overview Article Follows





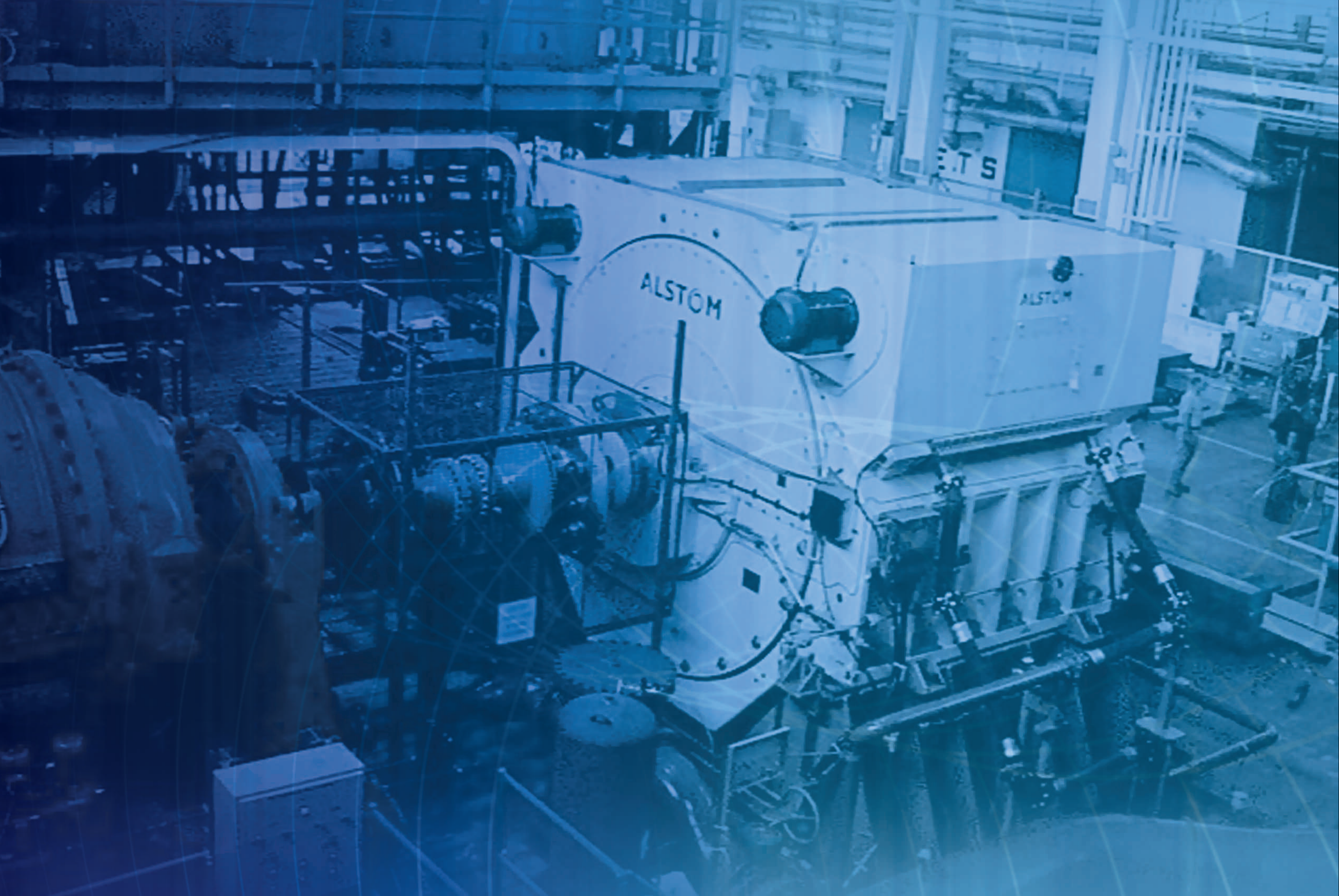


machinery

TECHNICAL DIGEST

MACHINERY SYSTEMS & COMPONENTS

Carderock Division scientists and engineers provide the technology development, acquisition support, and life cycle management for vital machinery systems and equipment which enable all Navy ships to meet performance and mission requirements for mobility, crew systems support, and combat systems interface. Included are: mechanical and electrical power and propulsion systems; auxiliary machinery systems; hull, deck, and habitability machinery systems; undersea vehicle sail and deployed systems; machinery automation, controls, sensors and network systems; and machinery integrated logistics systems and procedures. In their application, these products and their management over the life cycle greatly influence the viability of operation and affordability of naval platforms.



Machinery Systems and Components: An Overview

Arnold N. Ostroff

This paper examines several ongoing technology developments that offer potential design advantages for future ship machinery systems. Areas highlighted are fuel cells, quiet electric drive, thermal management, composite materials, electric actuators, machinery automation and control, and advanced sensors and networks. Anticipated machinery technology needs for a future all-electric ship are identified, and three ensuing technical papers are introduced.

Introduction

Since the early 1900s, NSWCCD has served as the Navy's leader in the development, evaluation, and integration of marine machinery systems and components. From formative work in naval fuel oils and machinery standards to today's developments in electric drive and fuel cells, the Division has been at the forefront in advancing naval machinery technology and providing systems that enable the Navy to maintain its military dominance.

Machinery systems and components represent the most diverse and numerous equipment installed on a modern warship. They include items such as engines, boilers, gears, shafting, bearings, pumps, air compressors, hydraulics, piping and valves, distillation plants, heat exchangers, heating and refrigeration systems, electric motors and generators, electric power conversion and control systems, electric distribution systems, elevators, conveyors, cranes, steering systems, underway replenishment, habitability, and hull outfitting systems.

Today's machinery systems and components are more complex and intelligent as a result of automation, network connectivity, and built-in diagnostics. They interact with other ship systems and are designed to meet stringent requirements that often relate to other ship design disciplines such as signature and silencing systems, structures and materials, and vulnerability and survivability systems. This paper describes several current technology areas that demonstrate the diversity and sophistication of today's machinery systems. They represent enabling technologies that are expected to significantly influence future ship machinery systems applications.

Fuel Cells

Recent advances in fuel cell technology make fuel cells increasingly attractive for electric power generation on naval ships, as well as in commercial marine applications. These include significant increases in cell and stack power density, the development of compact fossil fuel reformers, and emerging commercialization efforts. A significant technology push over the last decade by the U.S. Department of Energy and commercial partners may soon enable fuel cells to compete with commercial diesel and gas-turbine-powered generators. In 1997, the Office of Naval Research (ONR) initiated an advanced development program to demonstrate a ship service fuel cell (SSFC) power generation module. When completed, this program will provide the basis for new fuel cell based ship service power systems that will be a viable and attractive option for future U.S. Navy surface ships.

During the initial phase of the ONR SSFC program, competitive conceptual designs of 2.5 MW power plants were prepared, as were critical component demonstrations designed to reduce development risk. Two fuel cell systems were tested - a molten carbonate system and a proton exchange membrane (PEM) system. After critical review of both designs, the molten carbonate system was chosen to advance in the second phase of the program, which includes the construction of a nominal 500-kW fuel cell module. This system will be land-based tested at the Division's Philadelphia site in 2003. After testing, the module will be installed aboard a ship for an at-sea demonstration the following year. Further development of PEM systems is underway to advance technology for diesel fuel reforming.

Quiet Electric Drive

The objective of the ONR sponsored Quiet Electric Drive (QED) program is to demonstrate signature reduction technologies applicable to ship electric drive propulsion and auxiliary systems and to enhance war-fighting effectiveness, commonality, and affordability across platforms. The concept being pursued is integrated hydrodynamic, hydroacoustic, and structural acoustic signature control through the use of electric drive propulsion. The ONR Electrical Systems Task supports this Advanced Development Program. In this task, contributing technologies are investigated, developed, and transitioned to the QED program for demonstration in a direct fleet application. There are significant strategic naval payoffs associated with the QED program.

- Reduced acoustic signature over the full range of submarine operating speeds.
- Improved affordability through increased propulsion system modularity, simplification, and a reduced need for machinery isolation.
- Additional signature reduction when this technology is applied to auxiliary systems, such as main seawater pumps, secondary propulsion motors (Figure 1), and other submarine machinery.

Thermal Management

Nonchlorofluorocarbon chillers developed by NSWC-CD are being installed on U.S Navy surface ships and submarines. They are efficient, environmentally friendly, and exhibit reduced fuel consumption, acoustic signatures, and equipment footprint. As effective as these new chillers are today, they may prove to be unsuitable for future cooling requirements, because auxiliary systems of the future are being designed for decentralized and autonomous operation. The new architectures will require cooling systems that are also decentralized, programmable, and capable of operating in a zonal configuration. Furthermore, the transition from mechanical to electrical auxiliary equipment will result in significantly increased power density and heat dissipation. Increasing the number of cooling units (smaller, more efficient, and localized) may prove to be the means to provide a suitable environment for the crew and equipment. Some alternative cooling technologies being investigated are listed below.

- *Thermoelectric Air Conditioning* - Recent breakthroughs in thin-film thermoelectric materials have the potential for efficient solid-state cooling with no environmental impact.
- *Magnetic Refrigeration* - This is an emerging technology that offers the potential for high-energy and efficiency with minimal environmental hazard. It is based on the use of an active magnetic regenerator to produce chilled water efficiently.
- *Thermoacoustic Cooling* - This employs sound waves to produce cooling. Pennsylvania State University is building a 3-ton cooling system that will be tested in the near future.

New heat exchanger designs using novel methods and materials to remove heat passively are being explored as well.

- *Dry Sump Heat Exchangers* that use heat pipe technology to eliminate closed-water loops, external heat exchangers, and piping arrangements.
- *Waste Heat Recovery Systems* that turn the unwanted heat back into useful energy that could power secondary equipment or even be used to produce supplemental cooling.
- *Through-the-Hull Heat Exchangers* that eliminate the need for large, bulky freshwater-to-seawater heat exchangers

Figure 1. Submarine secondary propulsion motor.

Composite Construction Materials for Naval Machinery and Equipment

During the last two decades, the Navy has demonstrated the feasibility of propulsion and auxiliary machinery made of fiber-reinforced thermosetting resins (e.g., epoxies, vinylesters, and fire-resistant phenolics) in a number of shipboard applications - propulsion shafting, piping systems, centrifugal pumps, ball valves, heat exchangers, and supply-intake ventilation ducting (Figure 2).

Composite machinery components offer a number of advantages, such as corrosion/erosion-resistance, galvanic compatibility with metals, reduced life-cycle cost, improved structural efficiency, and reduced weight. Furthermore, composites are well suited to support numerous applications in future ship and autonomous vehicle concepts because of advances in the development of conductive reinforcing agents, as well as conductive polymer matrices. As a

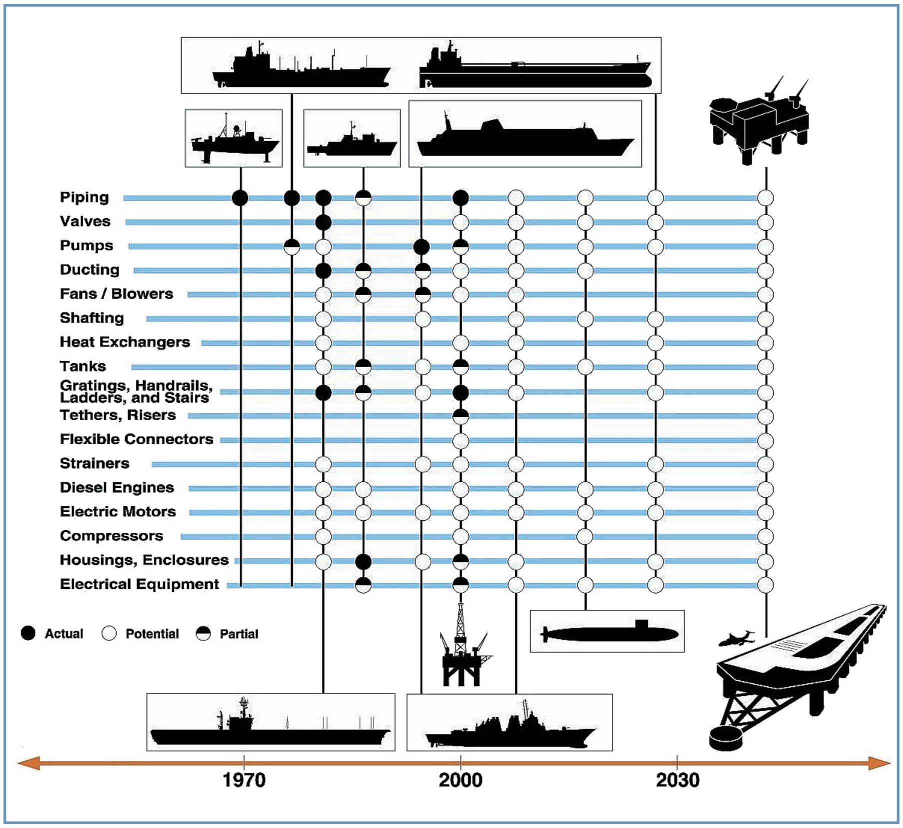


Figure 2. Some initial applications of composite materials on naval machinery.

result of successful at-sea trials, long-term development investments, and growing commercial use of composite construction materials in the United States, a wide variety of composite machinery components are becoming available for consideration in surface ship design and construction. Current efforts to expand the application of composite machinery are directed toward the identification of appropriate commercial specifications, standardization strategies, and design guidance to ensure compliance with performance and safety standards.

Electric Actuators For Submarines

The use of electric actuators on submarines is a potential enabling technology that will reduce manning via the eventual replacement of maintenance-intensive hydraulic actuators and fluid distribution systems. These systems operate several hundred valves, control surfaces, weapons handling, and other equipment in today's submarines. Their output torques range from 2.5 in.-lb (small 1/4-turn valves) to tens of millions of in-lb (control surfaces). At present, ONR and NAVSEA (SEA 93R) are developing electric actuator technology to address the wide range of actuation demands and satisfy all of the submarine service requirements.

Submarine actuator system performance requirements include minimal acoustic signature, resistance to shock and vibration, electromagnetic interference emissions and susceptibility, corrosion resistance, power density, fail-safe operation, back-up power, reliability, and maintainability. A wide variety of electric actuator systems are available or under development. Mature configurations such as electric motor and geared speed reducer are common in commercial and aerospace applications, but have not been qualified to satisfy submarine service requirements. New types of electric actuators (such as piezo-electric, magnetostrictive, electrohydrostatic, and shape-memory alloy) are being developed and show promise. The wide range of actuator output torque requirements suggests that a variety of electric actuator systems eventually will be needed for submarine actuator applications.

Integration of electric actuators on submarines is expected to be a long-term effort. The qualification program for electric actuator systems must include laboratory and shipboard tests to demonstrate satisfactory performance for long-term submarine service. Initially, they would be installed to replace hydraulic actuators in non-vital, non-sea-connected systems to obtain operating, reliability, and maintenance data. The submarine community has relied on hydraulic actuators for over 50 years. As confidence in the performance and reliability of electric actuator systems increases, they could replace the hydraulic fluid system, and the anticipated maintenance and manpower savings would be realized.

Machinery Automation and Control

Many of the machinery and auxiliary systems on Navy ships rely heavily on human intervention to operate the system and perform damage control functions. With the goal to reduce manning on the next generation of Navy ships, affordable and survivable automation technology is being investigated to replace the crew function through its deployment. Some of the major issues associated with implementing an automation system for a naval war ship include:

- Ensure that the system is highly survivable.
- Integrate multiple automated control systems at the ship control level.
- Design an affordable system to optimize control and fight-through capability.

Under the sponsorship of NAVSEA (SEA 05R), ONR, and the DD (X) Program Office, the Division developed, tested, and demonstrated control technologies to meet the manning reduction initiatives. Efforts focused on the development of highly distributed control systems and networks for improved survivability and automation to reduce manpower requirements for both machinery systems and distributed auxiliary systems. Recent research and development tasks used distributed control and network technology to accomplish the following.

- Demonstrate the techniques to detect and isolate leak and rupture damage from a warhead event and to reconfigure the highly distributed fluid system to regain the maximum capability possible with the remaining resources.
- Operate and manage the resources and distribution of a highly distributed closed- loop fluid system using control algorithms that also are distributed to all of the system components with no central controller.
- Demonstrate advanced network healing technology on a small Navy surface ship using advanced distributed control (Figure 3) algorithms.

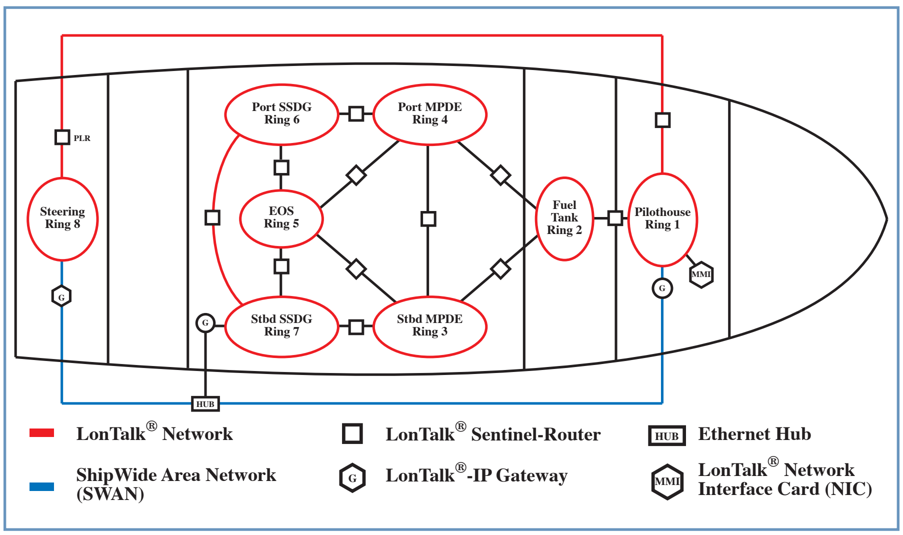


Figure 3. Distributed control network architecture.

Advanced Sensors and Networks

The research and development of advanced sensors is a multidisciplinary field serving machinery, damage control and materials applications. Recently, the technologies employed by the Division to serve Fleet needs included fiber optics, ultrasonics, and microelectromechanical systems (MEMS). Under programs primarily directed by ONR, the Division develops sensors and data acquisition systems that provide advanced capabilities in the measurement of flow, pressure, proximity, current, temperature, strain, material damage, wear, and other parameters. Current development efforts are shown below.

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- An ultrasonic hull damage sensor array that locates and estimates, in real time, the size of hull penetrations due to damage.
- A Bragg grating fiber optic strain sensor array that measures strain in absolute units (allowing for removal and reattachment of electronics) and allows real time/long- term monitoring.
- A fiber optic bearing wear sensor that remotely measures the wear of outboard water-lubricated propulsion bearing staves.
- Integrated fiber optic current and temperature sensors to measure such parameters within electrical components.

To operate with a reduced crew, a ship must have a reliable, accurate, and timely information system to monitor vital environmental, structural, machinery, and personnel conditions. An ONR sponsored Advanced Technology Demonstration called Reduced Ship-crew by Virtual Presence (RSVP) is investigating the necessary technologies. The RSVP program demonstrates elements of key high-risk technology areas in the implementation of a Navy shipboard wireless sensor network to support reduced ship manning. The program has defined three major areas of high-risk technology application development.

- Advanced sensors in a high-density configuration.
- Wireless shipboard intra-compartment networks.
- Data fusion and advanced reasoning to support situational awareness.

Land-based and at-sea evaluations of prototype components on full-scale naval machinery were completed in 2001. The DD (X) shipbuilder will use information provided by the RSVP program to select technologies that will support a reduced crew size.

Future Machinery Technology Developments

In January 2000, the Secretary of the Navy announced that the new Land Attack Destroyer (DD (X)) would be the Navy's first ship class designed and built during the 21st century to be powered by electric drive featuring an integrated power architecture. Integrated power is a flexible, open-architecture approach that permits any generating unit to supply propulsion or ship service power to support ship operational priorities. Looking beyond DD (X), there is strong interest to make future ships all-electric, thereby eliminating pneumatic, hydraulic, and other maintenance-intensive auxiliary systems. All-electric ships will also enable the deployment of high-energy weapons for long-range fire support. Operation of these weapons systems requires huge amounts of power over a very short time period, and depends on sophisticated high power solid-state switching and pulse-forming networks. Greater dependency on integrated power systems and the expanded use of electric power throughout the ship places a greater demand on the technologies that provide and maintain electrical distribution systems and their availability, survivability, and power quality. It is anticipated that future electric power systems will operate at higher voltage levels and use superconducting electric machines and energy storage systems. Superconductive machinery offers the advantages of reduced size and weight, high efficiency, design simplicity, and reduction of components that contribute to the platform's signature.

Intelligent systems, advanced sensors, and the greater use of electromechanical actuators are beginning to play a major role in the design of future machinery systems and equipment. The systems are becoming more modular, with "plug and play" capability, and will be logically interconnected and distributed via advanced ship-wide networks, thus enabling unmanned decision-making and reconfiguration. Other future developments include more energy-dense and environmentally compliant propulsion systems, decentralized auxiliary systems, enhanced shaftline components, and advanced machinery for autonomous vehicles. Fuel cells are expected be a significant source of shipboard electricity, especially for zonal power generation. In the near term, hydrogen for the fuel cells will be obtained from liquid hydrocarbon fuels; however, future developments will focus on the extraction of hydrogen from seawater to reduce dependence on fossil fuels. Advances in machinery technology cannot be made without attention given to the reduction of noise signatures. Future machinery designs for submarines and surface ships will demand improved stealth via reduced acoustic and electromagnetic signatures without degradation of performance levels.

Technical Papers

The three technical papers that follow demonstrate some of the work being done to support the expanded use of electric power on ships. The first paper describes an intelligent fault protection device that is under development. This device is designed to provide rapid isolation of bus level faults within a zonal electrical distribution system and maintain system-wide voltage to minimize potential damage to vital ship systems.

The second paper reports on the initial results of full-scale land-based testing of the Integrated Power System (IPS). It describes some of the design, construction, and integration issues that arose during the tests and explains how resolution of these issues led to advancements that are expected to facilitate the transition to more electric-capable ships of the future.

The third technical paper discusses the development of standard hardware interfaces to use with Power Electronic Building Blocks (PEBBs). These devices are general-purpose power-controller modules that can perform numerous electrical power conversion functions via software reconfiguration.

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An Intelligent Fault Detection Device for Shipboard Power Systems

Lyle R. Plesnick, Tracy L. Hannon, and Daniel P. Devine

An intelligent fault detection and isolation concept was developed and demonstrated as part of the Carderock Division's Electric Power System Survivability Program. The task was a joint effort between NSWCCD, academia, and industry and was sponsored by NAVSEA (SEA 05R), (SEA 05Z), (PMS 400), and (PMS 500). This paper describes the Multifunction Monitor III, which uses unique fault detection and control algorithms to provide rapid, intelligent isolation of bus-level faults within a zonal electrical distribution system.

Background

Electrical faults in a main power distribution system can result in system-wide voltage degradation while the generators provide large amounts of current to the on-line fault. Coordination among any simultaneous feeder faults may be problematic as the larger main bus fault starves the feeder faults of the current levels necessary to trip the feeder circuit breakers. These faults may be a result of physical damage to shipboard electrical distribution equipment, including bus-tie cabling and switchboards, when impacted by a fragmenting missile. If sensitive loads self-protect and shut down due to below-nominal voltage conditions, the delay in restarting these loads will most likely impact shipboard mission capabilities. Quick detection and isolation of electrical faults decreases the duration of voltage decay, and minimizes the impact on sensitive loads. If the fault is isolated quickly, the loads can ride through the fault event and increase the odds of maintaining critical mission capabilities throughout the event.

The basic protection of a shipboard electric plant is based on single-bolted-type fault events in which the appropriate time-current settings of the circuit breakers are chosen. The settings are designed to ensure that coordinated tripping occurs throughout the system upon a single-point failure. The Electric Power System Survivability Program has determined through various studies, analyses, and tests that combat-related damage does not necessarily result in a single-fault application and, therefore, may not result in the designed coordination.

In addition, Zonal Electric Distribution System (ZEDS) designs call for further protection to the basic coordination scheme by requiring a current direction-sensing device to ensure the proper basic coordination. Circuit breaker time-current curve protection alone may not provide coordinated protection in the event of a fault on the main bus.

The Multifunction Monitor III (MFM III) (Figure 1) was developed to demonstrate the concept of overall main-bus protection coordination and combat fault detection and isolation. The MFM III is the result of a joint effort between NSWCCD, Bath Iron Works (BIW), Inc., and TANO, Inc.

Introduction

The Division teamed with industry and academia to conduct science and technology research and development of advanced electrical systems. One of the program areas is the Electrical Power System Survivability Program. The goal of this program is to enable shipboard electric plant designs to provide continuous quality electric power to user systems throughout a fault scenario. The development and testing of the MFM III is a result of this program. The MFM III unit will be installed in the zonal power protection system of DDG 91AF (and follow) ships.

The device senses voltage and current, communicates with other devices in the system, and uses a unique fault detection algorithm to determine if a shunt-trip signal should be sent to its associated breaker. It is designed to sense faults within 0.5 millisecond (ms), and perform an intelligent, coordinated shunt-trip decision within 10 ms.

Approach

The DDG 51 Class ZEDS was used to develop and analyze a fast detection and isolation concept as a step towards improved electric power system survivability. This zonal main-bus distribution system (Figure 2) requires MFM III units to be located at each of the 11 bus-level circuit breakers, including longitudinal, cross-tie, and generator circuit breakers.

In the event of damage to the main bus, the MFM III is designed to initiate a shunt-trip of the adjacent circuit breakers within 10 ms after fault detection. Circuit breakers on either side of the fault are shunt-tripped, isolating a minimal section of the distribution bus and providing proper coordination for the AC zonal distribution system. The MFM III units at the generator breakers provide only the functions of a reverse power monitor, directional current monitor, and overpower power monitor to maintain overall coordination.[1]

Detailed computer simulations of the electrical distribution system were critical in the research and development of the coordinated shunt-trip algorithms. Modeling the targeted shipboard distribution system in computer simulations allowed the team to develop and assess the MFM III logic algorithm's effectiveness prior to installing the algorithms into hardware. Fault simulations were performed throughout the main bus with various fault impedances, and vulnerability assessments were used to determine the necessary algorithm actions. TANO, Inc., then installed these algorithms into the MFM III units.

A reduced-scale portion of the zonal system was constructed at the Division's Ship System Survivability Test Site (Figure 3) at the Army Test Center, Aberdeen Proving Grounds, Aberdeen, MD. MFM III proof-of-concept testing was performed there using a cable faulting/cutting device, a bolted fault switch device, and live ordnance to inflict combat-type damage to the electrical system. This test setup also was modeled and used to validate components of the shipboard system model.

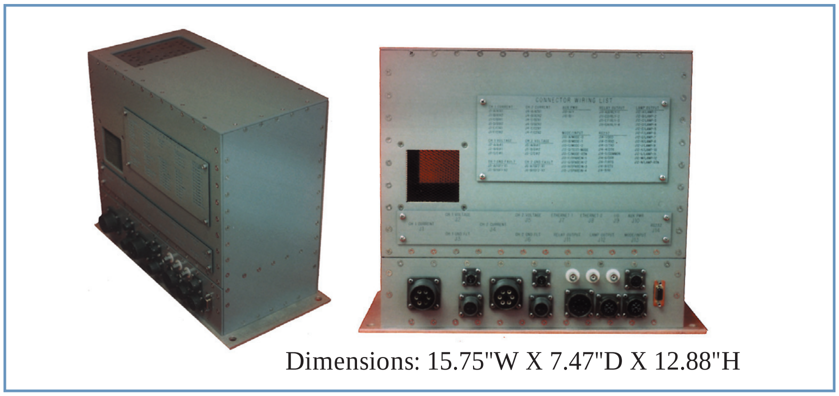

Figure 1. Multifunction Monitor III (MFM III).

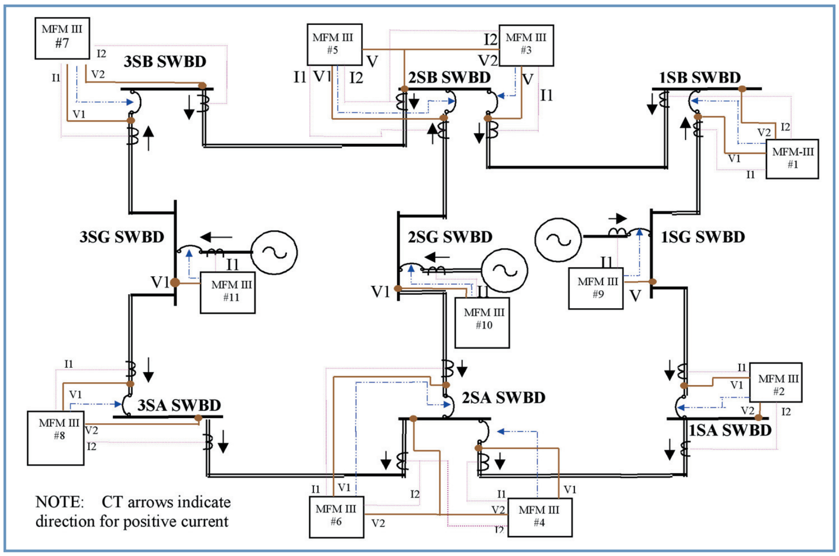

Figure 2. MFM III installation diagram for DDG 91AF.

Figure 3. Ship systems survivability test site, Army Test Center, Aberdeen Proving Grounds, MD

Development

Design

Each MFM III is responsible for importing local voltages, currents and circuit breaker status, processing the local voltages and currents to detect fault conditions, sending/receiving processed information to other MFM III units over three Ethernet ports, and processing locally generated and remotely received data to make proper shunt-trip decisions. The MFM III unit relies on a variety of algorithms to perform these functions. The MFM III manufacturer, TANO Inc., developed the system operation software of the MFM III units, providing signal processing, communication capabilities, data downloading capabilities, and proper execution of all logic algorithms. Under the direction of the Office of Naval Research and NSWCCD, Barron Associates Inc., developed the High-Speed Relay (HSR) fault detection algorithm.[2] Also, Bath Iron Works conceived the conceptual shunt-trip logic of the MFM III, called the Integrated Protective Coordination System (IPCS).[3] NSWCCD developed a routine, the IPCS algorithm, to use the information generated by the HSR algorithm and to implement the high-level IPCS logic. The IPCS algorithm processes fault detection data and system parameters from the HSR algorithm, determines fault current direction flow, and coordinates local information with remotely received information to make a coordinated shunt-trip response.

Local voltages and currents are acquired by the MFM III unit (Figure 2), which processes the data and determines the existence of a fault and the direction of the fault current flow. A three-port communication system transmits the information over a network to the other MFM III units, and a shunt-trip signal is sent to the adjacent bus-tie circuit breaker if dictated by the coordinated logic algorithms. The MFM III is capable of autonomous actions using shunt-trip logic based on overcurrent magnitudes and direction for a given time delay should one of the units be unable to communicate with other MFM III units.

A Barron Associates report[2] states that "*At each sampling instant, the Park transformation is applied to the input line-to-line voltages to produce a phasor (i.e., voltage magnitude and phase). A given event is classified as a fault, if the phasor magnitude deviates from the nominal value by more than a pre-specified amount. The phase quantity reflects conditions pertaining to variation in voltage phase and/or frequency. Normal loading does not perturb the phase significantly if the load is applied across all three phases, but line-to-line and single line faults disturb the phase quantity when power is drawn. A running window of normal behavior is maintained and sharp deviations that are detected are also considered fault events.*" These voltage and angle deviation thresholds are set for the desired sensitivity and characteristics of the power system; therefore, they are not dependent on sampling rates.

The IPCS algorithm uses the instantaneous normalized power levels from the HSR algorithm to calculate the steady-state power levels prior to a fault event. Also, the IPCS algorithm uses the instantaneous power levels during a fault event to establish average fault power. Fault direction is assigned if the absolute value of the difference of the average fault power and steady-state power exceeds the absolute value of the steady state power. However, if average fault power levels are below a given low power threshold, the power signals are considered too low to reliably allow fault current direction assignment. Similarly, if the voltage magnitude is less than a given low voltage threshold, the original voltage signals are considered in the noise, and no direction is assigned. These low power and voltage thresholds are necessary to prevent erroneous shunt-trip decisions and were determined through computer simulation and field tests conducted by the Division.

Fault current directions in combination with circuit breaker status are used to make a majority of the shunt-trip decisions. However, the IPCS algorithm also examines the relative magnitude of fault currents to assist in clearing bus-tie faults in nonstandard configurations, such as split-plant configurations. Flags are set for current magnitudes that exceed a high current threshold and fall below a low current threshold. A shunt-trip decision may be initiated if the current magnitude flags reflect that fault current flowing into one end of a longitudinal bus-tie is significantly different than at the other end of the same bus-tie.

The MFM III uses an Ethernet communication network (Figure 4) to pass information to the other MFM III units. A point-to-point network and ring communication system routes a matrix of information from unit to unit. The matrix includes data such as monitor number, location and type, current directions and magnitudes, adjacent circuit breaker status, fault detection status, fault reset status, local switchboard fault status, MFM action status, fault counter, breaker shunt-trip status, and unit health. All information is in integer format to minimize the transmitted packet size.

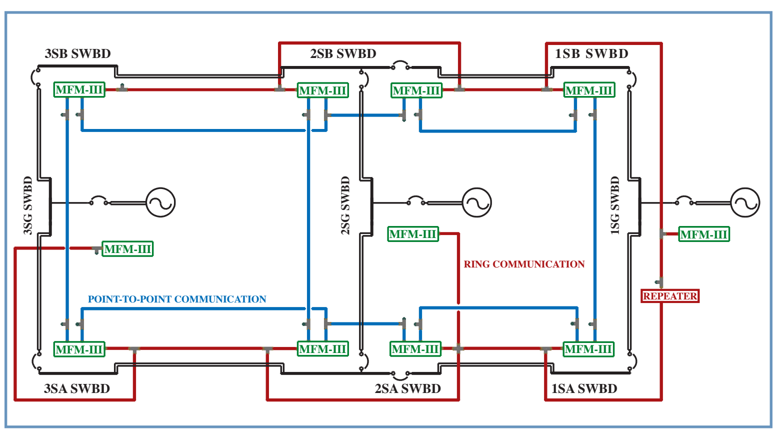

Figure 4. MFM III communication network.

Computer Simulation

A computer model was developed using the Advanced Continuous Simulation Language (ACSL) to determine electric power system response of an electric distribution system during fault scenarios. The computer simulation is based on a well-established, detailed digital model. Portions of the model were developed by P.C. Krause and Associates, with the core of the detailed digital model consisting of 3750 kVA ship-service gas turbine generators (SSGTGs) and distribution system components (cable and resistive and inductive loads). Further modifications to the detailed digital model were performed to include circuit breaker models, MFM III logic models, and enhanced fault models.

The main distribution system of DDG 79 and DDG 91–Class ships was modeled using ACSL for the development of the IPCS algorithms of the MFM III (Figure 5). While computer simulations are indispensable tools to develop and refine algorithms, hardware and software testing under faulted conditions was the critical next step to establish the MFM III unit's ability to perform as designed.

Testing

The MFM III prototypes underwent a series of proof-of-concept tests to demonstrate their ability to detect faults, to communicate information to other MFM III units, and to shunt-trip the appropriate circuit breakers. Tests were conducted at the Ship System Survivability Test Site at Aberdeen Proving Ground. Two prototype units were installed in a 1750-kW reduced-scale power system, and faults were placed on a power cable to replicate a bus-tie fault between two adjacent MFM III units. The cable was subjected to various types of damage including that caused by fragmenting ordnance (Figure 6).

Fault system information (voltages and currents) and communication data were recorded for analysis. Tests at Aberdeen proved that the MFM III units were able to detect a fault event and provide the shunt-trip signal to the adjacent circuit breakers within the targeted 10 ms. Performance issues were identified during the initial live-fire tests. TANO, Inc., and NSWCCD developed software solutions to these issues, and the new software was retested at NSWCCD.

In addition to the live-fire tests at Aberdeen, a full complement of MFM III production units will be installed at the Division's Land-Based Engineering Site (LBES) in Philadelphia PA. At the LBES, the 11 production units will be subjected to normal shipboard-type operations, which will include load transients, generator paralleling, and plant realignment to assess the performance of the MFM III in these conditions. Further tests are planned in Fiscal Year 02 at the LBES to fully investigate MFM III performance in a full-scale DDG 51 zonal system.

Summary

Development and testing of the MFM III has successfully demonstrated the concept of faster intelligent fault detection and isolation. Through increased communication and coordination of current and voltage information throughout the monitoring network, the MFM III unit decreased the area of fault isolation and performed faster than existing protection methods. Intelligent coordination combined with speed and accuracy provides a large forward departure from the slower current sensing circuit breakers

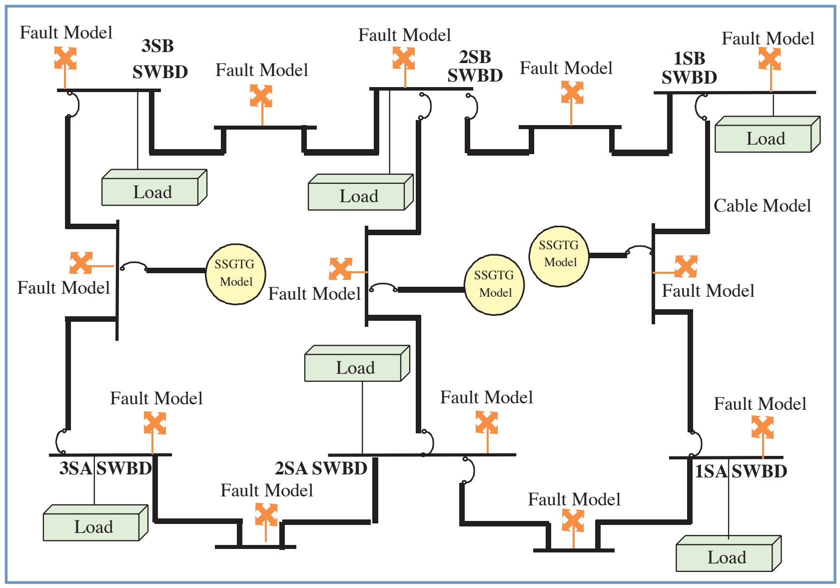

Figure 5. DDG 79 and DDG 91–Class ship electric plant ACSL models.

Figure 6. Live ordnance cable fault test.

presently in-use. Future concepts must be pursued to advance this type of intelligent technology further and implement it throughout the distribution system. This technology, in conjunction with advanced distribution technology, will enable critical equipment to remain on line in the event of combat damage.

While this program targeted a low voltage zonal electric system, the technology developed has direct application to the new architectures associated with the all-electric ship concept. These architectures must be approached in the same manner to ensure that the entire electric plant supports the critical equipment from a survivability standpoint.

Higher power/voltage systems offer unique challenges with respect to overall power continuity and power quality. The approach must include the appropriate mix of model development, simulation and validations, and live ordnance/combat damage demonstration. Simulation provides a cost-effective and flexible tool to perform extensive and detailed analyses of the electric plant. Appropriate validation of the model is important to ensure fidelity. Live ordnance demonstrations then allow the system to be analyzed with combat-type fault scenarios.

The goal of the Electric Power System Survivability Program is to minimize shipboard power interruption or power quality degradation in the event of combat damage and ultimately maintain mission capability. Higher power/voltage systems present significant challenges to reach this program goal.

Acknowledgments

The authors would like to thank NAVSEA (PMS 500), (PMS 400), (SEA 05R), and (SEA 05Z) for their sponsorship and support. In addition, we thank Bath Iron Works, Supervisor of Shipbuilding Bath, NMP, and TANO, Inc., for their collaboration on this project.

References

1. Hannon, T.L., and R. Cooley, "Computer and Laboratory Evaluation of the Multi-Function Monitor I for use in the Zonal Electric System of DDG Flt IIA," NSWC-CD Engineering Memo (Nov 1994).

2. Wipf, D.P., and E.B. Parker, "Demonstration and Assessment of High Speed Relay Algorithm," B. Barron Associates, Inc. Engineering Report (30 June 1997).

3. Sieleman, M., "DDG-51 Flt IIA Zonal Electrical Distribution System MFM-III Coordination Option," BIW Engineering Report (5 Jan 1996).

Bibliography

Hannon, Tracy, "Dynamic Multiple Fault Studies of an AC Zonal Shipboard Electric Distribution System with MFM-III" (July 1997).

Devine, Daniel P., et al, "Analysis of Shipboard Power Systems When Subjected to Severe Cable Damage," *All Electric Ship Symposium* (Sep 1998).

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Integrated Power System Development

Edward P. Harvey and Matthew A. Stauffer

The U.S. Navy has been researching integrated electric propulsion systems for many years. The present developmental program aims to adapt proven technology from the commercial marine industry, where applicable, to the warship environment. However, in some areas, commercial marine technology is inadequate to meet the more stringent military requirements of warships. A full-scale Integrated Power System Land-Based Engineering Site (LBES) was constructed to demonstrate the system architecture and feasibility of chosen technologies. Many of these technologies, such as direct-current zonal electrical distribution and high- power (20-MW) pulse-width-modulated motor drives have resulted in technological leaps forward in the areas of electric propulsion, power conversion, packaging, signatures, and control. Additionally, design issues such as electromagnetic compatibility, acoustic signatures, power quality, development of open interface standards, and validations of computer design models were evaluated. This paper discusses some of the technological advances, the requirements that led to the improvements, test site construction, system integration issues, and results of the LBES system tests conducted.

Introduction

An Integrated Power System (IPS) is an integrated electrical architecture for ships whereby power for propulsion and ship's service electricity is provided by a common set of prime movers. This will reduce the number of prime movers aboard ship, result in reduced fuel consumption, and provide a vast amount of electric power to the ship. Figure 1 is a representation of the IPS architecture. The economic advantages of an integrated electric architecture are well recognized, and such systems are used throughout many sectors of the commercial marine industry today. In addition to the economic advantages, there are military benefits when an IPS architecture is adopted, including increased reliability and survivability, reduced signatures, and greater flexibility and capability to support upgrades.

While IPS is based partially on commercial developments, some new advances were required for a military application. In those areas, technology was developed to meet the warship requirements in an affordable manner. Most of the developments (direct-current zonal electrical distribution and high-power (20-MW) pulse-width-modulated (PWM) motor drives, for example) resulted in technological leaps forward in many areas of electric propulsion, power conversion, packaging, signatures, and control.

The technology necessary to meet stringent military requirements demands an incremental build-and-test program to validate the design concepts and reduce the risk of introducing new technology aboard a naval vessel.

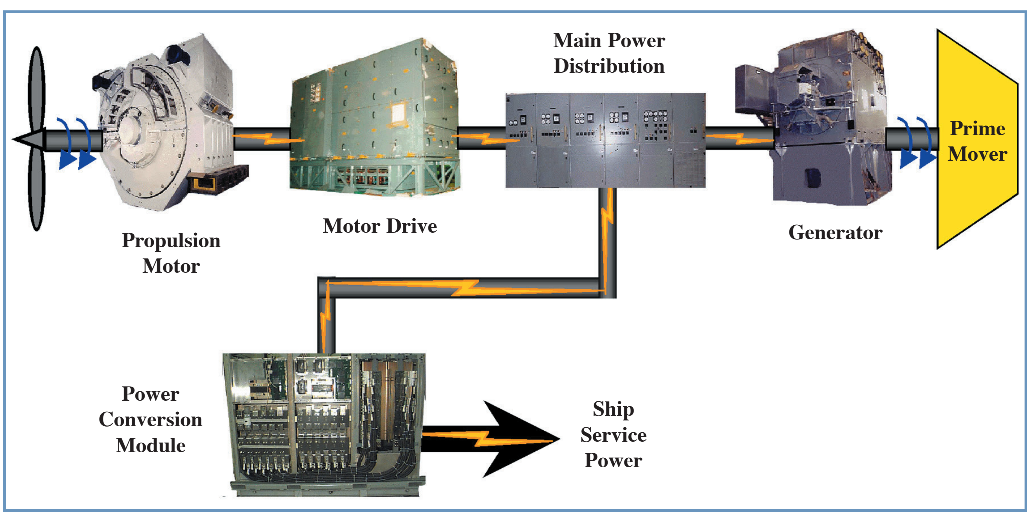

Figure 1. Integrated Power System architecture.

Typically, after shore-based tests, the U.S. Navy will conduct at-sea trials by back-fitting an existing ship with the new technology prior to full production of a new system. However, because the IPS is a new architecture, not simply a set of components, it is inextricably linked to the overall ship design. This close coupling between the power system and the ship design makes a back-fit application very unattractive from a cost and performance standpoint.

An affordable alternative is to develop a partial ship-set of full-scale hardware and conduct shore-side tests to validate performance predictions. The risks of introducing this advanced technology can be reduced to an acceptable level when it is combined with a set of comparative naval architectural studies to verify the advantages of the system.

The program was intended to prove the concept and demonstrate the feasibility of the system for a military ship application using "ship-like" hardware. While the hardware is not designed for qualification tests, shipboard standards were specified where significant development was needed to demonstrate risk reduction. Examples are shock, magnetic and acoustic signatures, electromagnetic compatibility, and power density.

Test Site Development

The Division's Advanced Propulsion and Power Generation Test Site has been under development since January 1993. While originally planned to test the Navy's Intercooled Recuperated (ICR) gas turbine engine development program, the facility has proven its versatility. It also provided a venue for performance tests of the Advanced Turbine System compressor for Westinghouse Electric Corporation before it was converted to test the IPS. Initial operation was in July 1997, when a General Electric LM 2500 gas turbine engine was brought into operation to support the Westinghouse test program. This established many of the test site support systems including the fuel, start air, cooling water, lube oil, inlet, exhaust and module cooling air systems, module fire suppression system, and control air systems, as well as the computerized facility monitoring and facility control systems.

The test site (shown in its IPS configuration in Figures 2 and 3) can support the IPS and ICR programs simultaneously. During ICR tests, the LM 2500 generator was removed and replaced by the ICR engine, a shaft torquemeter, and a high-speed waterbrake. IPS tests continued on the propulsion motor and the ship-service distribution system via a facility power feed. A main machinery pad supports the entire site, which is large enough to support the LM 2500, generator, motor, waterbrake, and electrical equipment platform.

Test Site Integration

Various system integration issues were encountered during the installation and commissioning stage of the program. This section addresses some of the major integration issues involved with the generator, motor drive, supervisory control system, and certain ship service distribution hardware.

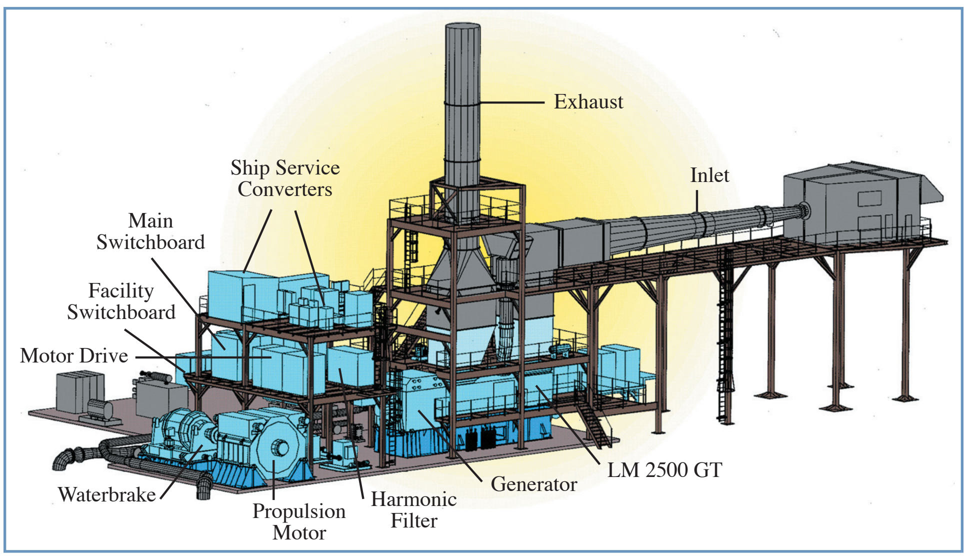

Figure 2. Advanced propulsion and power generation test site.

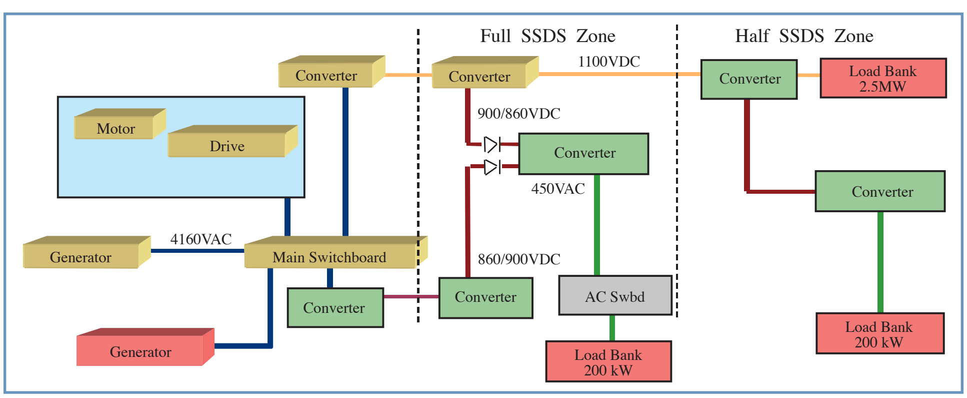

Figure 3. One-line diagram of IPS test configuration.

Generator High-Resistance Grounding

The generator is a three-phase, wye-connected, 21-MW, 4160-volt synchronous generator with a high-resistance neutral point grounding system. The original grounding system used a grounding transformer with a secondary resistor to limit the ground fault current to 10 amps for 10 seconds prior to tripping the generator circuit breaker. The protection relay measured the voltage developed across the secondary resistor to detect a ground fault. The transformer/resistor grounding system is a standard momentary-duty industrial means of ground fault protection for medium voltage applications (i.e., 5 kV).

The motor drive has three, nonisolated six-pulse rectifiers that convert the supply 4160 Vac to 5600 Vdc for the direct-current link. The silicon-controlled rectifier devices have a unique thermally conductive, electrically insulating layer between the power device and the water-cooled, grounded heat sink. Failures of the insulating layer were experienced during factory tests due to manufacturing defects in the material. However, the power source experienced no problems due to the ground faults. When the generator was used as the source, a failure of the insulating layer tied the devices to the ground via the heat sink in the drive and the grounding transformer circuit of the generator. Since transformers only transfer alternating current, the result was a catastrophic failure of the grounding transformer. Analysis revealed that the earth fault current on the grounding system was primarily direct current, which saturated the grounding transformer. No limiting or detection of the ground fault current occurred because the protection relay was not able to detect the ground fault with the earthing resistor connected via transformer to the ground circuit. This was corrected by installing a high-voltage grounding resistor directly from the neutral to ground, so isolation for any type of fault could be obtained from a protection circuit specifically designed to detect the presence of either a-c or d-c neutral voltage or current.

Motor Drive Power Regulation Instability

As the motor drive attempted to develop nearly full-rated power, its inverter current output became unstable due to insufficient d-c link voltage to provide a modulation depth within maximum operating limits. This lower than expected d-c link voltage initially was thought to stem from an error in the phase reference for commutation of the supply bridge. Also, it was thought that just rescaling the motor current limitations would correct the problem, because the d-c link voltage is only slightly reduced near rated power. However, that adjustment, and even the addition of a compensating term in the drive control software to increase the operating margin for a greater stability ceiling, proved inadequate.

Not until recently was it realized that the effect of the negative resistance characteristics of the machine bridge control actually had been countered from the resulting increase of current in the d-c link. This current increase occurs because more voltage drop or droop from the inductance and capacitance is produced in the d-c link than the supply bridge compensation control can counter. Accordingly, the modulation depth simply increases until it reaches its maximum limitation in a cyclical diminishing-returns effect near full-rated power. Thus, the inverter output current eventually becomes unstable despite the control features designed to maintain correct d-c link voltage throughout the power range.

The proposed solution to this problem involves adding a dampening control term to respond to the calculated value of d-c link current and compensating the firing angle of the rectifier as required to correct the anticipated voltage droop of the d-c link before it actually occurs. Such a control approach is achieved by estimating the d-c link current from the difference between the drive's input rectifier current and inverter output current. This provides a 90-degree phase advance relative to the original d-c link voltage feedback control scheme due to the inherent 90-degree lead of current to voltage.

LM 2500 Flameout Event

During a high power-commissioning run (90% of rated power or 24,000 hp) of the motor, an instability in the motor drive (described in the previous section) occurred causing the unit to trip off-line. A loud bang was heard immediately following the trip, and operators manually tripped the engine. After evaluating the data, the conclusion was that a flameout in the gas turbine engine had occurred.

In response to unloading, the LM 2500 fuel-metering valve was commanded to its minimum position by the engine controller to prevent an engine overspeed. After the engine speed dropped below its nominal speed of 3600 rpm, the valve opened again at a level required to maintain nominal speed at no load. However, the fuel manifold pressure fell below the acceptable level that is normally maintained when the valve is commanded to minimum. Analysis of the event indicated that the transition of the fuel-metering valve from 90% to 0% may have caused insufficient fuel flow to sustain ignition, resulting in the flameout. The bang resulted from reignition of fuel in the hot section of the engine when the valve reopened and injected large amounts of fuel into the engine. Figure 4 is a graphic representation of this event.

A safety trip circuit was installed as an interim solution to allow continued high-power tests that would perform an emergency stop of the engine if the generator or motor drive circuit breaker tripped above 50% motor power again. While the fuel valve was expected to prevent flameout, the U.S. Navy and manufacturers of the gas turbine and engine controller have determined that an overly aggressive fuel rate schedule control was implemented to support the valve design. This design aspect had just been addressed recently by the manufacturers in the first commercial ship applications of gas turbine generator sets via a more moderate fuel rate schedule. The design engineering from this cruise line

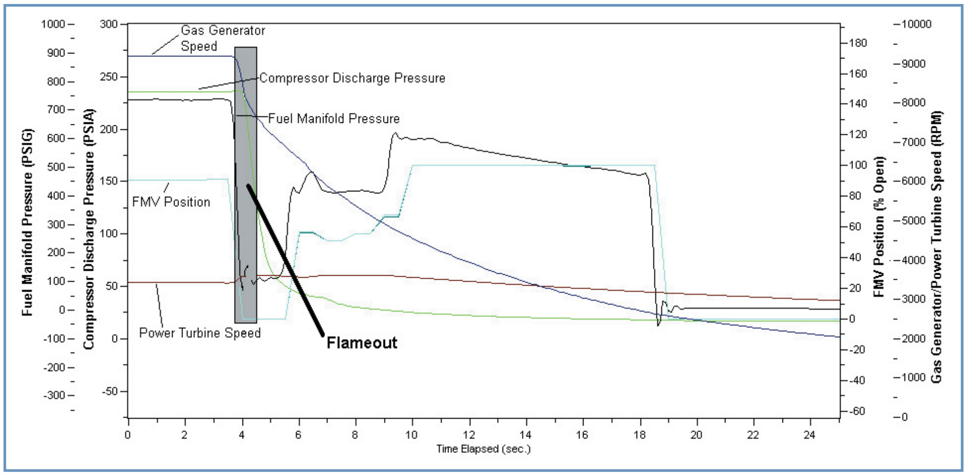

Figure 4. Record of LM 2500 flameout event.

application is being adopted into the fuel rate control schedule of the generator set.

Harmonic Filter Inductor Overheating

The inductor for the harmonic filter exhibited fuming during tests because its insulation was not fully cured by baking. While this was disconcerting, the real concern for the inductor was the overheating experienced at higher power levels of the motor. The inductor reached an overtemperature condition within about 30 minutes whenever the power levels were well above 50% of rated power of the motor. Overheating occurred despite the current loading and harmonic current content from the motor being well within the design specification limits of the harmonic filter. The inductor was removed from the harmonic filter and sent to the manufacturer for analysis, because such a limitation makes it awkward to operate the motor at higher power conditions and prevents heat runs.

After analysis by the manufacturer, the inductor core was rebuilt to decrease the heating losses. The new inductor design maintains the same effective air gap length, but the number of individual air gap sections was increased to reduce the fringing losses. In addition, the coil shields were shortened to reduce the fringing effect (magnetic flux leakage around edge of shield) and associated heating.

Modified Converter Operation

During system integration, the d-c link voltage control scheme was changed just prior to testing. The final d-c link voltage was shaped to reduce voltage to 70% at speeds up to 70%; then, the voltage was increased linearly to 93% at full speed. The reduced d-c link voltage was required to minimize the partial electrical discharge or corona occurring in the end turn region of the motor. Such discharge causes insulation breakdown and could eventually result in a stator-winding fault. The 70% d-c link voltage level was chosen because significant ozone generation, which is a byproduct of corona, was noticed at about 80% of d-c link voltage. The 93% d-c link voltage level corresponds to the minimal current level that had to be provided to develop full-rated power at the motor.

Ambient Signature Level Interferences

Acoustic tests were impaired by various interferences. Often the DDG 51 LBES, adjacent to the IPS site, was operating during testing so all acoustic measurements had to be scheduled when that particular site was not operational. Ironically, the IPS system itself was primarily its worst interference to acoustic testing. Airborne background noise from the generator windage made it virtually impossible to determine the motor airborne noise levels. Also, there were significant structureborne background noise sources that made analysis of the motor data difficult. The foremost of these was from the cooling fans for the motor and the waterbrake, but the other motor support auxiliaries such as jacking oil were significant contributors as well.

During electromagnetic tests, the radiated electric field testing was not conducted due to the high ambient background fields present at the site. This is a particularly difficult issue to address with large systems that cannot economically be placed in a test chamber for isolated tests. The positive side to this is that the IPS equipment did not seem to add significantly to the background electric fields measured.

The test site was a difficult environment in which to conduct magnetic measurements due to the considerably higher steady state and dynamic background d-c magnetic fields than normally experienced for magnetic field testing. However, the constant ambient magnetic field could be nullified, and obvious dynamic interference (cranes, trucks, and other large metal vehicles or objects) was limited sufficiently to acquire rough order magnitudes.

Test Results

Steady-State Performance

The intent of the steady-state system tests was to determine the efficiency of the components in the system and to characterize the power quality of the main (4160 Vac at 60 Hz) and ship service (450 Vac at 60 Hz) power systems in terms of harmonic content and steady-state voltage and frequency performance over the entire operating range. This was conducted with and without the harmonic filter; however, the propulsion power without the harmonic filter was not particularly useful because it was limited to less than 15% of rated power. The motor was operated on fifteen, ten

Table 1. Main power system interface goals.

Criteria	Nominal Value	Steady-State Performance	Transient Performance
Frequency Level	60 Hz	+/- 5%	+/- 10%
Frequency Response	NA	NA	1.5 seconds
Frequency Droop	3.3% at rated power	+/- 1%	NA
Voltage Level	4160 Volts	+/- 10%	+20% / -15%
Voltage Response	NA	NA	5 seconds
Voltage Droop	3% at rated power	+/- 5%	NA
Current Harmonics (PGM-1 specified limit)	NA	291 Amps at 5^{th} (8% at rated power)	NA
Voltage Harmonics (PCM-4 design limit)	NA	13%	NA

and five phases, and no appreciable impact on power quality was noted in the operation with five and ten phases. The motor was limited to 90% of rated power because the commissioning was not completed to full-rated power before system tests began; Phase III will complete testing to full-rated conditions.

The harmonic power quality requirements for the main power system are driven by the need to protect the generator. The power quality interface goals are listed in Table 1. These goals were derived from commercial standards. The test results for the main power system were well within the steady-state interface design goals established for voltage (0.8%) and frequency (0.06%) of the 4160 Vac power source. The resulting frequency droop for the generator from no-load to near full-load conditions essentially matched the constant droop slope predicted for the design setting of 3%. However, the voltage droop characteristic setting of 3.3% did not result in the expected constant droop, due to the power factor correction effect of the harmonic filter. Figure 5 is a graphic representation of measured voltage and frequency characteristics.

The current waveform of the motor is a classic square wave shape typical of six-pulse rectifiers. However, the voltage waveform of the main power system has more pronounced peaks and notches than anticipated. The comparison of voltage waveforms from the generator and ship's service converter (Figure 6) dramatically illustrates the ability of the power conversion modules to improve the power quality delivered to the user loads.

The harmonic power quality requirements for the ship service power system are given in MIL-STD-1399 as less than 3% individual harmonic distortion in voltage (IHD_V) and 5% total harmonic distortion (THD_V), but the IPS goal is 2% THD_V. The harmonic content of the 450-volt port bus was 0.83% at 50% of rated propulsion power (Figure 6). However, it should be noted that this bus consisted of functionally equivalent ship's service conversion modules that were never designed for the highly distorted input waveform. The full-scale ship's service conversion that will be used in the next phase of tests is designed specifically to withstand such input waveforms.

Dynamic Performance

The purpose of the dynamic system tests was to characterize the power quality at the main (4160 Vac at 60 Hz) and ship service (450 Vac at 60 Hz) power system levels in terms of voltage and frequency response to major propulsion load changes. The load-step testing rate was constrained by the motor drive loading ramp rate of 2% of rating per second due to the limited commissioning work satisfactorily accomplished before system tests had to begin. The unload-step-testing rate was conducted by opening the circuit breaker to the motor drive. Both ramped-load and drop-load tests were performed with all 15 phases of the motor and with and without the harmonic filter on line. Ramp-load tests were conducted at propulsion power levels from zero to 90% of rating in 10% steps, and step unload tests were completed from 25% and 50% of rating to zero.

The test results from the 50% drop-load event were well within the interface design goals. The transient voltage response for this event was a + 5% excursion with 0.6 second required to resume steady-state performance levels. The frequency response was + 0.5% with 1 second required to resume steady-state conditions. While the ship service port

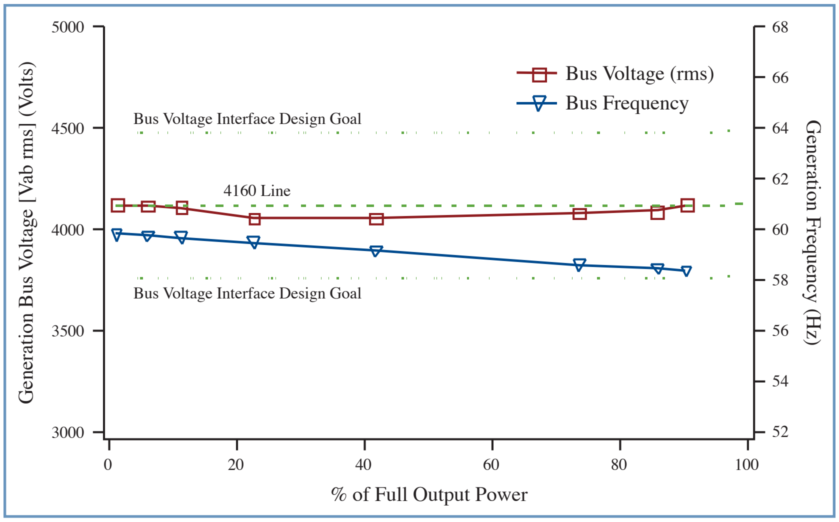

Figure 5. Voltage and frequency regulation.

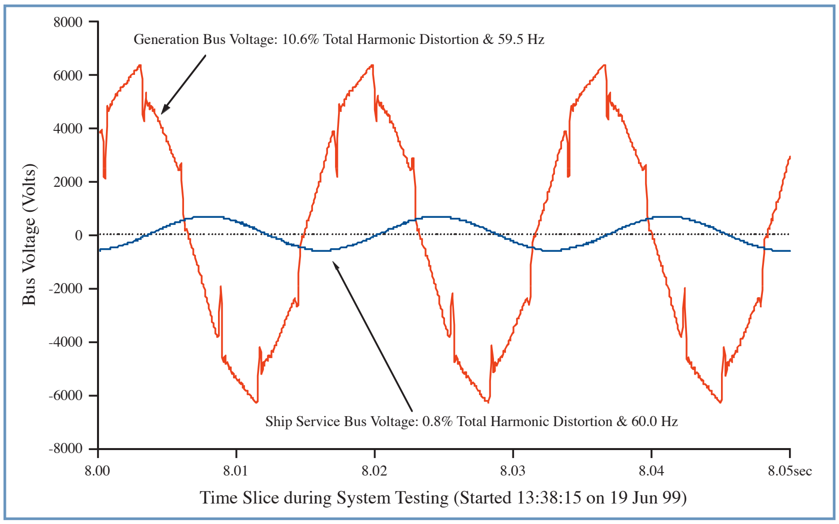

Figure 6. Comparison of medium voltage bus and ship service bus waveforms.

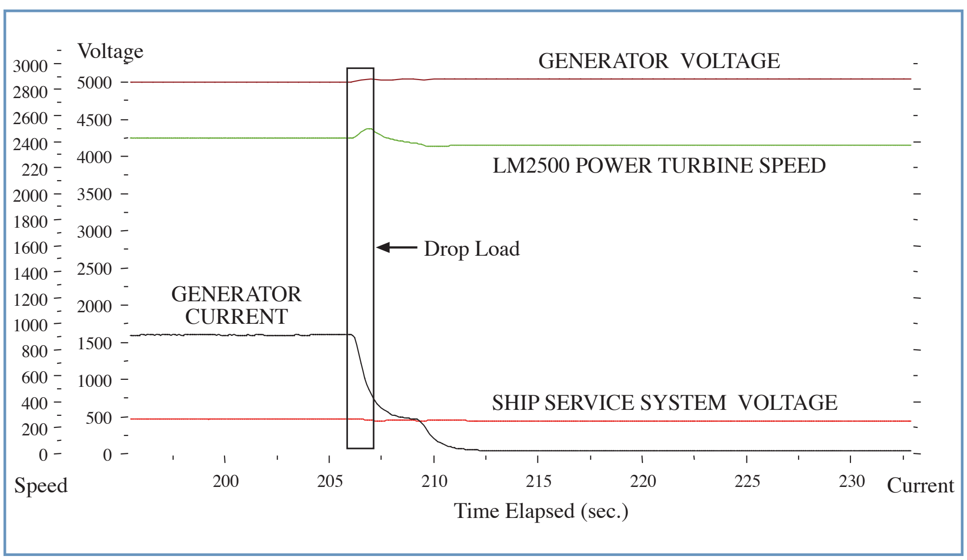

Figure 7. 50% drop-load event.

bus was not functional for the 50% drop-load event, the system performance at the 25% drop-load event dramatically illustrates the system's potential to improve the power quality delivered from the main power system (Figure 7).

The ramped-load tests were not stressful for the generator, and no significant voltage or frequency excursions occurred for the 2% of rating per second load ramping rate of the motor. A 10% of rating per second has been the established goal for the converter ramp rate when available (1% is typical of commercial steam-driven ships).

Acoustic Tests

The primary objective of acoustic tests was to obtain structureborne noise (vibration) data on the motor and the generator. Airborne noise also was measured for both units. The structureborne acoustic requirements and measurements were developed in the standard MIL SPEC format of one-third octaves. The airborne noise requirements and measurements were in standard MIL SPEC format of whole octaves. Airborne background noise from the generator made it virtually impossible to determine the motor airborne noise levels. There also were significant structureborne background noise sources that made analysis of the motor data difficult. The foremost of these was from the cooling fans for the motor and the water brake, but the other motor support auxiliaries were significant contributors as well. However, the acoustic performance of all motor auxiliaries could be improved greatly in a naval application because all tests were conducted on standard commercial design units that were not optimized for noise quieting.

The structureborne noise requirements were met for the motor, except for the highest band spectrum. The airborne noise requirements for the generator were met, except for the lowest band spectrum.No detailed analysis of the generator's airborne noise has been developed yet because the initial acoustic analysis of the LBES did not address it. As expected, the high frequency structureborne noise in the motor is dominated by the 2 kHz PWM switching frequency of the motor drive.

Power Management

Power management tests were conducted to demonstrate that the supervisory power control system would adequately control the allocation of load under various power availability and loading changes. The system is designed to manage the load demand based on set priorities and the amount of power available. When the power allocated was changed to be less than the demand, it responded properly according to the loading priorities by lowering the power demand on the propulsion motor. It should be noted that the system reserves or allocates power for loads based on priority whether or not they are on line. However, the system does not reinstate load demand automatically, so the loads with the next highest priority will not be provided power when additional source power becomes available until a manual command is initiated to place that particular load on line. This prevents dated commands from being acted on just because power becomes available. Thus, when the system was allocated more power during this test, it only permitted the next priority loads to be activated when commanded. Also, the load shedding feature was demonstrated successfully on both propulsion and ship service loads.

Summary

Phase I tests were highly successful. An integrated system designed to meet military requirements was assembled and tested, demonstrating the feasibility of integrated power systems for military applications. There are numerous lessons learned and improvements to be implemented for an actual shipboard system, but the concept has been proven conclusively.

The issues raised in this paper will be corrected during the next phase of tests, and the motor will be commissioned to full power (25,000 hp). Fault tests of the ship service system, additional power management, and additional dynamic and steady-state tests remain to be completed. Newer technology components will be incorporated into the test site as they become available.

The Integrated Power System has been accepted as a concept for application to a Navy surface combatant. The Secretary of the Navy has announced that the Navy's next surface combatant will use IPS architecture for its propulsion and electrical distribution system. The successful risk reduction tests performed at the test site contributed to this decision and have proved invaluable in advancing the IPS concept.

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Power Electronic Building Blocks: Electrical Power Converter Control Partitioning

Joseph R. Sullivan, Todd L. Lewis, and Joseph P. Borraccini

This paper describes the Navy's efforts to develop a general-purpose power controller that can perform numerous electrical power conversion functions simply through software reconfiguration. A particular soft switched-power conversion topology, the Auxiliary Resonant Commutated Pole (ARCP), was developed to demonstrate a Power Electronic Building Block (PEBB) for control partitioning, and to test emerging semiconductor devices, namely the p-type and n-type MOS-Controlled Thyristors (MCT) from Silicon Power Corporation. Original hardware demonstrations of the PEBB ARCP converter concept relied on complex feedback control implementations that would make it difficult for the technology to compete with traditional hard-switched converter techniques employed in commercial industry. The control partitioning effort is exploring a means to develop standard hardware interfaces between converter functional blocks that would allow application-specific digital controllers to seamlessly connect to circuit topology-specific (i.e., hardware-specific) power electronics. This would produce a flexible and expandable line of electrical power conversion equipment to meet the present and future needs of the Navy's ship service electrical distribution system.

Introduction

The Power Electronic Building Block (PEBB) Program, sponsored by the Office of Naval Research (ONR 334, Ship Hull, Mechanical, and Electrical Systems Science and Technology Division), investigated technologies that could lead to improvements in the cost, size, and weight of electrical power conversion equipment, which is considered an important enabler of more electric ship designs. The Navy is investigating the application of more electric energy conversion in lieu of hydraulic, pneumatic, and other methods implemented on today's ships. Potential benefits include architectural flexibility, reduced maintenance, and reduced hazardous materials handling requirements compared to other power conversion means. Electrical energy conversion is considered the best method to take the large amount of power produced onboard for ship's propulsion and make it available for future high-energy weapons and aircraft launch and recovery systems. ONR's initial look at the trends in electrical power conversion equipment revealed that it was difficult for electrical alternatives to compete with the present traditional energy conversion implementations on a cost basis. To solve this problem, ONR initiated a multi-tiered technology investment in the following areas.

- New power semiconductor materials (silicon carbide) and device technology (the MOS-Controlled Thyristor (MCT) and Fast Turn-Off Thyristor (FTO)) to increase power density in the materials used.[1]
- Advanced power semiconductor packaging (hermetic, solderable die, the ThinPak™, with copper straps replacing aluminum wire bonds) to reduce thermal cycling stresses and parasitic circuit inductance.[1]
- Advanced power module cooling techniques (foam copper sponge, AlSiC base plates and pin fin turbulator).[2]
- Advanced converter topologies (the auxiliary resonant commutated pole (ARCP) soft switching converter) for higher efficiency.[3,4]
- Common power circuit back-planes (Power Node Control Center) for modular, expandable power conversion implementations covering a wide assortment of applications.[5]
- Power circuit control partitioning to minimize the cost to add more complex control associated with soft switching converters.[6]

NSWCCD teamed with industry and academic partners as an active participant in many of the technology thrusts. Several products from the technology investments were combined in hardware demonstrations.

™ThinPak is a trademark of Silicon Power Corp.

An NSWCCD-built ARCP converter employing PEBB 1.0 power modules (MCTs and ThinPak technology) was demonstrated as a multi-functional power converter concept demonstrator. It was part of an operating display setup and was demonstrated at several conferences in the U.S. and abroad, including Las Vegas, NV; Baltimore, MD; Chicago, IL; Santa Clara, CA; and Sydney, Australia.

A second NSWCCD-built ARCP employing PEBB 1.5 and subsequently PEBB 2.0 modules (MCTs, ThinPaks, and pin-fin cooling) was demonstrated at its goal of 250 kW output, operating as a 900 Vdc to 450 Vac inverter.[4] Figure 1 shows one of three phase legs that comprise the inverter. This design became the basis for a third unit that was built to demonstrate its applicability as a PCM2 ship service inverter module, which is one of the power modules comprising the Integrated Power Systems (IPS).

Control Partitioning

A monolithic control architecture can be cumbersome to modify or difficult to add new power conversion applications. NSWCCD is investigating a re-partition of the control into two parts, an application specific/hardware generic part and hardware specific/application generic part. This would allow control algorithms developed for one application to be compatible with any hardware-specific implementation meeting the application's needs.

Control partitioning has the potential to be an especially important design philosophy with significant implications for the Navy and the commercial market. During development, control partitioning would make new devices less prone to failure due to a single mistake made in the development of control code.

Control partitioning enables circuit topologies to be developed with greater value to the Navy at a lower cost by permitting the use of control algorithms developed for commercial applications, such as those used in standard hard-switched converters, in the ARCP soft-switched converter. In this instance, an ARCP circuit topology could be used without developing an entirely new line of application controls made specifically for an ARCP.

Power converter control partitioning was investigated as a result of the desire for an open plug-and-play architecture applicable to power electronics.[7,8] NSWCCD technologists learned first-hand during their development of the ARCP soft switching converter that, while meeting its power goals, the implementation was complex compared to traditional hard-switched conversion methods. Celanovic, et al,[6] provided a possible solution to the problem by describing a partitioning method that falls across the boundaries of the technical expertise of the two groups involved with the power converter - the control engineers, who focus on the application of the converter (e.g., motor drive, voltage source inverter, rectifier, etc.), and the power electronic engineers, who are responsible for its safe operation (e.g., power switch stresses, maximum/minimum pulse-width modulated (PWM) duty cycles, main/auxiliary switching event timing, etc.).

The application program code developed on an existing circuit topology can be shared with a completely new circuit topology by providing a control boundary between these two areas. The equipment will carry out the application as best it can within its safe operating area as long as the power electronic engineer incorporated the proper safe operating limits into the hardware. In the fully configured control partition, two separate processors are employed, one to run the Application Control Code and one to run the Hardware Control Code. The two processors are connected by a high-speed serial communications link. Figure 2 depicts the control partitions, and indicates the approximate speeds at which each functional block must operate. A plug-n-play design approach is attainable by establishing standard communication protocols between each functional block.

A complete hardware partition consistent with the control partition just described has many benefits in the design and maintenance of a controller, but may not be cost-effective in all designs. It is foreseeable that if hardware partitioning does not occur between each boundary, control partitioning can still occur through software partitioning

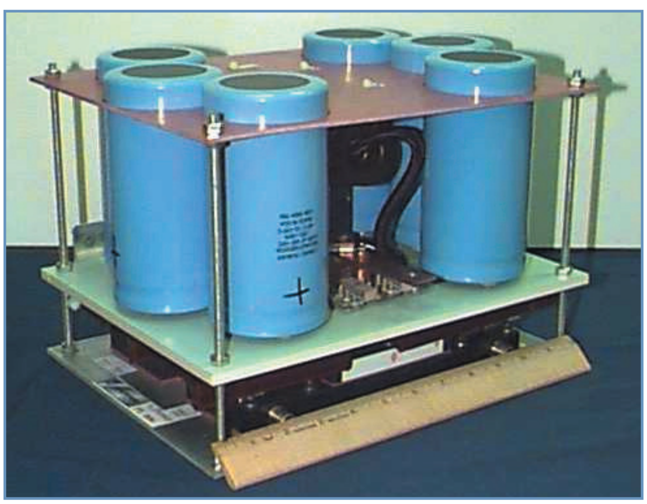

Figure 1. ARCP phase leg.

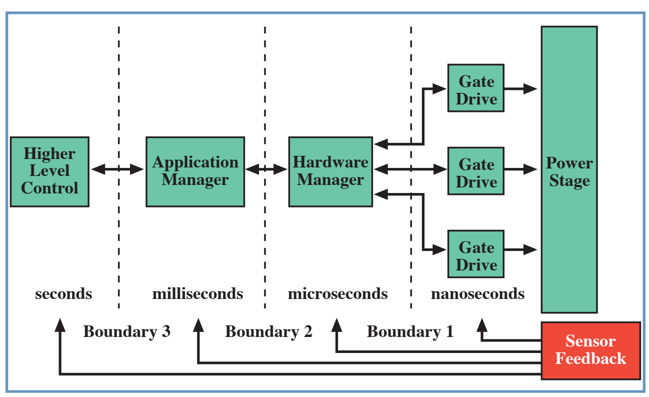

Figure 2. Converter control partitioning.

(e.g., subroutines running in a single processor) or replacing the high-speed serial link with a parallel bus if a large physical separation is not required. These approaches allow the functional hardware blocks in Figure 2 to be combined to reduce cost, and still allow the existing partitioned software modules to be re-used.

ARCP Power Converter Topology

The ARCP (Figure 3), is the PEBB circuit topology selected by NSWCCD. It offers many challenges in implementing a partitioned control design, most importantly, the critical timing of switching events between the main (S1 and S2) and auxiliary switches (A1 and A2). The ARCP has a host of time-critical calculations and events that must be followed to ensure proper operation compared to a traditional hard-switched power converter, where the hardware-specific control issues boil down to dead time settings to prevent a direct-current bus short (eliminate upper and lower switch overlap times) and minimum and maximum PWM duty cycle settings to minimize device stresses. ARCP operation is described in detail elsewhere.[3,4]

First-Generation ARCP Control

Initially, NSWCCD implemented an ARCP controller using the configuration shown in Figure 4. The digital signal processor (DSP) and field-programmable gate array (FPGA) operated from a 10-MHz clock. The FPGA had very few gates, so it was serving as a support chip for the DSP. The initial ARCP control algorithm, although it had time-critical switching events, relied on a simple set of sensing and boost calculations that were compatible with the control hardware employed. The software implementation partitioned the hardware-specific control code from the application code through the use of subroutines running on the DSP. Test results showed that the ARCP could be operated, but with limited performance due to the simplified implementation. The energy supplied by the ARCP auxiliary switches was set at worst-case level for all switch transitions by the algorithm. This added more resonant energy than was needed for the ARCP to operate over most switching events, resulting in lower available output power.

A more efficient control algorithm was developed to take advantage of the load current to assist in the ARCP switch transitions. This method required the feedback of instant load current information into the hardware manager control code to adjust the amount of energy supplied by the auxiliary switches at each switch transition.

This upgrade was implemented using a software partition between application manager and hardware manager control routines. The DSP time-slices for load current samples and boost current calculations were delayed in time from their points of application because critical switch timing events needed to occur, in some cases within 100 nanoseconds of each other. As a result of these data latencies, a level of uncertainty arose over the level of boost current needed for a safe switch transition. Longer-than-calculated auxiliary switch boost times were generated by the control code to compensate for the uncertainty and ensure proper circuit operation. This algorithm was an improvement over the simplified algorithm; however, it still limited maximum output power.

The near-term solution to the problem was to abandon the software partition and intertwine the hardware management code with the application control code, eliminating time delays caused by subroutine calls and interrupted service routines. This allowed the Analog/digital (A/D) sampled data and boost current calculations to occur clos-

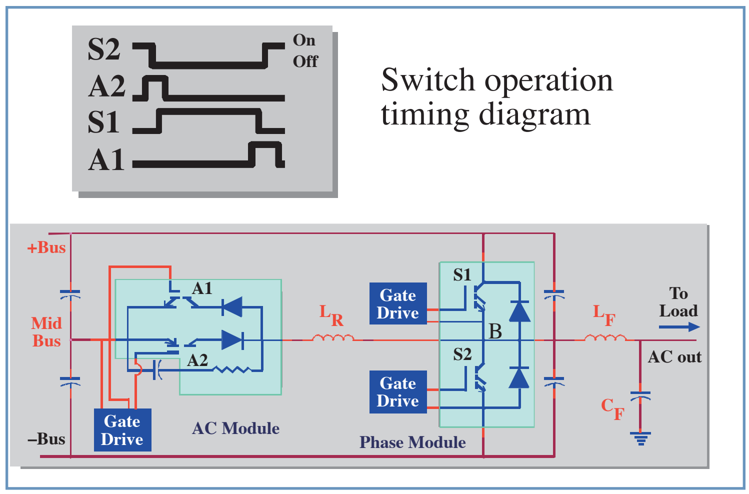

Figure 3. ARCP circuit topology.

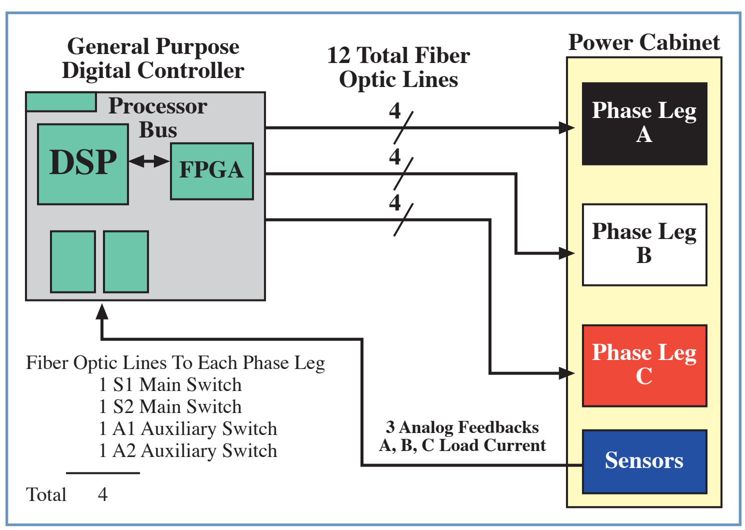

Figure 4. First-generation ARCP control.

er to the actual switching events, making the boost calculations "less uncertain" than in the earlier case. This allowed the programmer to remove some of the boost time compensation, making the converter operate more efficiently and ultimately allowed us to reach our 250 kW power goal. Unfortunately, the intertwined control code became very difficult to debug and unforgiving of coding mistakes, which resulted in numerous hardware failures during code development. Additionally, the coding method employed made it extremely difficult to modify the application control code to change the unit's operation from a direct- to alternating-current voltage source inverter to a motor drive or other converter application.

Second-Generation ARCP Control

In the NSWCCD follow-on effort, a second-generation controller was implemented using more of the control partitioning concepts discussed by Celanovic, et al.[6] The second-generation controller used a faster processor and a larger and faster FPGA, operating from a 60-MHz clock. In this design, the application control code was partitioned into the DSP, and the ARCP hardware control code was partitioned into the FPGA (Figure 5). While the DSP and FPGA reside on the same board, a virtual line can be drawn between them to denote the separation of the Application Manager and the Hardware Manager. This was done in lieu of the high-speed serial communications link described by Celanovic.

NSWCCD successfully demonstrated 106 kW of output power at a single-phase line-to-line voltage of 430 Vac using a single-phase version of the ARCP and the second-generation controller The input direct-current bus was at 825 Vdc and the converter was switching at 10 kHz, which was double the frequency attained with the first-generation controller.

Summary/Future Plans

NSWCCD successfully partitioned the controls for an ARCP power converter in a single-phase operation. Future plans are to apply control partitioning to a three-phase ARCP. Figure 6 shows an implementation that employs a high-speed serial communications link to separate the Application Controller from the Hardware Manager, more closely following the control partition concepts described by Celanovic. It should be noted that NSWCCD is employing two second-generation controllers to provide enough flexi-

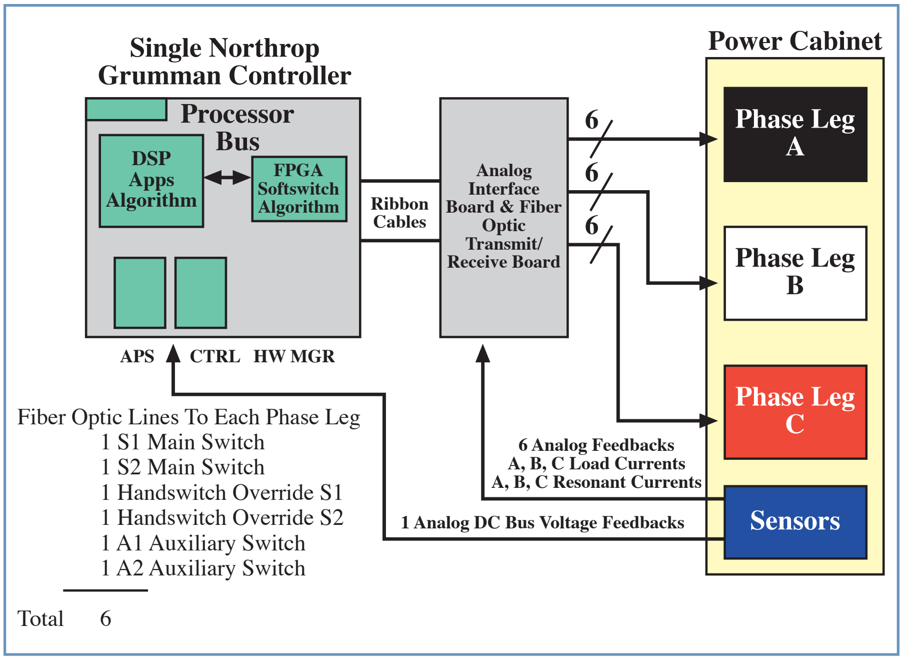

Figure 5. Second-Generation ARCP control.

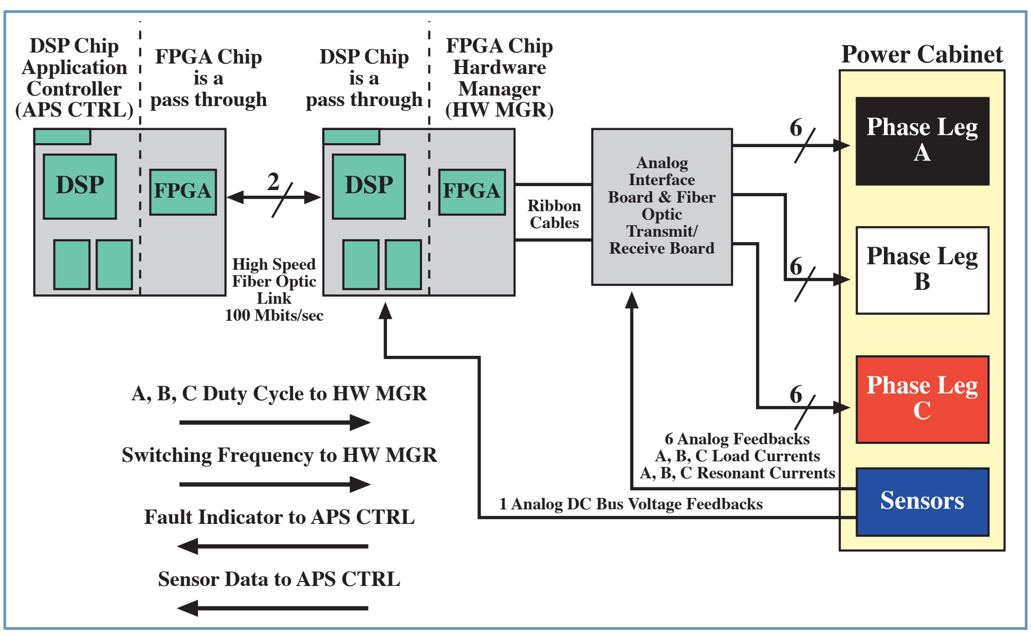

Figure 6. Next Generation ARCP control.

bility and design margin to work out control partition details. It is envisioned that an optimized Application Manager and Hardware Manager would replace the two controllers.

Acknowledgments

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References

1. Temple, V., "ThinPak™ Technology Shrinks Power Modules, Power Hybrids and Ultra-High Speed Switching Devices," *PCIM Magazine*, pp. 32-38 (May 2000).

2. Cannell, M., and G. Green, "Thermal Testing and Modeling of a Pin-Fin Turbulator Heat Exchanger to Liquid Cool a PEBB, IGBT Phase Switch," Maritime Applied Physics Corp. *Technical Report under NSWCCD Contract No. N00167-99-D-001* (Apr 2000).

3. DeDoncker, R.W., and J.P. Lyons, "The Auxiliary Resonant Commutated Pole Converter," IEEE-IAS *Conference Proceedings* (1990).

4. Borraccini, J., et al, "Power Electronic Building Block Design and Hardware Demonstrator - Results From December 1996 Through May 1998," *PCIM Power Systems World Conference Proceedings,* Santa Clara, CA (1998).

5. Ykema, J., et al, "Power Node Control Centers (PNCC) Concept Feasibility Demonstration Report" (23 Mar 1999).

6. Celanovic, I., "A New Distributed Digital Controller for the Next Generation of Power Electronics Building Blocks," *APEC Applied Power Electronics Conference, Dallas,* TX (14 March 1999).

7. Ericsen, T., "The Big PEBB Picture," PCIM Magazine, p. 61 (Jan 2000).

8. Ericsen, T., "Open Plug and Play Power Architecture Simplifies System Integration," *PCIM Magazine*, pp, 70-71 (Feb 2000).

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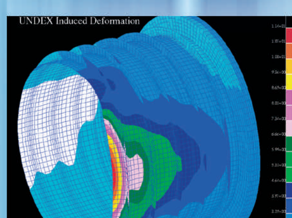
Materials

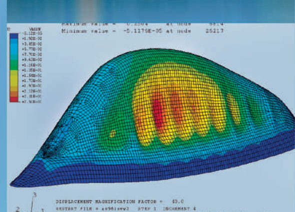
Structures and Materials

Overview Article Follows

TECHNICAL DIGEST

Structures





STRUCTURES & MATERIALS

Structures and Materials is a combination of specialized expertise and unique facilities for the full spectrum of research, development, testing, evaluation, design, acquisition support, operations and maintenance, and in-service engineering for naval vehicles – surface ships, submarines, advanced craft, other vehicles, and their component systems (including weapons). Structures and Materials includes the development of technology, concepts and procedures which enable the manufacture and safe operation of Navy ships and their component systems. These products to a large degree determine the efficiency of operation and affordability of the platform, its signatures, and its survivability.

Structures and Materials: An Overview

Jeffrey E. Beach and Joseph L. Cavallaro

This paper identifies and discusses the requirements and scope of structures and materials technologies being pursued by the Carderock Division. This work ensures that ships, submarines, advanced craft, and other naval vehicles can be designed, constructed, operated, and maintained using the most suitable and cost-effective materials in optimized structural configurations. Principal structural efforts focus on innovative structural concepts, structural integrity, analysis methods, design procedures, and validation techniques for advanced ship and submarine hulls and topside ship structures. Principal materials and materials processing technologies being pursued include the development and characterization of metallic and nonmetallic structural materials, propulsion and auxiliary machinery materials, and functional materials.

Introduction

The U.S. Navy historically has been in the forefront of introducing innovative ship concepts to meet ever-changing mission requirements. The Division has been at the leading edge of technological advances in structures and materials technologies, which have enabled the new ship concepts to become a reality. Navy ships must be designed to provide a robust stable platform for the operation of its combat systems, sustain the rigors of combat, maintain the ability to fight hurt, and interact with support ships while forward deployed. Ships must have relatively lightweight hulls made of tough materials that have an adequate tolerance for flaws and can resist the dynamic loading effects of combat air explosions (AIREX) and underwater explosions (UNDEX).

Structures make up the largest weight group of the ship, typically contributing 35% to 45% of the overall vehicle weight. Thus, ship structures have a major effect on the overall vehicle characteristics such as displacement, payload, signatures, combat system effectiveness, survivability, safety, producibility, readiness, maintainability, reconfigurability, and acquisition and life-cycle cost. Future ship design requirements will include platform flexibility and rapid reconfigurability, which ultimately lead to increased force affordability. A new ship must be able to perform multimissions in a multitheater environment. Flexibility in design, construction, and configuration/reconfiguration is essential if mission capability at an affordable cost is to be achieved. Innovative ideas in structures and materials will be required from the Navy, the shipbuilder, industry, and academia to achieve this goal.

The ship structure is the skeleton and the skin of the vehicle, which is made up of various materials and configured in a manner to optimally meet the vessel's requirements. Those requirements include predictable and reliable responses to seaway loads, other environmental conditions, and combat forces. Traditionally the most important metrics for a marine structure have been it's structural integrity, weight, and cost. While these are still principal parameters, today multifunctional requirements dictate the final design of naval platforms. Multifunctionality of the structure must contribute to signature control, combat system performance, ship monitoring, etc, and must meet all the basic structural requirements. Structural design requirements for future naval combatants are becoming very demanding because of these new multifunctional requirements.

When effectively integrated with structures, survivability, machinery, hydrodynamics, and signature control technologies, materials technology can enable timely identification and insertion of advanced concepts that are essential to meet ship systems goals. Materials and materials processing is pervasive throughout all ship systems and is an enabling foundation technology, which permits performance and/or affordability goals to be met. Materials developments support common requirements for ships and submarines and the unique requirements of each platform.

Surface Ship Structures and Materials

The structure of a surface ship is a geometrically complex shape that provides the platform to integrate all ship systems. The fundamental requirement of the ship structure is to ensure integrity of the ship under normal and severe operating conditions. Thus, structural technologies are needed to ensure safe and reliable performance of current and future ship structures. The scope of RDT&E activities at the Division includes analytical, numerical, and experimental support to develop structural design guidance and analysis methods; conduct large- and small-scale fatigue/fracture and instability tests and analyses; analyze seaway loadings and conduct sea trials to verify prediction methods and validate actual performance; develop new ship concepts and evaluate them with respect to structural integrity, affordability, reliability, survivability, and increased combat effectiveness; develop reliability/risk assessment methods; and conduct Fleet inspections.

It is expected that future demands will increase the emphasis on new materials and structural configurations for hull systems such as the use of non-magnetic stainless steel for *Advanced Double Hull* designs (see paper by *Sikora and Beach* in this section) as well as the use of composites, particularly in topside structure. The development of future surface ship structures will be driven by increased demand for integrated systems engineering solutions, including affordable ship structure/materials systems. One of the more obvious examples is in signature control. Structural configuration, material properties, and geometric effects of structural details directly influence acoustic as well as non-acoustic signatures.

Historically, steel has been the primary structural material used for ships and submarines. There has been a steady decline of R&D on naval steels in the private sector. Therefore, the Navy established a world-class R&D team in-house at the Carderock Division and the Naval Research Laboratory to address cutting-edge naval steel metallurgy. Over the last decade, the Division focused on the development of high-strength low-alloy steel (HSLA-65, -80, and -100) for ship construction in the thickness range of 5/16-in. to 1 5/8 in. HSLA-80 and HSLA-100 steels provided major increases in shipbuilding productivity and cost reduction in the CG 47, DDG 51, CVN 68, and SSN 774-Class ships and resulted in cost savings in excess of $130M to date. About 40,000 tons of HSLA-80 steel and 30,000 tons of HSLA-100 will be used in naval ship construction through the year 2001 (Figure 1). HSLA-65 and HSLA-100 steels are being considered for immediate application as the primary structure in the DD (X), CVN 77, and CVNX 1 for weight reduction and fabrication cost savings. More recently, Division metallurgists have collaborated with researchers from Japan in a cooperative program to develop structurally acceptable methods to use "under-matched" strength weldments for use with high-strength steel alloys (yield strength greater than 150 ksi). This technology has the potential to significantly reduce the costs of high-strength steel in ship construction.

In addition to high-strength steels, possible future structural materials include non-magnetic austenitic stainless steel (AL6XN, Nitronic 50), greater use of composites, amorphous metals, and lightweight, high-stiffness metallic materials/panels (lattice block materials (LBM), foam metals, LASCOR panels, etc). Figure 2 shows a developmental as-cast stainless steel watertight (WT) door panel stiffened by LBM technology. The Division anticipates that LBM technology will solve the problem of distortion in WT doors, which has plagued the surface Fleet for many years. Distortion-free metal fabrication technology for ship structure also is being explored to satisfy projected future signature control requirements (resulting in the elimination of the "hungry-horse" effect in ship structure) and includes laser cutting and welding and friction-stir welding. The Advanced Double Hull concept and technologies related to welding automation and robotics will reduce the number of structural pieces needed in combatant design and facilitate the installation of distributive systems without jeopardizing structural integrity.

One of the biggest challenges of the future is the development of simulations and computational models that satisfy designer confidence to permit accelerated insertion of new structural materials in ship design with a minimum of expensive and time-consuming physical testing.

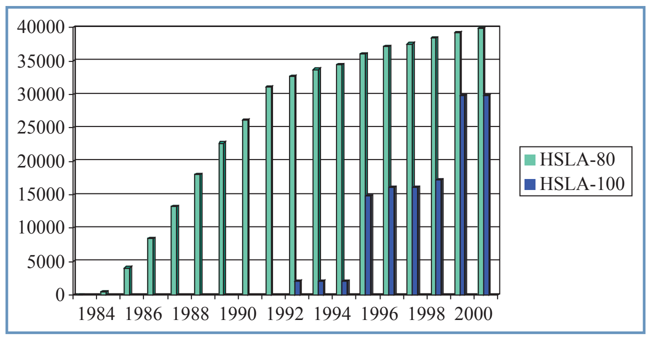


Figure 1. HSLA-80 and HSLA-100 steel plate for naval ship construction through 2001 (cumulative tons).

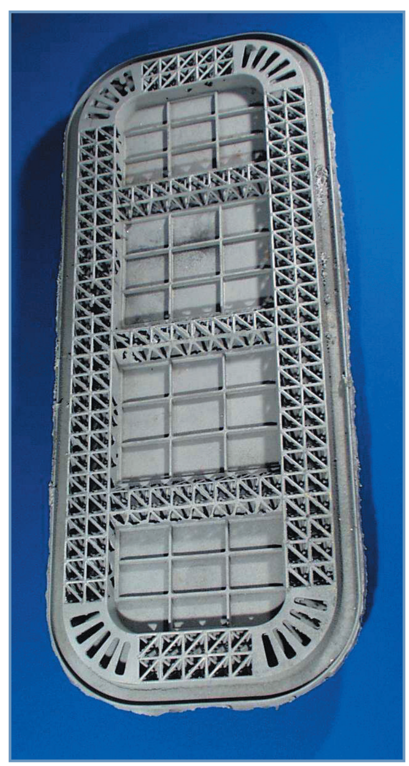


Figure 2. Experimental 316 stainless-steel watertight door panel stiffened with lattice block material.

Submarine Structures and Materials

Structural analysis methods and the development of new materials and fabrication methodologies used to design and construct submarines have a significant impact on submarine performance, affordability, and overall mission effectiveness. Throughout the design process, a balance is sought between weight, strength, interior space, and overall size. Since the 1930's, the Division has been involved in the development of complex analysis tools, design procedures, scaled structural model tests, and sea trials. The Division has developed structural failure-mode prediction methods and design procedures for all structural failure-modes for the traditional internally-stiffened right circular cylinder submarine design. This information has been incorporated into design data sheets, which have been used in the design of each new submarine class. Future submarine classes and other undersea vehicles continue to pose unique structural and materials challenges.

The Navy is looking at broad new focus areas for future submarines (information technology connectivity, increased and varied payload, modularity, all electric systems, and affordability) that will create significant design departures from presently accepted design practices and enable a multimission platform capability. Modular design and construction is one of the critical keys to the future and is the most cost-effective and operationally supportable means to provide timely advanced technology insertion into the submarine Fleet. Therefore, modular design will facilitate planned technology insertion over the life of the class and provide for rapid reconfiguration of the platform to support changing tactical mission requirements. Future naval capabilities may range from advanced intelligence, surveillance, and reconnaissance missions to submarine strike warfare.

Structures R&D addresses all required technologies to ensure safe, reliable performance and contributes to the achievement of other functional requirements as well. Structural instability, fatigue, fracture, and impact strength of new materials and fabrication procedures are among the phenomena investigated. The scope of work includes: (1) development of advanced analytical methods to predict the response of submarine structures to various hydrostatic, hydrodynamic, and ice loads; (2) development of validated design procedures for submarine pressure hulls; (3) planning and conducting complex model tests to evaluate new structural concepts and to verify prediction methods; (4) at-sea trials for first-of-class; (5) proof-testing specialized hydrospace vehicles; (6) design and evaluation of advanced hull and propulsor concepts; and (7) conducting highly accurate and precise measurements of complex structures.

The demands for future submarine structures also include multifunctionality with an increased emphasis on structural acoustics. Additionally, electromagnetic (EM) goals may cause a dramatic change in the structural designs and materials required for the hull-structure system. Titanium, austenitic stainless steel pressure hulls, and composite external non-pressure outer hulls are options that may be considered in the future. Today's hulls are fabricated using 2-in.-thick quenched and tempered ferromagnetic HY-80/HY-100 steels and are degaussed to acceptable EM levels. However, an advanced HSLA-100 steel formulation using improved welding consumables is a viable alternative if degaussing alone remains adequate. This provides increased cost reduction for pressure hull and non-pressure hull fabricated structures. HSLA steels are less sensitive to welding cooling rates than HY steels; they lend themselves to alternative higher deposition-rate arc-welding and concentrated energy-beam welding processes, increasing the potential for significant cost reduction.

Materials challenges to support a modular constructed, reconfigurable platform include greater use of higher specific strength materials for pressure hull and non-pressure hull structures. Materials to be considered include titanium, aluminum, HY-130 steel and other high strength steel alloys, LASCOR panels, metal foams, lattice block material, and possibly amorphous metals (stainless-steel alloy formulations). Also, there is a need to develop optimized welding fabrication methods with minimum distortion and high speed cutting procedures for hull break points for the various platform function modules to ensure sub-safe structural integrity and enable rapid platform reconfigurability.

Physics-based materials modeling and simulation tools to design and analyze materials failure/damage behavior, including the response to UNDEX loading, are being developed. Once validated, these tools will reduce the extent of physical testing required to certify new structural materials systems and thus reduce overall certification time and cost.

Composite Structures and Materials for Surface Ships and Submarines

The development of advanced polymer matrix composite structures and materials technologies are critical to improve the performance, survivability, and reliability of current and future naval ships and submarines. Composite materials for these applications offer significant benefits by providing lightweight and blast-, shock- and fatigue-resistant marine structures and systems with reduced magnetic, acoustic, infrared (IR), and radar signatures. In addition, composites provide reduced maintenance costs due to their inherent marine corrosion resistance. Emerging design requirements have forced the designer to favor a multidisciplinary/multifunctional approach to topside structure design. In addition to meeting structural requirements, topside structure must provide adequate shielding for electromagnetic interference (EMI) effects, have a low radar cross section (RCS), and a low IR signature. The future trend toward increased ship topside integration of sensors/antennas and cleaner external structures (e.g., removal of topside clutter) is readily achievable through the use of composites technologies. (See Figure 3, which also includes hull applications.)

Efficient radar-absorbing structure (RAS) can be achieved using composites; but the material also must be suitably engineered/tailored to satisfy EMI and IR requirements. Integrated composite systems are a cost-effective way to satisfy emerging and future stealth requirements and are rapidly becoming the material of choice for topside structure. Current innovative prototype composite structures like the *Advanced Enclosed Mast Sensor System* (AEMS) (see paper by *Caponeschi and Wilson*) and the *Low-Observable Multifunction Stack* (LMS) (refer to *Signatures and Silencing Systems* Section of the Digest) are paving the way to revolutionize topside ship structure in the future Fleet.

In addition to topside structure, composites are candidate structural materials for craft and ship hulls <300 ft long (minehunter/sweeper, frigate, corvette class, etc) and steel/composite hybrid ship hulls >300 ft long where composites would be used for the bow and stern, and steel would be used for the ship mid-body.

Composites will also play a key role in future submarines. However, until the fire, smoke and toxicity issues are adequately resolved, composites will be used primarily for external applications. Composites are being pursued for the bow dome, the lightweight wide aperture array, and the advanced sail as technology insertion bundles for the VIRGINIA-Class. The Division, under ONR and DARPA sponsorship, has developed a scientific and technical (S&T) knowledge base on thick-section (1-in. and greater) marine composites over the last 35 years for selected submarine applications, including pressure hull and non-pressure hull structure, control surfaces, sail, air flasks, dry deck shelter, shafting, and propulsion and auxiliary machinery components (Figure 4). Composites will be key enablers to achieve future modular submarine concepts, particularly for the envisioned interface module and payload container host structure, and for an outer hull in a double hull or wasp-waist configuration.

The technical risks and cost of composites must be reduced to levels acceptable to the designer before they can be used on a larger scale in naval vehicles. RDT&E efforts are continuing on thick-section marine composites including monolithic, stiffened, and sandwich systems. Unique materials processing and fabrication methods need to be developed so that they are suitable for shipbuilding and produce high quality, low cost ship structure and components. Research is being performed on the flammability and elevated temperature effects of composites by addressing improved resins, advanced core materials, fire barrier materials, and fire-spread modeling. The E-glass/vinyl-ester resin materials system and the vacuum-assisted resin-transfer molding (VARTM) and its variations have emerged as the current base-line composite materials and fabrication methodology for shipbuilding. Research is continuing on advanced fibers, improved resins, and cost-effective processing/manufacturing methods. There are many S&T and RDT&E issues that need to be resolved in addition to flammability and affordable materials and processing before composites can be used to their full potential. Some of these technical issues include developing a greater scientific understanding of deformation and failure mechanics/fracture toughness. Also critical static, dynamic and non-linear material properties including long-term environmental behavior/durability must be characterized. In addition, structural design/analysis tools must be developed to ensure structural integrity of metal-composites joints and connections and to be able to design advanced multifunctional and smart materials into future structural configurations. Reliable quality assurance methods (non-destructive evaluation techniques) to support structural integrity assessments and material variability also must be developed in a fieldable system.

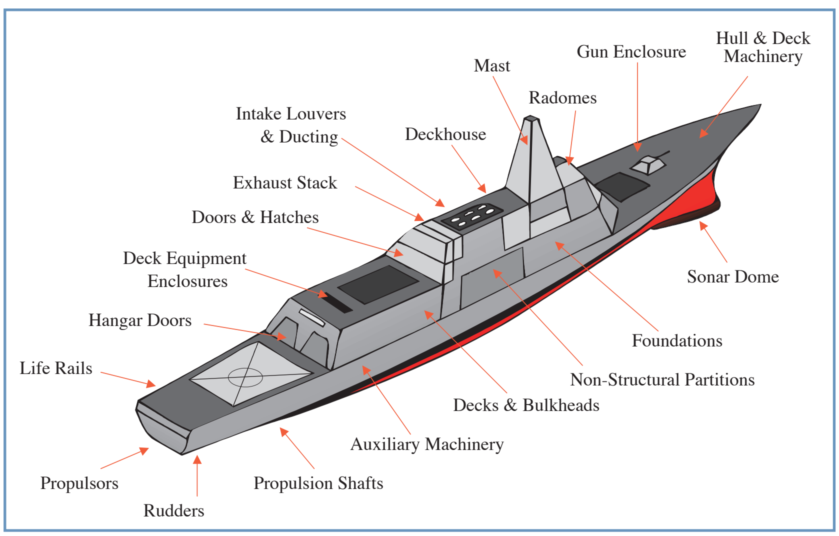


Figure 3. Potential composite surface ship applications.

Other Materials Technologies

In addition to marine structural materials, the Division conducts research on advanced materials and processes for naval vehicle propulsion and auxiliary machinery and functional applications. Machinery materials systems include metal alloys; metal matrix composites; non-metallic materials and corrosion; and wear-resistant and antifouling coatings for propulsors, shafting, seals, piping, and other non-nuclear hull, mechanical, and electrical (HM&E) systems components. Advanced materials are needed to enable future propulsor designs to meet increasingly more demanding hydrodynamic and

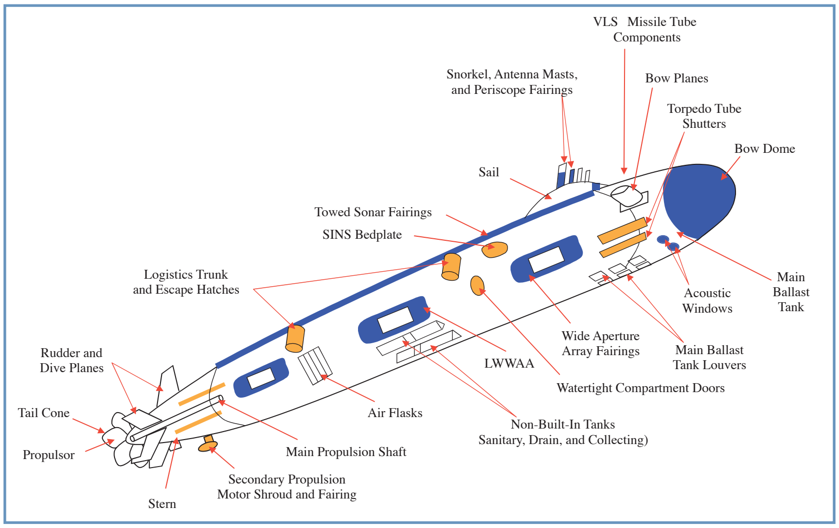


Figure 4. Potential composite submarine applications.

hydroacoustic performance requirements. The current material of choice for propulsors has been Ni-Al bronze, but its mechanical properties will soon become limiting and will require higher strength-to-mass (yield strength greater than 50 ksi) propulsor materials to permit out-of-the-box design flexibility. Future propulsor material system options include higher tensile and fatigue-strength metallic materials, advanced composites, hybrid materials systems, and smart materials to meet reduced weight and acoustic performance requirements. Also, there is a need to develop an interactive design/build rapid-prototyping manufacturing methodology to reduce the time and costs incurred to develop new submarine-class propulsor designs. On-going and planned future propulsion machinery materials efforts include leachable core casting technology, elastomer encapsulated steel propulsor spar, high speed machining, TiC-bronze metal matrix castings, laser cladding, electroslag surfacing, nano-phase and amorphous metal coatings, titanium super plastic forming diffusion bonding (SPFDB), and laser-forming and LBM technologies.

Functional materials satisfy either a single function or can be tailored and optimized to satisfy multiple functions. These materials include signature materials, paints, coatings, smart materials (electrical actuators and sensors), and corrosion control technology. The Division has conducted research on magnetostrictive materials for naval ship applications for many years. The Terfenol-D alloy, which was invented by our materials scientists, has been used in sonar transducers, vibration control actuators, and high-torque motors. Future research is aimed at increased displacement (striction) and lower hysteresis effects. Higher performance magnetostrictive materials will be used in sensors for structural health monitoring, in electrical actuators for active and passive damping, and in integral structural and sensor functions. Lightweight, compact electrical actuators of various types eventually will replace bulky and heavy hydraulic actuation systems while removing hazardous materials (hydraulic fluids) from the ship. Signature materials efforts include enhanced broadband performance in the marine environment, extended life/durability, and affordability (material costs, large-area coverage/installation and maintenance costs) for acoustic and non-acoustic materials. Non-acoustic materials include appliqués, paints, coatings, and tailored sandwich composite materials for applications above the waterline.

Corrosion control technology is a high priority interest area for the Navy because corrosion affects all seaborne vehicles. Marine corrosion degrades metallic materials, reduces the availability of equipment and machinery, and results in costly maintenance. Corrosion is believed to be the single largest cost driver to Fleet maintenance, amounting to about 25% of the maintenance budget with an overall total cost to the Navy estimated in the range of $2B per year. Effort is required to develop new corrosion-resistant materials, new coating application techniques, materials resistant to environmental cracking, advanced preservation coatings, and improved cathodic protection systems. Greater scientific knowledge is required to understand the controlling mechanism(s) and to develop a means to detect, describe, predict, and prevent corrosion, environmental cracking, and oxidation in shipboard systems. The development of predictive methodologies coupled with in-place sensor technology is imperative to meet these demands. In addition, efforts are underway to develop extended life-preservation and antifouling coatings, sensors to monitor coating degradation in remote limited-access areas (e.g., tanks and voids), antifouling coatings for high velocity flow areas (bow stems, rudder, struts, sea-chest grating, propulsor components, etc), and underwater application methods. Other current efforts include metal-sprayed 50Ni-50Cr alloys for incinerators, advanced high-strength fasteners (yield strength greater than 150 ksi), and low-volatile organic compound coatings.

Summary

This paper has discussed the overarching aspects of structures and materials and their interrelationships in ships and submarines. A wide range of phenomena, technologies, and potential issues are identified. The Division's accomplishments in these technology areas have led to a myriad of increased naval capabilities in the past and will continue to contribute to revolutionary changes in naval platform systems in the future. Ultimately, structures and materials provide a sound foundation to enable enhanced technologies for the fully capable ship of the future.

Technical Papers

The technical papers that follow illustrate some of the key foundational technologies and future direction in the structures and materials core area. The first two papers discuss ship and submarine structures. The submarine paper discusses structural integrity issues, analysis tools, design criteria, and future challenges. The Advanced Double Hull combatant ship concept paper is based on unidirectional framing that provides increased survivability, stealth, and producibility, and looks promising for littoral operations. The next two papers discuss two new novel composite material systems. One presents innovative approaches in the use of metal matrix composites to achieve extraordinary wear resistance and high specific strength. A notable example is the highly successful use of TiC-bronze surfacing of the friction drum in the Navy standard hauling winch. Its life was extended from 6 months with no noticeable signs of wear after 2 years, and the operating performance of the winch was greatly improved. The other paper addresses the potential use of polyurethane matrix composites for applications that require flexibility, high damping, and energy absorption. The final paper in this section discusses a corrosion failure analysis of a submarine piping system and provides recommendations to eliminate reoccurrence of the problem.

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Joseph L. Cavallaro *was the Associate Director for Materials Technology in the Survivability, Structures, and Materials Directorate until his recent retirement. He earned a B.S. degree in metallurgical engineering from Drexel University and a M.S. degree in materials engineering science from the Virginia Polytechnic Institute. He held positions as senior metallurgist, head of the Fatigue and Fracture Branch, and head of the Titanium Technology Program Office. His interests include structural alloys with a strong focus in new areas of materials science and technology and all aspects of titanium metallurgy. Mr. Cavallaro received the Meritorious Civilian Service Award, the prestigious George W. Melville Award, and is a Fellow in the American Society of Materials-International. He is currently employed with DDL Omni Engineering as a consultant working on materials aspects of weight-critical naval and Marine Corps structural applications.*

Submarine Pressure Hull Design and Analysis Methods

Michael J. Cheamitru and David T. McDevitt

The modern submarine pressure hull continues to pose unique structural challenges. Structural design is influenced by arrangements, operational requirements, and materials. The structural response often is complex and difficult to analyze when subjected to hydrostatic pressure load. The response is complicated by stability and stress states and hull strength is influenced by imperfections and local discontinuities. The designer's concern is structural efficiency, optimization, and structural adequacy. Optimizing structural weight and cost must not compromise structural integrity. Structural failure modes, the application of the finite element method, and the continuing need for parallel technological advances are presented.

Introduction

The primary design requirement of a submarine's pressure hull structure is to keep the ocean out and to provide a reliable platform for systems, payload, and personnel. The ocean is an infinite source of energy, and loads are unforgiving. The hull is a non-redundant structure with no alternate or back-up system and is designed with the lowest factor of safety of any major heavily manned Navy vehicle. The designer's challenge is to minimize hull structural weight and allow for increased payload, while still ensuring hull structural integrity (the safety of the ship and crew) in the hostile operating environment of the sea.

Background

Gone are the days when, with reasonable confidence and an assumed factor of safety somewhat greater than two, a submarine pressure hull designer would simply hew to the design dictum - "Keep the frames strong and design for an axisymmetric or asymmetric elastic shell buckling failure." –These were the only predictable modes of hull collapse. In the 1950's this design strategy transitioned into the development of hull scantlings with 'strong frames' and sufficient shell stability to take full advantage of a higher strength steel, 45 to 50 ksi. Thus, the design collapse mode was constrained to a predictable failure of the shell in the inelastic domain rather than the elastic domain. A design criterion was established that set the minimum elastic shell buckling pressure at a specifically higher value than the inelastic shell design collapse pressure. This revolutionary change in design strategy eventually demanded identification and solution of all other potential modes of buckling failure in the elastic and inelastic domains.

In the ensuing years, theoretical solutions were developed in the R&D laboratory including general solutions, which encompassed individual and combined longitudinal/circumferential buckling modes with all possible combinations of mixed wave numbers. These theoretical solutions were based on perfect geometries with uniform scantlings, arranged symmetrically, and did not completely address or satisfy all the remaining design issues associated with the complex arrangement and structural details attendant to a submarine.

Parallel experimental effort was undertaken to verify that the theoretical solutions were sufficiently general and accurate, when accompanied by empirical adjustments, across a broad range of geometric parameters and pressure ranges. Thus, the fundamental underpinning of the Navy's current design methodology for steels was validated. Much more was needed to fill the gaps in technology such that a comprehensive methodology for the design of complex submarine pressure hull structures could be accomplished with a high level of confidence. This advance in structural mechanics technologies provided the necessary basis to support the introduction of significantly higher strength steels into current submarines. Without this parallel advance in structural R&D, it is probable that higher strength steels would not efficiently increase hull strength in proportion to the increase in the strength of HY steels.

Design Considerations

The design of pressure hull structures (primarily spherical shells and ring- stiffened cylinders) subjected to external hydrostatic pressure is of limited interest to the general population. The technology is primarily submarine specific; therefore, the R&D and the particular advanced analysis methodologies have been sponsored by the Navy and the resultant design procedures have been developed, maintained, and remain in-house. The Navy has maintained its level of effort while design procedures continue to change significantly through the years. The following discussion summarizes recent trends and demonstrates the need to increase understanding of collapse strength phenomena. New effects must be considered that may not have adversely influenced the highly stable designs of the past.

The quest for deeper diving hulls required changes in material, investigation of a number of failure modes, and recognition that failure is influenced by many theoretical and practical factors that may not be directly addressed with older tools. Failure in specific theoretical failure modes was demonstrated experimentally via hydrostatic collapse tests of pressure hull structural models in high-pressure test tanks (Figure 1).

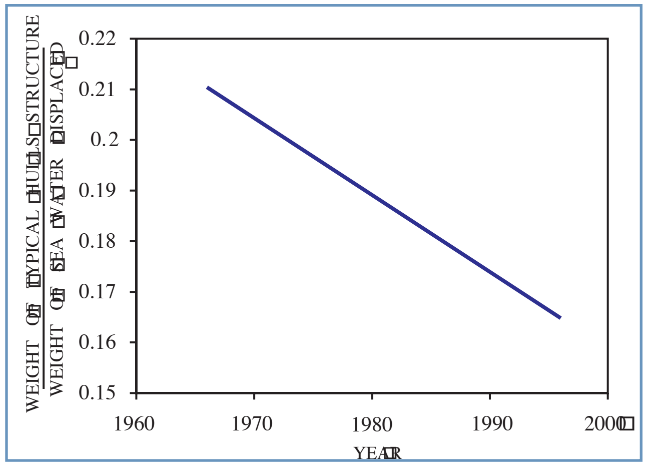


Figure 2. The trend to reduce pressure hull structure weight.

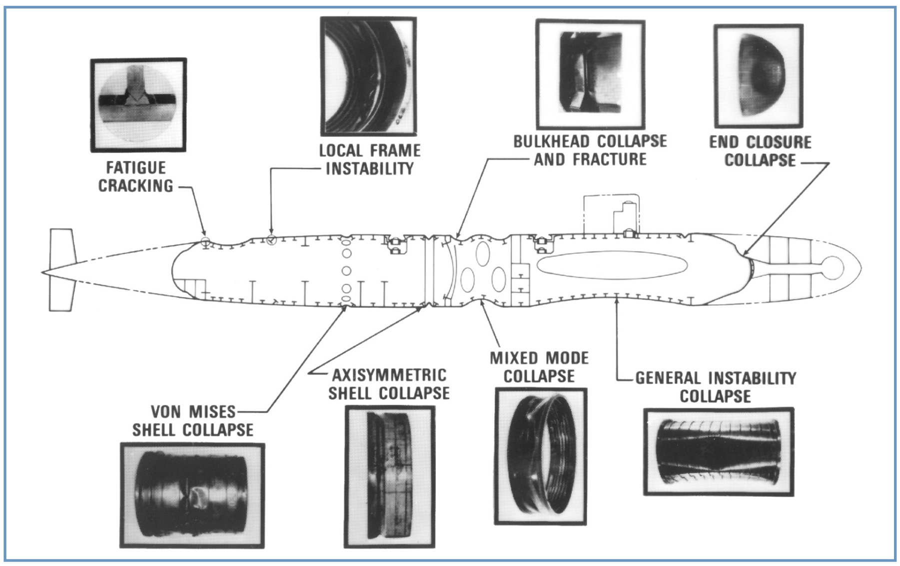


Figure 1. Submarine structural failure modes.

Characterization of various buckling modes contributed to the development of new procedures that could predict the collapse pressure for each mode of failure. At the same time, the development of new higher strength materials with yield strengths of 80-to130 ksi was underway. These developments allowed the designer more flexibility in sizing scantlings for lighter weight hull structure. Current designs minimize weight by using high strength steels and simultaneously satisfying minimun design allowable margins of stability; i.e., the ratio of elastic to inelastic buckling pressure for each failure mode. Figure 2 shows the trend to reduce pressure hull weight, a result of the structures community being able to characterize failure modes of high strength steels and develop rigorous techniques to accurately predict collapse for these modes. As characterized by the ratio of pressure hull weight/pressure hull displacement a typically framed section of the USS SEAWOLF (SSN-21) is over 25% more efficient than a typically framed section of the USS STURGEON (SSN 637).

The trend to reduce weight and the use of higher strength materials creates new concerns for the structural community. The modern hull is less robust in structural stability than pressure hull designs, circa 1950/1980, and is more susceptible to the adverse effects of imperfections, residual stresses, and has the potential for adverse buckling mode coupling. Fortunately, there have been technological changes that allow the Navy to address these issues. Advances in computational capability and numerical methods allow many variables to be studied that could not be considered previously, including varying meriodinal geometry, asymmetric structure, imperfections, lower yield strength welds, and others. At best, these parameters were accounted for in welded model tests by inclusion in the models, although the difficulty of building models that include such things as critical mode shape imperfections with specific magnitudes is a topic in its own right. The advent of the finite element method has allowed these effects to be addressed in parametric studies and in studies of as-built conditions. Large sections of the structure are being analyzed, but the actual “full ship” structure has not been analyzed as a single entity.

A finite element representation of a pressure hull structural model is shown in Figure 3. This analytical model can be used to evaluate the effects of imperfections on collapse and includes both non-linear geometry and non-linear stress-strain material characteristics. Figure 4 shows modal displacements at failure when the model is perturbed by an imperfection in a pure n=3 circumferential overall mode shape. Figure 5 shows modal displacements at failure when the model is simultaneously perturbed by an n=3 circumferential mode shape and an n=0 axisymmetric inward-outward mode between frames.

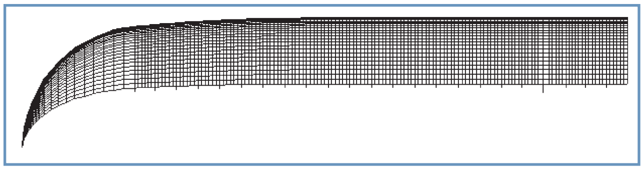


Figure 3. Finite element model discretization.

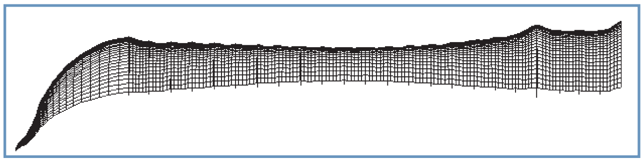


Figure 4. Inelastic general instability modal displacements at failure.

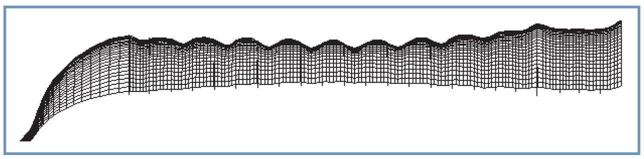


Figure 5. Inelastic mixed mode modal displacements at failure.

An examination of the figures clearly shows the influence of imperfections on displacements due to bending imposed by the imperfect shapes and demonstrates a limitation of the method. The model will fail in an applied or perturbed shape. This shape may not be the critical mode, and consequently the critical minimum collapse pressure and corresponding critical mode may be missed. It is important to maintain a variety of analytical tools to address collapse whereby accuracy is attained by assessing structural response with more than one method. Analogously, it is important that the designer or analyst have a sophisticated understanding of the tools used and their limitations with regard to predicting hull collapse. It should be noted that many finite element analysis codes over-predict the collapse strength of submarine pressure hulls.

Results of varying the magnitude of overall imperfections are shown in Figure 6. There are several subtle implications that result from inspection of this figure. It is obvious that the increase in imperfection amplitude reduces collapse pressure significantly. The addition of a constant amplitude axisymmetric inward-outward imperfection reduces the collapse pressure further. The designers then must be concerned with whether or not the combined mode (imperfection) causes a more severe reduction in collapse strength than a pure mode. The rate of reduction of collapse pressure with increasing amplitude of out-of-roundness is different for the case with and without the constant axisymmetric imperfection. Recognize that the response will change for different geometries and combinations of imperfections. Fortunately, the tools of today allow us to quantitatively adjust for the effects of these types of parameters on the strength of current pressure hulls.

The design of optimized structure requires that complex issues such as mode interaction be addressed. Similar tools have allowed for the inclusion of asymmetric structure and imperfections in predicting stresses. Because of the nature of today's submarine structure, the designer must rely on accurate predictions and possess an extremely high level of confidence in those predictions. Two things that maximize the level of confidence for a new hull design are pressure hull structural confirmation models and initial deep dives of the submarine at sea. Confirmation models are large- scale model representations of hull structure that are tested to collapse in a pressure tank. Figure 7 depicts a large-scale model tested to collapse. Deep dives of the first of a class of a submarine hull are conducted to Design Test Depth to evaluate the structure in situ by taking strain measurements at selected hull locations. Results of the evaluations derived from these tests not only validate the structural performance of the design, but feed into future designs by identifying potential areas of future design concern.

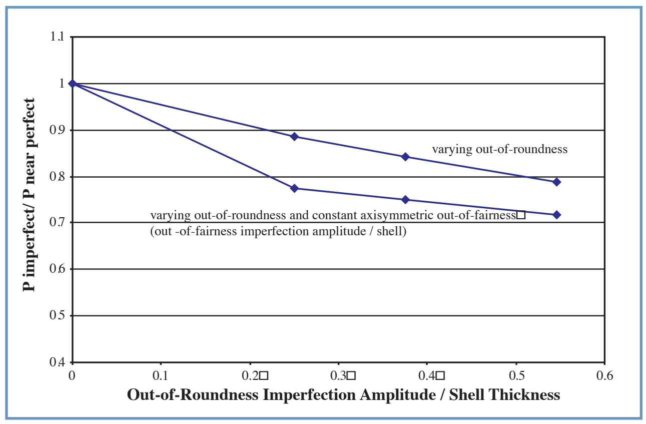


Figure 6. The effects of imperfections on hull collapse.

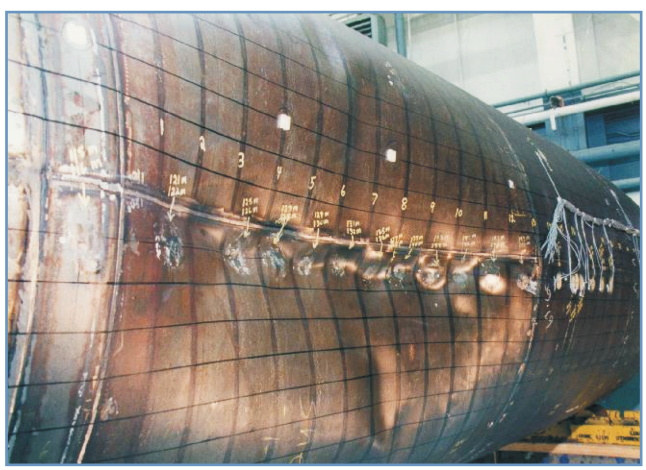


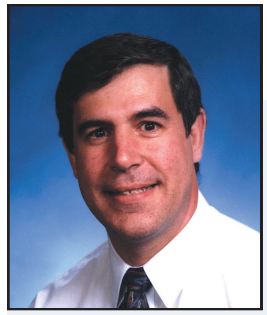
Figure 7. Large-scale model tested to collapse.

Future Design Considerations

Understanding of the physics of the hull collapse phenomenon has advanced and continues to do so with ever changing analytical capabilities. The challenge to future designers will be to maintain the ability to design with as high a level of confidence as in today's designs while incorporating technological advances in new materials and concepts that may not be amenable to rigorous analysis with current tools. Even today the pursuit of increased payload, modularity, and "out-of-the-box" concepts challenges the suite of tools used for analysis and design. Current designs are very close to the mark for all known modes of failure. Improvements in computational and program capabilities are required to pursue analysis (or design) of the total structure, including many structural details and imperfections. The enabling technologies that will support the future development of design capability for unique structural configurations and materials other than HY steels are not in place at this time. There is no magic formula to provide instant results. The quest to develop new tools and methods must continue to guarantee future success.

Reference

1. Brogan, F.A., et al, *Structural analysis of general shells, STAGS users manual*. Version 2.0, Lockheed Missiles and Space Company Report LMSC-P032594 (June 1994).



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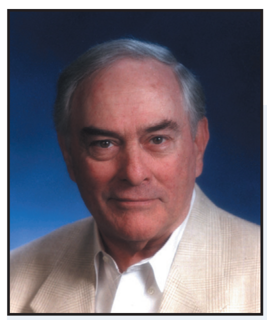


***David T. McDevitt** received his Bachelor of civil engineering degree from Villanova University in 1957. He began his career as a structural research engineer in the Submarine Division of the Structural Mechanics Laboratory at the David Taylor Model Basin (now Carderock Division, Naval Surface Warfare Center, Naval Sea Systems Command). He directed major portions of the Navy's Exploratory Research and Advanced Development programs on submarine hull structures. He also directed numerous deep-dive structural evaluations of combatant submarines during initial Builder's Trials and conducted similar evaluations of research submersibles and unmanned underwater vehicles. The results of these investigations have been incorporated in the Navy's Design Procedure for Submarine Pressure Hull Structure. Currently, he is an independent consultant to DDL OMNI Engineering, Inc., and has been involved in static and dynamic analyses of submarine and surface ship structures.*

Advanced Double Hull

Jerome P. Sikora and Jeffrey E. Beach

The Advanced Double Hull is a unidirectional framing concept for surface ship hull structures. The simplification of ship's structure leads to producibility savings of $50M for a combatant by eliminating thousands of piece parts and providing smooth internal surfaces. Redundant structure (inner and outer hulls) provides survivability benefits and is advantageous for new thermal and acoustic signature reduction methods. Future developments using nonmagnetic stainless steels may provide enhanced corrosion resistance and reduced magnetic signatures.

Introduction

The Advanced Double Hull (ADH) concept was developed in response to the overall need for more affordable surface combatants with increased survivability. While the Cold War has ended, the recent incident with USS COLE shows that the need has not diminished.

The framing systems of conventional, single-hull ships consist of shell plating supported by longitudinal stiffeners that are, in turn, supported by transverse web frames. The ADH concept has inner and outer hull plating connected by longitudinal floors or web girders that form a cellular structure (Figure 1). The inherent strength of the cellular structure allows the elimination of conventional transverse web frames and longitudinal stiffeners on the shell plating. Figure 2 shows notional hull section modules of an ADH SC 21 combatant.

There are many advantages to the ADH concept.

1. Construction cost savings resulting from the elimination of thousands of stiffeners, chocks, brackets, and collars. The smooth internal surfaces of the ship provide easier installation of distributive systems (electrical, piping, insulation, and ductwork) which, along with automated painting methods, generate further cost savings.

2. Improved survivability during collisions and groundings and the potential to better survive weapon effects resulting from the redundancy of an inner and outer hull.

3. New acoustic and infrared (IR) signature reduction methods are made easier through the use of the cellular structures.

4. Reduced life-cycle and maintenance costs resulting from improved fatigue resistance.

5. Future benefits from the use of nonmagnetic stainless steels to enhance corrosion resistance and reduce magnetic signatures.

Under sponsorship of the Office of Naval Research, NSWCCD is engaged in research and development efforts leading to practical application of advanced double hull structural design concepts to naval combatants, auxiliaries, and commercial tanker vessels. The Fast Sealift Technology Development Program has provided additional support to develop structural and producibility design tools for a commercial containership/roll-on-roll-off ship.

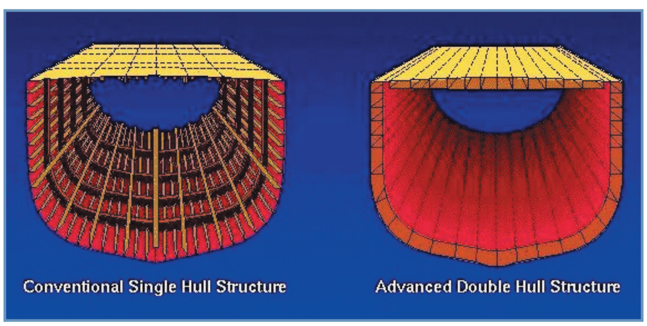


Figure 1. Cross section of conventional and ADH ships

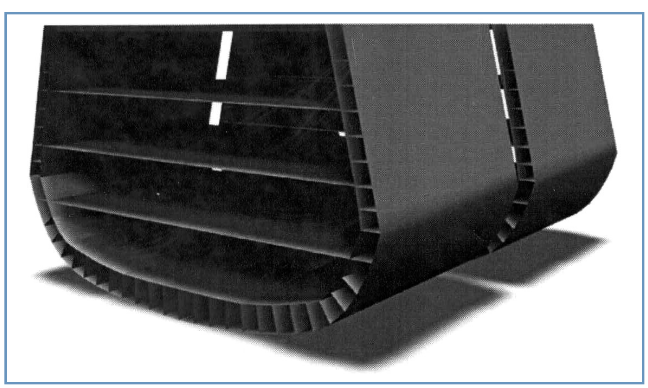


Figure 2. Notional ADH SC 21 hull section/modules

Technology Development

Structures

The structural behavior of the ADH cellular construction differs significantly from that of conventionally framed grillage structure. In a conventional ship, the pressure loads from both the sea and the ship's cargo act on the shell plating and are transmitted partly to the transverse frames and partly to the longitudinal stiffeners. These members transmit the loads to transverse and longitudinal bulkheads. In the no-frame ADH configuration, the lateral loads on the shell plating are transmitted via bending to the longitudinal web members, and then to the transverse bulkheads through shear. Under primary loading (i.e., hull girder bending), the plate stiffener collapse behavior of conventional framing is replaced by cellular column collapse behavior of the ADH. To understand these phenomena, a number of large-scale structural models were developed along with innovative test fixtures to determine the strength of cellular structures from initial elastic buckling, through plastic failure, and on to the ultimate collapse strength. As a result of these unique tests, the structural behavior of the ADH structure with its additional post-damage reserve strength can be incorporated into a ship's design phase. Figure 3 shows the progressive damage of a half-scale cellular structural model being tested to collapse in the world's largest test machine (12M lb of axial load) at the National Institute of Standards and Technology (NIST).

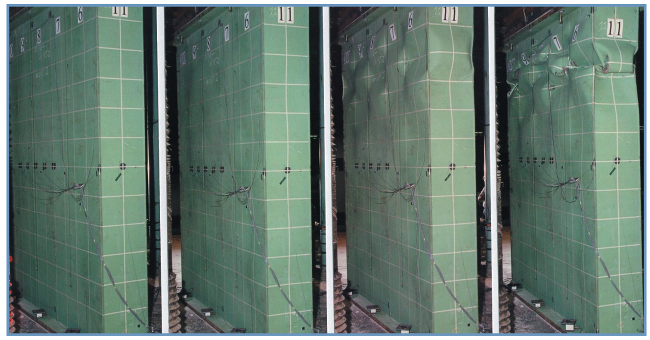


Figure 3. Cellular column collapse models

Fatigue

Fatigue is the accumulated, irreversible damage in a structure, which results from exposure to cyclic or oscillating stresses. The levels of stress necessary to cause fatigue can be very low, easily within the normal operating range of sea-induced loads. The Advanced Double Hull structure is characterized by an assemblage of intersecting plates. As such, tests were conducted on specimens representing various basic joint details (e.g., the intersection of longitudinal plating with transverse (bulkhead) plating). The details were fabricated using shipyard welding methods. Figure 4 shows a full-scale ADH component model being fatigue-tested under realistic load conditions that simulate the random nature of the seaway. Figure 5 shows that the simplified ADH structure improves fatigue life by many years (millions of cycles) over conventional ship details. This represents repair cost savings in the millions of dollars over the life of a typical ADH ship.

Figure 4. ADH fatigue specimen under test

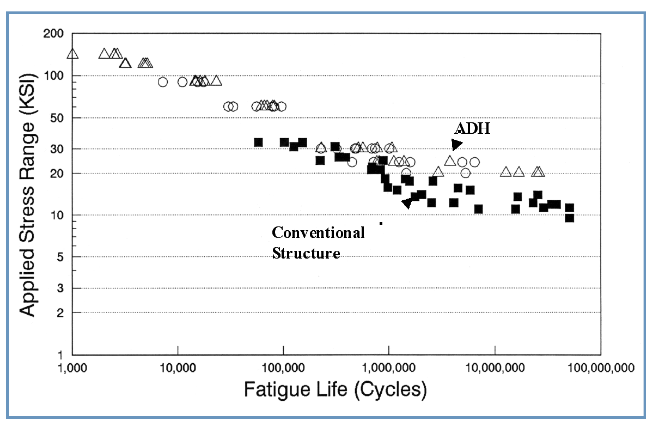


Figure 5. Fatigue life as a function of applied stress

Joining and Welding

The use of the ADH configuration greatly simplifies the geometry of the structure through the elimination of the transverse frames. Not only are the weld runs uninterrupted in the longitudinal direction, but nearly all of the chocks, collars, and brackets are eliminated. Thus, more efficient automated welding processes can be used to the fullest extent. Several studies have been conducted on the various automated welding processes and joint designs with potential applications to the ADH configuration. Included in this body of research are flux-cored arc welding, gas-metal arc welding, submerged-arc welding, electrogas welding, electron beam welding, and laser welding. Much of the work focused on a variety of one-sided weld joint designs.

A cost comparison of an ADH variant was conducted with the conventional DDG–51 Class to quantify potential cost reductions. An 8.3% labor savings in the cost to fabricate the primary hull structure was attributed to reduced welding costs from a smaller number of linear feet of weld required. Other factors contributing to reduced welding costs, such as increased use of modern, automated welding, were not included in the analysis. While this study was conservative, the findings reveal the potential of the ADH configuration to reduce welding costs.

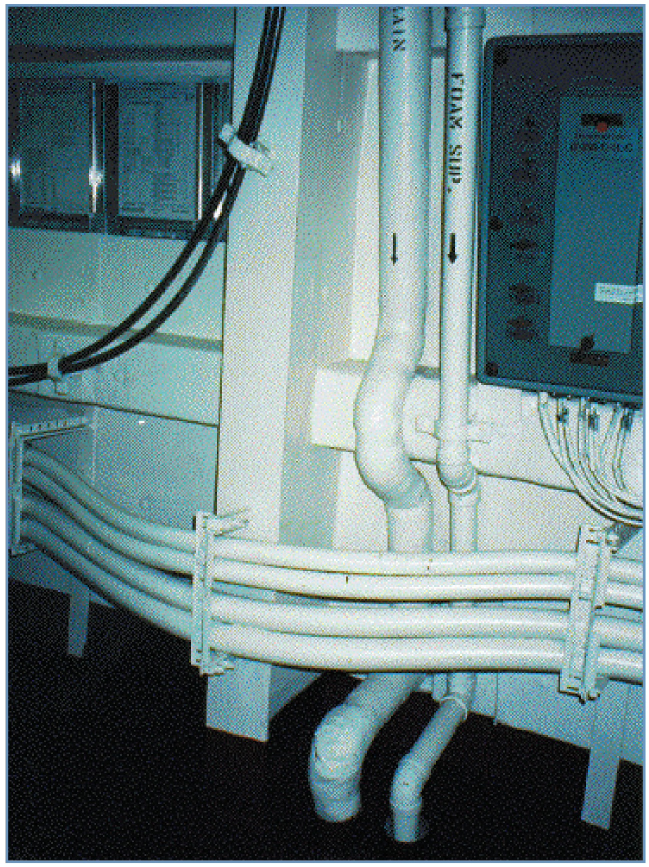


Figure 6. Distributive systems bending around conventional structure

Outfitting of Distributed Systems

Distributive systems consist of the piping; electrical cabling; and heating, ventilation, and air conditioning (HVAC) ducts. On conventional ships, these systems must be routed around or through the transverse frames and longitudinal stiffeners, thus increasing their cost and complexity (Figure 6). On ADH ships, the smooth, uninterrupted surfaces of the inner shell greatly simplify the routing of distributive systems, eliminate many bends, shorten system lines, and significantly reduce installation costs. A cost comparison was conducted for electrical, HVAC, and piping systems in a DDG 51–Class ship. This analysis conservatively estimated that the use of an ADH configuration would result in an 18% labor hour savings in the electrical craft, an 18% labor hour savings in the sheet metal craft (ventilation ducts), and a 24% labor hour savings in the piping craft. A third of a million labor hours can be saved with the ADH, because almost half of the 4 million trade craft hours in ship construction are used to install distributive systems. Additionally, a reduction in the length of the system runs results in 118 ltons of weight savings and $4M in material cost savings.

Conventional ADH

The ADH has a smaller hole and less internal damage than the conventional structure.

Figure 7. ADH and conventional structures after UNDEX attack

Survivability

Ship combat survivability is a function of many features and attributes built into the ship, which can be either active or passive in nature. Passive protection is designed into the ship so that it can take a hit and continue to function and fight. The use of double hull ships has been recognized as a means to enhance the passive survivability of combatants.

Weapons may be detonated in air, underwater, or at the waterline as in the case of USS COLE. Airborne explosions (AIREX) from missile attacks can result in fragment damage and blast holing, generally at or above the waterline. Ships can be subject to underwater explosion (UNDEX) attacks from mines, torpedoes, near-miss bombs and missiles, terrorist attacks, and the effects of the ship's own offensive or defensive weapons. UNDEX also can result in holing, generally below the waterline, which frequently results in flooding. Figure 7 shows an ADH model with less damage than an equivalent conventional ship structure subject to identical UNDEX attack.

Equipment Shock

An extensive numerical analysis was conducted on an ADH cruiser subject to an underwater explosion. It showed that an ADH was better at attenuating shock on equipment than a conventional ship, because it reduced accelerations and peak velocities, and had similar or larger absolute displacements (Figure 8). Also, internal decks and platforms on ADH ships can be shock-isolated to handle commercial off-the-shelf equipment. This cannot be done readily on conventional, single-hull ships because shock isolation normally disconnects these decks, and continuity of structure is required for longitudinal strength.

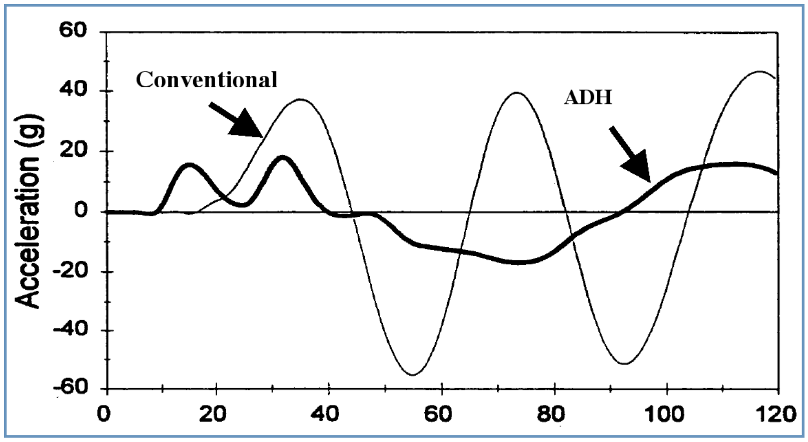


Figure 8. Time history of the ADH with lower accelerations than a conventional structure

Damage Control

Damage control measures must address both the hydrostatic stability of a partially flooded vessel and the emergency procedures needed to plug a hole. A series of model tests investigated the damage stability of ADH combatants. The current Navy criteria were found to apply to the ADH configuration, but the designer must consider damage stability early in the design cycle. Damage control tests conducted on Ex-USS SHADWELL showed that an ADH configuration has significant advantages over a single-hull configuration to stop flooding. For example, bladders can be inserted within the damaged cells and inflated, thus sealing the hole without resorting to extensive shoring.

Signature Control

Infrared energy from machinery, equipment, etc, is emitted from the portion of the ship that is above the waterline. Air-filled cells in the ADH configuration have an inherent insulating value equivalent to 1 in. of conventional fiberglass insulation. Furthermore, the ADH cells tend to reduce the high thermal gradients on the ship. An additional potential control measure would be to spray a controlled fluid inside the cells. Work is continuing in this area.

Acoustic energy from machinery and equipment is emitted through the wetted portion of the hull. A number of model tests were run to determine the acoustic behavior of the ADH cellular structure. It was found that the cells below the waterline could be more easily coated with acoustic absorbing material than conventional grillage structures to reduce acoustic signatures.

Corrosion

The cost of corrosion maintenance and repair of surface and sub-surface naval ships has been estimated to be at least $1.2B annually for approximately 360 ships. These costs can be minimized for new ships with close attention to design, manufacturing techniques, quality control, materials selection, and other corrosion control techniques. Corrosion control of structures exposed to seawater traditionally is accomplished through the combined use of coatings and cathodic protection and through the selection of corrosion-resistant materials.

There are two unique features of all double-hull ships, which increase corrosion susceptibility versus single-hull ships. One is moisture condensation inside double hull cells caused by a variation in temperature between the inner and outer cell walls. The second is the increased number of horizontal surfaces on which water may accumulate. Fortunately, new corrosion-resistant techniques are being developed to mitigate these issues, and the smooth surfaces within the cells ease the application of treatments and coatings.

Inspection, Maintenance and Repair

The small size of the cells (approximately 3ft by 3 ft) on combatants frequently is perceived as an inspection and maintenance problem. While personnel can work inside these cells, unmanned methods are preferred. A remotely controlled vehicle has been developed and demonstrated to inspect, clean, paint, and keep a maintenance history of cells as small as 18in. by 18 in. This self-propelled robot (Figure 9) can be inserted through a 12in. by 12-in. access opening.

Future Developments

The ADH configuration is compatible with replacing the ordinary shipboard steels with nonmagnetic materials (such as austenitic stainless steel, aluminum, or titanium) to significantly reduce magnetic signatures. In addition to magnetic signatures, stainless steels have an advantage in general corrosion resistance over conventional steels, thus reducing life-cycle costs.

Over the last 3 years, this work has been augmented to look into the application of nonmagnetic stainless steels for the ADH concept. Cost analyses of the nonmagnetic, stainless steel ADH concept have been performed to establish its effect on acquisition costs in the areas of hull fabrication and outfitting vis a vis a conventional combatant. Survivability analyses for both the blue water and littoral environments have been performed establishing the hull girder strength

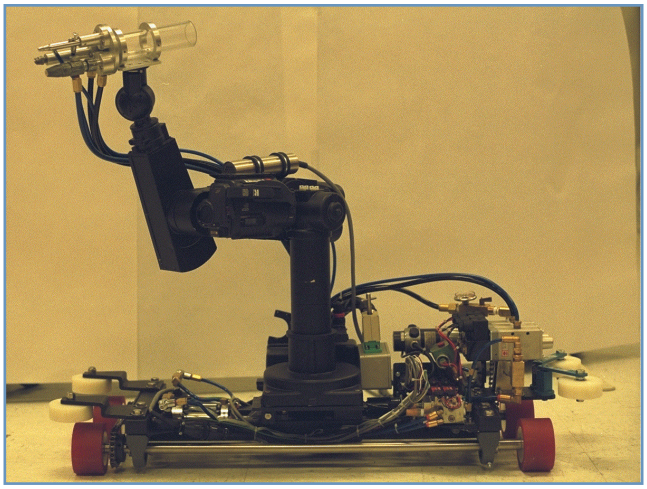


Figure 9. Self-propelled robot welds, cleans, and paints inside cells

Figure 10. Comparison of AL6XN stainless steel resistance to blast damage

provided by this concept against underwater and air threats, and the ship IR, acoustic, and magnetic signatures. Figure 10 shows the ability of a promising stainless steel (AL6XN) to resist blast damage better than conventional and high strength shipboard steels.

The nonmagnetic, stainless steel ADH concept offers the potential to reduce acquisition costs in excess of $30M per ship for destroyer class ships, reduce operational and support costs, and improve survivability in both blue water and littoral environments.

Summary

The Advanced Double Hull concept shows real potential for a more affordable surface combatant with increased survivability. Affordability arises from both reduced construction costs as well as lower life-cycle costs. Survivability is increased by reducing signatures thus avoiding detection, and by increasing the ability to fight hurt after a combat incident has occurred. The future development of nonmagnetic stainless steels has the potential to reduce corrosion, magnetic signatures, and vulnerability to weapons.

__Jerome P. Sikora__ is head of the Design Applications Branch of the Structures and Composites Department. He earned a B.S. degree in physics from the University of Detroit. He began his career at NSWCCD in 1969, in the field of static and dynamic optical measurements of structural stress, deformations, and vibration modes. His methods of holographic and speckle three-dimensional displacement measurements are referenced in textbooks. He has performed numerous finite element stress analyses, tests of rigid plastic models, and ultimate strength studies of most major classes of U.S. Navy combatants. Mr. Sikora has been involved in the development of Small Waterplane Twin Hull (SWATH) ships, tri-hull ships, and an offshore mobile base. His SWATH design loading algorithms for primary bending and secondary pressure loads have been incorporated into ABS rules for these ships.

__Dr. Jeffrey E. Beach__ is head of the Structures and Composites Department and has been employed at NSWCCD since 1969. He earned B.S. and M.S. degrees in aerospace engineering from the University of Maryland and has had additional graduate training in naval architecture and structural engineering. He earned his doctorate in engineering management at the George Washington University. Beach manages a diverse program of exploratory, advanced, and engineering development research aimed at the application of composite and advanced metallic structures to marine structural systems. He is active nationally and internationally in professional societies, organizations, and exchanges, and has published and presented numerous technical papers in the international community. Among his awards are the 1984 ASNE Solberg Award for research and the 1998 ASNE Gold Medal Award.

Wear-Resistant Metal Matrix Composites for Naval Applications

Amarnath P. Divecha

A Navy requirement mandated that carcinogenic asbestos shoes be removed from the braking mechanism of shipboard underway replenishment systems. As a direct result, brake drum failure increased several-fold to a point where they required replacement after less than 80 hr of operation. Metal matrix composite (MMC) centrifugal casting technology developed at NSWCCD, provided an affordable wear-resistant material to solve the problem. Previously, MMCs were expensive to process and were used exclusively for structural applications. This paper traces the history of centrifugal casting of MMCs with special attention to Navy applications of titanium carbide (TiC) particle-reinforced bronze (TiC/bronze) and a new tungsten carbide (WC) particle-reinforced bronze (WC/bronze). The potential use of centrifugal cast silicon carbide/aluminum in Marine Corps vehicles is presented also.

Introduction

Until recently, the friction shoes in the air-brake mechanism of the Navy Standard Hauling Winch Underway Replenishment (UNREP) system have been asbestos-based. The hauling winch uses a high horsepower, continuous-slip air clutch to control and limit wire rope tension (Figure 1a & 1b). The Navy requirement to eliminate carcinogenic asbestos was addressed by NSWCCD, Philadelphia, the In-Service Engineering Agent (ISEA) of the Navy Standard Hauling Winch. Extensive tests by Port Hueneme of available non-asbestos shoes with different types of aluminum bronze friction drums resulted in excessive friction shoe wear, excessive friction drum wear (Figure 1c), erratic friction characteristics, or combinations of these undesirable features. The solution was to develop a new wear-resistant friction drum. Earlier work, which led to a Carderock Division Navy patent,[1] demonstrated the advantages of centrifugal casting of MMCs to produce novel structures and microstructures. By centrifugal casting hard, lightweight (4.9 g/cc) particles of titanium carbide (TiC) suspended in heavier molten aluminum bronze (7.48 g/cc), the TiC particles would be forced to migrate en masse to the inner diameter in the final product. Wisconsin Centrifugal, Inc. (WCI), an industrial foundry familiar with the centrifugal casting method and the NSWCCD patent, used the technology to fabricate TiC/bronze friction drums. In 1000 hrs of land-based tests by NSWCCD, Philadelphia, at Port Hueneme, some of the TiC/bronze drums showed negligible or zero wear (Figure 1d).

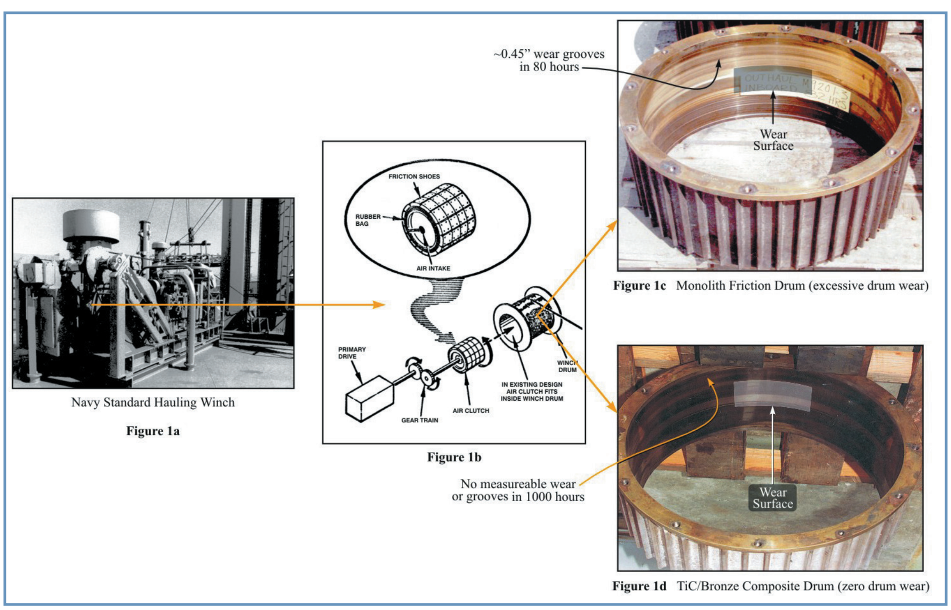


Figure 1. Navy Standard Hauling Winch.

WCI needed assistance to develop a robust production process to fabricate high quality TiC/bronze friction drums consistently and with low rejection rates. Accordingly, NSWCCD and the Naval Sea Systems Command (NAVSEA) initiated a Mantech program sponsored by the Office of Naval Research (ONR) at the National Center for Excellence in Metalworking Technology (NCEMT) in Johnstown, PA. Concurrently, NSWCCD, Philadelphia, selected four friction drums that exhibited good wear resistance in their land-based tests to install on USNS KILAUEA. The four friction drums showed no signs of wear or corrosion after 2 years in service. As a result, NSWCCD, Philadelphia, has planned to equip all UNREP ships with the new composite friction drums by the end of FY 02, saving an estimated 68 million dollars over a 10-year period.

Two other applications of centrifugal casting technology for wear resistance have been identified. The Carderock Division is fabricating prototype WC/bronze face and circumferential seals to be tested by John Crane LIPS in their facility in Havant, England. And, the Advanced Amphibious Assault Vehicle (AAAV) Program Office is in need of a lightweight road wheel with wear resistance comparable to that of 4140 steel. The Division will develop centrifugal cast SiC/Al road wheels to address this problem. The silicon carbide/aluminum (SiC/Al) road wheel, TiC/bronze friction drum, and tungsten carbide (WC)/bronze seals are described below.

Centrifugal Casting of Metal Matrix Composites

The centrifugal casting process has been used for over 100 years in the industry at large to produce symmetrical shapes including turbine cases, combustor liners, turbine seals, compressor cases, bronze bushings, bearings, gears, and cast-iron sewer pipes. Centrifugal casting is an inexpensive, reliable, versatile, and simple process. In a typical centrifugal casting sequence in a foundry, a charge of metal or alloy is first melted in a crucible. The molten metal is poured in a heated ladle that can be transported by a crane to a casting station (Figure 2). The ladle may be tilted remotely to pour the metal into a rotating mold for centrifugal casting. The mold is heated to a predetermined temperature to control the solidification time of the metal or alloy, which is usually within a few minutes after pouring. Horizontal centrifugal casting (HCC) is preferred for large diameter, long tubes or pipes; vertical centrifugal casting (VCC) is more suitable for short length-to-diameter (L/D) ratio or aspect ratio components, usually under 1.5; see Figure 2.

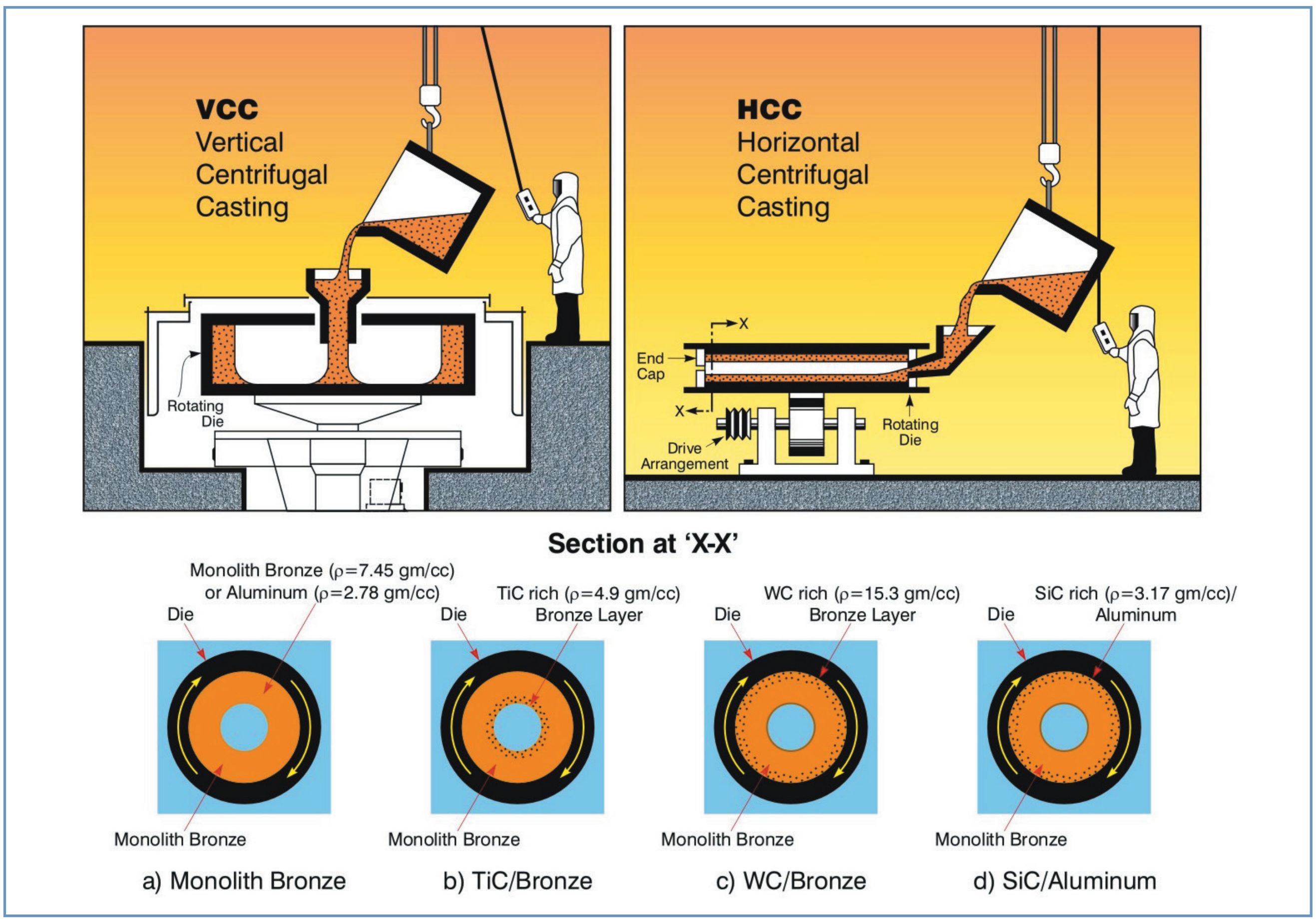


Figure 2. Centrifugal casting of monolith bronze and aluminum, TiC bronze, WC bronze, and SiC/Al.

The centrifugal force on the homogeneous or heterogeneous liquid is governed by a simple equation.

$F = (W/G) R\omega^2$

where

F = centrifugal force

ω = angular velocity of the mold, which is equal to $2\pi N/60$

N = rpm of the mold.

Note that the monolithic and MMC castings prepared as above are always fully dense because of the high G forces and produce pressures ranging from 50 to 500 psi.

Conventional centrifugal casting as described above was used exclusively for monolithic, *homogeneous*, melts until recently. In the late 1980s, Carderock Division used the process to cast *heterogeneous* melts with a suspension of hard, solid, higher melting temperature, ceramic particles. The homogeneous base, or matrix, alloy is melted as usual followed by the addition of a small volume fraction of chemically compatible, solid ceramic particles. After a well-dispersed suspension is achieved, this heterogeneous mixture is poured into a rotating mold (Figure 2). A new material is produced, depending on the density of the ceramic particles (Table 1). Particles that are heavier than the liquid metal will centrifuge to the outer diameter (OD). Conversely, lighter particles will migrate *en masse* to the inner diameter (ID) of the casting. This is the principle exploited in the patent described below.

As mentioned, the Division examined three MMC systems via centrifugal casting. Selected properties including melting point temperature, density (or specific gravity), composition of the matrix alloys and the reinforcements are presented in Table 1. There is a significant difference between the matrix and the reinforcement particle density in each MMC system. Also, the melting point temperatures of the reinforcement particles, SiC, TiC, and WC are much higher than the respective metal matrices. SiC is chemically and thermodynamically stable in molten aluminum alloy (A356) at 700°C for long periods of time. Similarly, TiC and WC are compatible with molten aluminum bronze (CA954) at least up to 1045°C. A356 Al and CA954 bronze are casting alloys that exhibit excellent fluidity even in the presence of small volume fractions of fine solid particles. Viscosity increases as the particle volume fraction increases above 0.3, which adversely affects castability. The best initial volume fraction range of reinforcement particles for most applications is 0.1 to 0.2 in the molten matrix.

After casting in a rotating mold, particle volume fraction increases at the ID or OD in a well-defined band, as determined by particle density, mold diameter, mold temperature, and mold rpm. Under proper processing conditions, particle concentration as high as 0.45 is possible in the finished (SiC/Al) product near the surface.[2] The majority of the cast part thickness remains as unreinforced matrix metal at the end of the process. Thus, the centrifugal casting method efficiently produces a part with a unique structure of a hard, wear-resistant surface that is an integral part of an unreinforced, tough substrate. Typical MMC materials have embrittling ceramic reinforcements distributed throughout the entire part and are susceptible to failure from dynamic loading. Centrifugal cast parts have dynamic toughness consistent with the choice of the matrix material.

Knowledge of corrosion behavior is important for service in naval systems. The presence of ceramic particles is expected to affect corrosion in MMCs. Limited salt fog data show that corrosion resistance[3] of SiC/Al and TiC/bronze is comparable to the respective matrices, namely, A356 Al and CA954 bronze. Corrosion behavior of parts is being monitored in these systems as they are tested and used in the Fleet.

Table 1. MMC materials and their properties.

Material	Melting Point (C°)	Density gms/cc	Compatibility with Molten Metal Matrix	Preferred Initial Ceramic Particulate V% in the Melt
A356 alumninum* alloy	615	615	—	—
Silicon Carbide SiC	2300	2300	Max. 1 hr @ 615°C	10 - 20
CA 954 Bronze*	1045	1045	—	—
Titanium Carbide TiC	3067	3067	Max. 1 hr 1045°C	7 - 10
Tungsten Carbide WC	2800	2800	Max. 1 hr @ 1045°C	7 - 15

* **Nominal composition:**
A356 Aluminum Alloy: 7Si - 0.3 Mg - 92.7 Al
Ca954 Bronze Alloy: 4Fe - 11A1 - 85 Cu

Wear-Resistant SiC/Al Road Wheels for AAAV

Metal matrix composites were investigated for their mechanical properties. Accordingly, SiC/Al was an option for the advanced lightweight torpedo (ALWT) because of its increased specific stiffness over aluminum. The NSWCCD patent on centrifugal casting was well suited to fabricate ALWT tubes. Westinghouse Research and Development (WRD) was interested in this process as suppliers of monolithic 6061 aluminum alloy torpedo hulls to the Navy. Wisconsin Centrifugal, Inc. (a fabricator of aluminum, bronze, and steel components), NSWCCD and WRD formed a team to examine the feasibility of centrifugal cast SiC/Al "torpedo" hulls.[4,5] While the joint program was successful, the need to reduce torpedo hull weight disappeared with the end of cold war and attendant declining defense budgets. Now, more emphasis is placed on affordability, condition-based maintenance and total ownership cost reduction. Consequently, the excellent wear resistance of MMCs is receiving increased attention. For instance, SiC/Al is being considered as a candidate for AAAV road wheels. This application requires a material as light as aluminum with wear and corrosion resistance equal to or greater than that of 4140 steel, and at a low cost. There is evidence that SiC/Al possesses good corrosion resistance. At a volume fraction of SiC above 0.3, a SiC/Al composite has wear resistance equivalent to that of 4140 steel under similar test conditions. Projections are that the AAAV program will need one million or more replacement wheels over its lifetime; therefore, a wear-resistant SiC/Al wheel may be very economical. The SiC/Al AAAV road wheel development program began in April 00. It is endorsed and supported by ONR (6.2) Science and Technology funds as well as U.S. Marine Corps AAAV (6.4) Development funds. A Mantech program is envisioned for FY 03.

Titanium Carbide Reinforced Aluminum Bronze Friction Drums

The success of TiC/bronze friction drums is due to unique macro and microstructures. Figure 3 shows polished and etched longitudinal slices of typical drums. The top section is part of a drum manufactured by WCI. Macro etching reveals two distinct shades at low magnification. The dark area of the WCI section is enriched with TiC and is uneven. This part was cast by VCC. During vertical centrifugal casting, almost all TiC particles accumulate at the inner surface because of density differences (Table 1). The TiC-rich layer is thicker at the top of the casting (the left side of the top section in Figure 3) because lighter TiC has a tendency to rise in the mold to the top. There have been instances where the TiC layer was very thin or non-existent in the WCI parts. In such a case, the wear resistance of the drum is affected adversely. In drums that exhibited good wear resistance, the particles are well distributed as shown in Figure 3. It has been learned that a TiC particle volume fraction in the range of 0.20 to 0.25 is sufficient for a minimum of 650 hr of winch service.

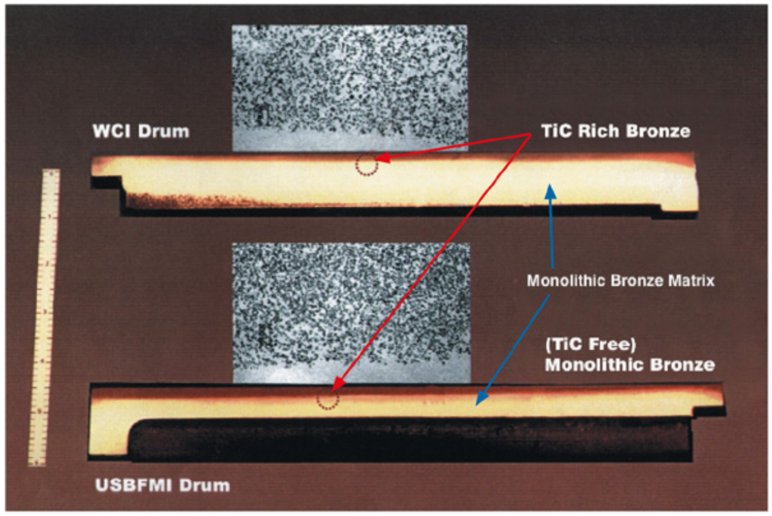


Figure 3. Macro and microstructure of a longitudinal slice of a typical composite drum.

It is desirable that the Navy be able to procure materials and components from multiple suppliers rather than a single source. Until late 1998, WCI was the sole supplier of TiC/bronze friction drums. Under the Mantech program, NCEMT with the concurrence of NSWCCD, Philadelphia, sought assistance from the Division to encourage and qualify a second source. Within a short period of 10 months, NSWCCD and NCEMT transferred the entire technology to a small foundry, U.S. Bronze and Foundry Machine, Inc (USBFMI) of Meadville, PA. Figure 3 shows representative macro and microstructures of TiC/bronze drum manufactured by USBFMI and WCI. Note that the USBFMI drum shows a more uniform TiC-rich layer than the drum produced by WCI. The particle distribution of the USBFMI drum is comparable to that in the WCI drum, as seen in Figure 3. In limited wear testing performed at NCEMT, it was evident that all USBFMI/NSWCCD drum samples exhibited wear resistance superior to that of the monolithic bronze. However, incidence of cracking in the TiC-rich area prevented USBFMI from completing the Mantech development in a timely fashion as a qualified vendor. Given time and effort, however, it is certain that the cracking problem can be solved. Thus, USBFMI is a potential second source.

Tungsten Carbide Reinforced Aluminum Bronze

During the transition of TiC/bronze friction drum technology to the industry, it was felt that many more applications requiring superior wear resistance might exist in the Navy (and probably in the industry at large). Efforts to find additional applications of MMCs in the Fleet led to a contact with a company called John Crane LIPS, Inc (JCLI), Havant, England. In contrast to the friction drum, parts requiring wear resistance on the OD were identified. The MMC of choice for this application is a heavier particle (e.g., WC) in bronze. Centrifugal casting of WC/bronze results in segregation of the hard particles to the outer diameter where wear resistance is needed. With the exploratory development support (6.2) funds from ONR, NSWCCD synthesized WC/bronze ingots of consistent quality. Subsequently, MMC ingot re-melting methods were established, followed by VCC experiments in the bench-scale apparatus at NSWCCD. The current effort aims to provide WC/bronze sub-scale seal samples to JCLI to test at their facility. A 3-year ONR/Navy International Cooperative Program with JCLI was launched in June 2000. JCLI was selected because they provide more than 95% of all the face and shaft seals to our Navy. The seals are tested and qualified in Havant, England, before installation on U.S. Navy ships. If wear is negligible, WC/bronze seals will not need replacement for the life of the ship, substantially lowering total ownership costs. While this program is in its early stages, it is following a path similar to the one that resulted in transition of TiC/bronze drums for use in Fleet UNREP. ONR's Industrial Programs Office is being kept informed of the developments so that transition to a Mantech program may be initiated in a timely fashion.

Summary

Centrifugal casting of MMCs is a proven technology to induce wear resistance in metallic materials. It is a low cost process because the manufacturing infrastructure already exists. Only minor modifications are required to initiate production of wear-resistant MMC components. Centrifugal casting is versatile, encompassing many MMC systems without serious technical difficulties. Accordingly, SiC/Al, TiC/bronze and WC/bronze composites have enabled transition from 6.1 through 7.8 levels in a short period of time. Above all, centrifugal casting has the potential to reduce manpower requirements, almost eliminating maintenance on selected components and increasing our warfighting readiness at an affordable cost.

Acknowledgments

The support of the Office of Naval Research (ONR), particularly, Drs. Fishman, Pohanka, and Yoder was and continues to be instrumental in our progress thus far. Special thanks are also due ONR's Mantech Office Director, Mr. Steve Linder, in cooperation with Mr. Robert Jenkins, of NAVSEA for accelerating the transition by supporting NCEMT via a Mantech program.

References

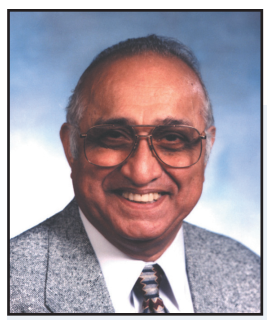
1. Karmarkar, S.D., and A.P. Divecha, "Centrifugal Casting of Composites," U.S. Patent 5,025,894 (25 June 1991).

2. Maltby, J.D., "Mechanical Properties of Centrifugally Cast Metal Matrix Composites," Naval Command, Control and Ocean Surveillance Center, RDT & E Division, San Diego, CA, Technical Report 1517 (July 1992).

3. Crowe, C.R., and D.F. Hasson, "Corrosion Fatigue of SiC/Al Metal Matrix Composites in Salt Ladened Moist Air," *Proceedings of the ICSMA No. 6 Conference* (Aug 1982).

4. Gungor, M.N., et al, "Structure and Mechanical Properties of Centrifugally Cast SiC/Al," Eds. S.W. Rsai and G.S. Springer, *ICCM VIII Proceedings*, Honolulu, Hawaii, Published by SAMPE, pp. 18G I -G 15 (July 1991)..

5. Divecha, A.P., et al, "Structure and Mechanical Properties of Centrifugally Cast SiC/Al Composites," Technical Digest, Naval Surface warfare Center, Dahlgren Division, pp. 42-51 (Sep 1993).



Amarnath P. Divecha *received his B.S. from the University of Bombay India and a M.S. in metallurgy from the University of Utah. Mr. Divecha has 39 years of experience in the fields of metal matrix composites, aluminum lithium alloys, and superconductors. Since 1976, Mr. Divecha has been a group leader in the Materials Department at NSWCCD. Mr. Divecha has authored over 30 technical papers and reports and has received 30 patents. He has received several awards including the Dahlgren Award from NSWC (1982), the Del Monte Award from SAMPE International (1985), the Life Cycle Cost Reduction Award from DoD (1997), the Cheapskate Award for Affordability from ONR (1999), and the Technology Transfer Award from the Federal Laboratory Consortium (2001).*

Urethane Matrix Composite Materials for High Energy Absorbing Naval Applications

Roger M. Crane

NSWCCD has been involved in the development of a novel composite system that uses a non-traditional matrix material - polyurethane. The low stiffness of this particular polymer matrix allows for large global deformation and high energy dissipation. Research at the Division has concentrated on material processing and use of the urethane matrix composite materials system for applications requiring flexibility, high damping and high energy absorption. These applications include fender systems for berthing ships, machinery vibration isolation mounts, and flexible stanchions. This paper discusses the unique characteristics of this new composite material system, the transitioning of the technology, and the design of components that will be used by the Navy.

Introduction

NSWCCD has developed a novel material system that uses an elastomeric polymer material as the matrix for various fiber-reinforced composite systems. The elastomeric material system used is a polyurethane with a tensile modulus of 1,100 psi and a strain-to-failure of 400%. These properties differ significantly from conventional thermoset materials such as epoxy, which has a tensile modulus of 550,000 psi and a strain-to-failure of 1.5%. With these properties, the urethane matrix composite system is mechanically flexible and has high inherent energy dissipation as a result of the high damping loss factor (greater than 1.0) of the urethane. This magnitude of loss factor typically is at least an order of magnitude greater than conventional thermoset or thermoplastic resins that are used for composite construction. There are numerous naval structural components that could benefit from a material that is compliant, damage tolerant, and supports design structural loading.

Initial investigations looked at developing the processing methods to manufacture structural configurations with the polyurethane matrix material. The processing techniques that were demonstrated successfully included wet filament winding, resin transfer molding (RTM), vacuum-assisted resin transfer molding (VARTM), and prepreg manufacturing. These processing investigations resulted in two patents on the processing of the fiber-reinforced urethane (FRU).[1,2]

Investigations of Structural Components

The manufacturing success with this material form led to in-house investigation on its use for structural components. The initial component investigated was a compliant shaft coupling. The intent was to use the physical characteristics of the system to provide mechanical vibration damping of axial excitation while also allowing for a misalignment, as well as taking advantage of the mechanical properties to transmit the design torque levels for scaled main propulsion shafting. For this application, a cylindrical braided carbon fiber preform was used as the structural constituent. The elastomeric material used to infiltrate this braid was Uniroyal Adiprene L-100.[3] The impregnation was accomplished using an RTM process. The resulting component possessed the appropriate structural characteristics of strength and stiffness and could undergo large global deformations, while simultaneously dissipating significant levels of mechanical vibration energy. Specifically, the coupling was designed with the following structural loading capabilities - a torsional requirement that results in a maximum shear stress of 8000 psi, and an axial stress of 2000 psi.

Quasi-static tests of this component with applied torque and axial loading successfully met requirements. The interesting aspect of the component was its failure mode. Failure of conventional composite materials typically is very energetic, occurring with a sudden release of energy. Most often the failure is accompanied by significant fiber breakage and delamination. With the FRU, failure occurred gracefully, with a gradual increase in angle of twist as the torque was continually applied. In the test to failure of the 12-inch-long coupling, one end was allowed to twist relative to the other fixed end until the limit switch was activated, which occurred at an angle of approximately 60 degrees. It should be noted that the coupling was still in one piece even after this amount of deformation and subsequent fiber failure..

The damping properties of the coupling were determined also. It was assumed that the use of the polyurethane matrix would provide significant attenuation of the axial vibration transmitted from the attached machinery. This creates problems because the energy can be transmitted to other portions of the ship hull, equipment, or the surrounding medium. Tests showed that the axial damping provided by this new coupling design was approximately two orders of magnitude greater than a baseline steel shaft section.[4]

Demonstration of the energy absorbing characteristics and relative ease of fabrication of the compliant coupling led to additional investigations on the energy absorption characteristics of this material, i.e., ballistic performance. The material form used for this test was a plate with dimensions of 24 in x 24 in x 1 in., made from 42 plies of 24-oz, 5 x 5 S-2 glass fabric infiltrated with the Uniroyal Adiprene L-100. Panels were fabricated using an RTM process.

In composite ballistic design, the material constituents are chosen to allow the fibers to significantly strain when the system is subjected to high impact energy. In conventional composites, this occurs by allowing the fabric plies to delaminate. The delaminated panel can then globally deform to the maximum extent, dissipating significant energy levels. With the FRU panels, it was thought that global fabric deformation could occur with minimal delamination and without spalling. If delamination is minimized then structural characteristics are not significantly degraded. Also, the FRU should provide significant attenuation of the resulting mechanical shock wave that results from the impact, reducing the resultant severity of the ballistic event. This attenuation occurs by virtue of the viscoelastic properties of the matrix material and the constraint provided by the fibers. In addition, there is significant interference of the shock wave from the interfaces that occur in the composite and the difference in the elastic properties between the fibers and matrix.

V_{50} ballistic tests were conducted by the U.S. Army Research Laboratory in Watertown, MA.[5] There was a marked difference in the size and type of damage between a conventional composite system and the FRU. The conventional composite material absorbs energy by the creation and propagation of damage. In these laminated composite materials, the damage that is created is primarily delamination. At the V_{50} velocities, the delamination size is typically larger than 10 in. in diameter.[5] The 50-caliber fragment that is used for the impact is approximately 1 in. in diameter. The visible damage created in the FRU panels was only minimally larger than the fragment diameter. In fact, the FRU panel was subjected to ballistic impacts that were approximately 4.5 in. center-to-center. Each of the two FRU panels that were tested had a minimum of eight penetrations, and the visible damage from these penetrations did not coalesce. Therefore, the FRU material configuration exhibited tremendous multi-hit capability.

Additionally, at high impact velocities where complete penetration occurred, there was no hole and minimal material was removed. This was demonstrated by the inability to pass a 0.040-in. diameter drill through the impacted site. For a ballistic panel using a conventional matrix material, a 50-caliber penetration removes enough material to leave a finger-sized hole. This reduction or elimination of spalling is a significant advantage for armor plating, because any material that spalls into the compartment can cause serious injury or death to personnel.

The use of this material as a damping treatment was investigated as part of the Division's research effort on this material. One technique used to protect a material from damage and enhance its mechanical vibration damping is through the incorporation of a free layer of viscoelastic material. It is well known that the constrained layer damping configuration is an efficient method of damping for structural applications.[7-11] However, for structurally critical designs, such a treatment is parasitic and can detract from an efficient design, especially if the structure is required to support bending loads. If a FRU free layer is used instead, the damping treatment would not structurally detract from component performance, as long as the system loss factor was equivalent to a conventional free layer. Testing showed that the use of fiber-reinforced urethane material as a free layer provides levels of damping that exceed that which could be expected from a typical treatment of unreinforced urethane (Figure 1). In addition, it was shown that the low frequencies exhibited very high damping, which is typically not realized in the use of free layer damping treatments. Tests of the FRU in this configuration showed that the system damping contributions come from the damping properties of the viscoelastic material itself as well as from a "micro-constrained layer damping" mechanism.[6]

Technology Transitions to Industry

Bumper Systems

Success of the in-house work led to the submission of an Small Business Innovation Research (SBIR) solicitation to use this material for the design of a new fender system for ships. From the success of a resulting Phase I contract effort, a Phase II contract was awarded to Production Products Manufacturing and Sales (PPMS) for the development of an elastomeric composite fender using the fiber-reinforced urethane material system developed at NSWCCD. The filament winding manufacturing technique was transferred from NSWCCD to PPMS for their fabrication of this new fender system

In this Phase II program, PPMS completed the engineering evaluation of an Elastomeric Composite (EMC) bumper system based on initial work performed at the Division. This system included a smart bumper (actively controlled with a hydraulic valve), a passive bumper (hydraulic energy absorption with no moving parts, lower cost), and bumper design software. The software allows for the design of a bumper system with a tailored load stroke curve for specific pier installations and sizes of ships by selecting orifice sizes for these specific applications. The Phase II Program included design, fabrication, and development of 2- and 4-ft-diameter bumpers that can be used for a wide range of energy absorption applications and both Navy and commercial pier and harbor installations (Figure 2). The computer control enabled PPMS to provide detailed engineering design and data generation to allow tailored design of the EMC bumpers to meet any bumper design requirements with the load stroke curve optimized and hull load minimized. PPMS also demonstrated the high abrasion resistance and damage tolerance of EMCs through a laboratory test program. The program culminated in the structural evaluation of a full-scale EMC bumper system with the best features arising from the engineering prototype evaluation. Two joint patents were issued on the design and manufacture of the fender system.[12,13]

The full-scale bumper system tests verified the bumper design software as a viable design tool and demonstrated that the passive and smart bumper systems exceed the energy absorption capability of conventional bumper systems.[14] The stiffness of the conventional fender was approximately four times that of the passive bumper. This increased stiffness caused higher hull loading than the passive bumper, and the higher load/lower stroke increases the chances of hull or pier damage. Furthermore, the large hysteresis during unloading of the passive bumper caused less rebounding of the ship than occurred with conventional fenders. The software tool developed in the SBIR provides a useful tool to design ship bumpers. PPMS will pursue marketing in the marine industry of the hardware and software through Svedala Trellex who has provided technical guidance and support on this program for Phase III transitioning.

The results of initial tests on the hydraulic fender (smart bumper) have

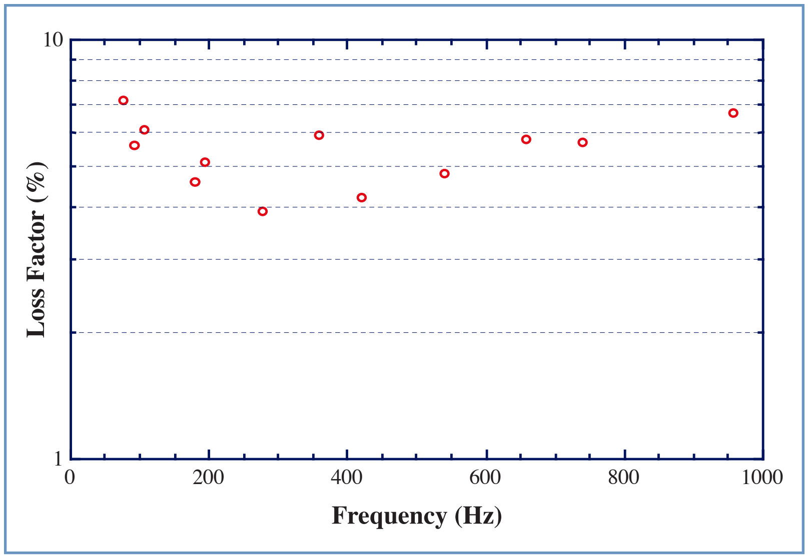


Figure 1. Damping loss factor for S-2 glass/urethane composite plate.

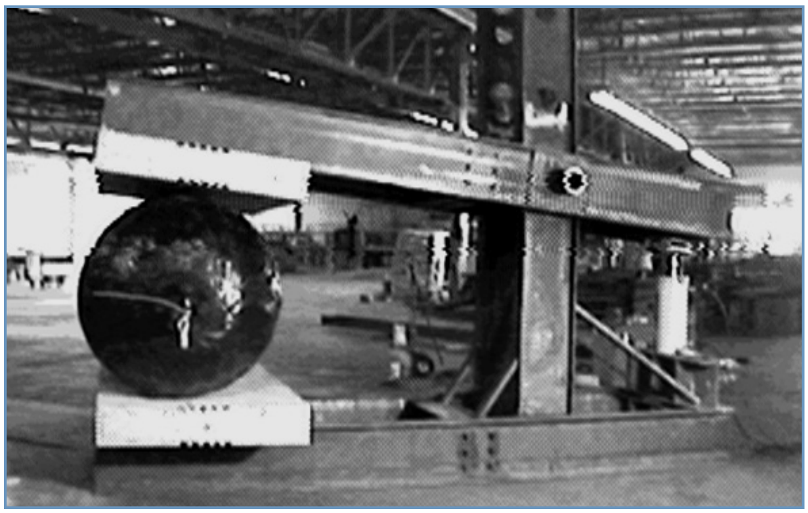


Figure 2. Full-scale 4-ft-diameter bumper test setup, side view.

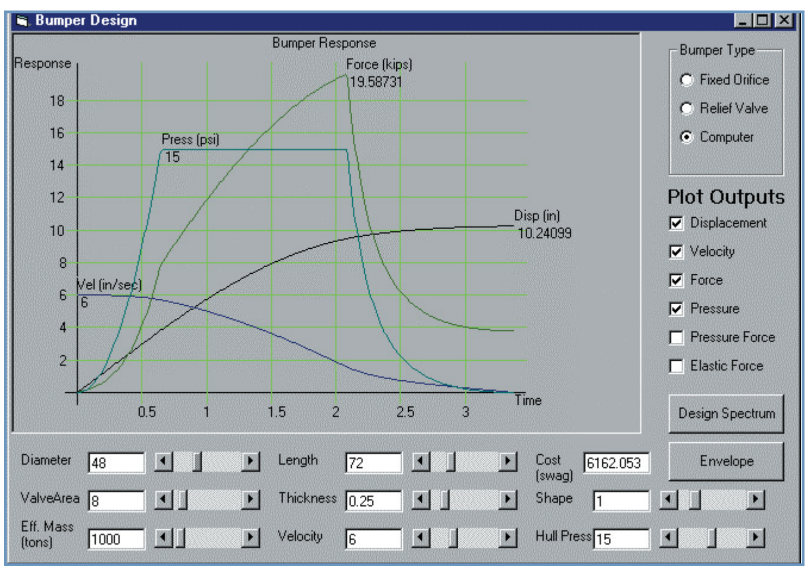


Figure 3. Bumper design computer model program screen.

demonstrated the potential of this system to produce a more effective fendering system using glass-reinforced polyurethane composites. By controlling the force/displacement history to approach an optimal shape that can be modified automatically given the mass and velocity of the docking ship, a single fendering system will be able to handle a wide range of ships while minimizing the maximum force on the dock structure. PPMS has continued to refine the hardware and control algorithm to gain a full understanding of the response of the system and develop rules to scale the prototype to the full-scale system. A sample of the design software for a 1000-ton ship with an initial berthing speed of 6 knots is shown in Figure 3.

The design envelope algorithm selects effective mass values incrementally from 200 to 10,000 tons. Velocity is increased incrementally for each mass, and each case is analyzed until a velocity value is reached which violates one of the design parameters -allowable displacement or hull pressure. The envelope is drawn at the maximum allowable velocity for the given mass.

The new filament-wound, elastomeric composite bumper design is lightweight, affordable, durable, environmentally superior, and offers significant operational advantages because of its lightweight, long life, and energy absorption. The lower cost passive smart bumper answers the needs for the low end of the bumper market, and the bumbers can be produced in larger or smaller sizes if the market shows a need. The advantage of the PPMS smart bumper is that it handles a large range of ship sizes and velocities, yet minimizes the load on the ship and any potential damage. This provides a large range of energy absorption capability with a standard bumper size, minimizing the logistics of having to manufacture, distribute, and store a large number of different products. In conclusion, the hydraulic bumper systems developed in this program have lower hull pressure, larger deflection capability, a tailorable load/stoke curve for various harbor installations (orifice size can be selected for specific installations/sizes of ships using the bumper design software developed in this program), and have less rebound of the ship than current Navy bumpers.

Automotive Crush Tubes

An investigation to compare the performance of the FRU to conventional composite materials for use as flange tube support structures was undertaken because of the large elastic deformations possible with the urethane matrix composite material. Intense research has been conducted on the integration of composite structures in automotive applications for impact resistance and crash worthiness. The structure of the automobile must be able to absorb impact energies involving large deformations and overall durability, without transferring the energy to the engine or passenger compartments, and must simultaneously ensure solid ride characteristics under the aspects of noise, vibration, and stiffness. The integration of these demands requires that a component be designed to provide the structural performance required and to fail through a sequence of predetermined failure mechanisms that would absorb crush energy.

In comparison to metals, most composites used for such applications are characterized by brittle rather than ductile behavior. The major difference, however, is that metal structures collapse by buckling and folding in an accordion-like fashion causing extensive plastic deformation. Composites fail through a sequence of fracture mechanisms that include fiber failure, matrix crazing and cracking, fiber-matrix debonding, kinking, and delamination. While significant research has been conducted in the generic area of damage mechanisms, a comprehensive understanding of the sequence and contribution to energy absorption from these various mechanisms has not yet been achieved. The primary objective of this study was to investigate the crush behavior of a flanged tube structure with an e1astomeric matrix system. The results are related to earlier studies with a more traditional vinyl ester matrix to provide a base for further studies on materials selections and fiber architecture.

Four different types of specimens were investigated, a baseline conventional composite and three FRU configurations. The baseline crush tube was manufactured using an E-glass/vinyl-ester material system with a fiber orientation of ±45 degrees made using the RTM process. The three FRU crush tube configurations investigated had fiber orientations of ±45, ±80, and ±10/90 degrees. All of these E-glass/polyurethane tubes were manufactured using a filament winding technique.

It was observed that the polyurethane specimens exhibit a ductile crush behavior different from the traditional brittle composite crush experiments (Figure 4). The elastomeric specimens remained as one part, and very little material was jettisoned from the test cylinders. The tubes rebound, sometimes dramatically, after the crush load has been removed. The comparison of the critical values for the

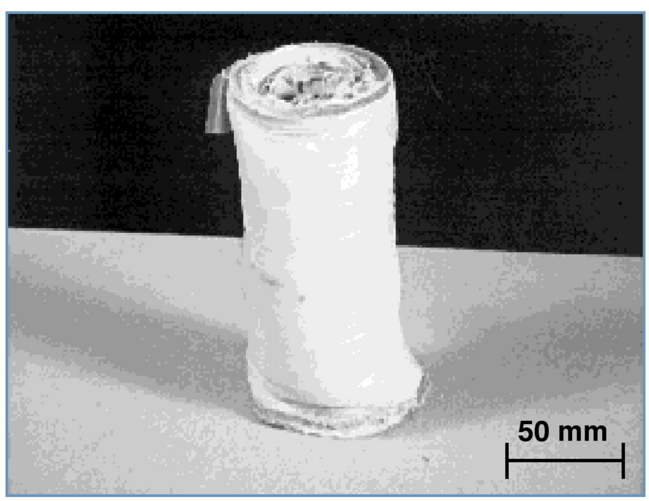


Figure 4: Image of crushed glass/polyurethane specimen RC 2A (±80 degrees).

crush specimens shows that the performance depends heavily on the fiber orientation of the filament-wound section. Similar fiber orientations showed that the values for the polyurethane parts approach the vinyl ester baseline performance. Of particular importance, the mean crush stress actually reaches the baseline value.

Several potential advantages for polyurethane-covered crush structures may increase the attractiveness for this hybrid material concept. It has the ability to protect a brittle, crush-energy absorbing core structure from stone throws or other external damage due to its superior impact tolerance. Also, it can keep the crush structure together and thus reduce the costs associated with post-crush repairs on a vehicle. The data obtained in this exploratory study showed encouraging results and will hopefully open the door for additional research projects to optimize these hybrid structures. Detailed test results are reported elsewhere.[15]

Vibration Isolation Mount

The investigation of the energy absorbing characteristics of the FRU led to an investigation of the use of the material for components of a vibration isolation mount. Proposals were solicited for a Phase I SBIR to develop a new design to take advantage of the mechanical characteristics of the FRU. Success in this effort has led to a Phase II program, which will fully qualify the mounts for general Navy use. Initially, the mounts will be installed and tested on DDG 86.

For this effort, the RTM processing technology was transitioned from the Division to PPMS. It was shown that a prototype mount developed in Phase I could support a wider range of static loads than any existing single mount. The new mount also outperformed existing mounts over the range of loads. For example, over the static load range of 350 to 2000 lb, the *single* prototype mount has a natural frequency of approximately 5 Hz, which is between 1.5 and 6 Hz lower than that achieved using three mounts from the Engineering Experimentation Station family of mounts (6 series). This constant lower frequency provides reduced vibrational energy transfer. An example of the frequency performance for one of the designs is shown in Figure 5. Figure 6 shows the configuration of the mount designed in Phase I.

The objective of the Phase II program is to transition the analytical and experimental findings of the Phase I effort into a second-generation mount system for a family of mounts. The family of mounts will be designed, fabricated, and characterized to determine their static and dynamic properties. Shock and vibration tests will be used to verify performance predictions. PPMS will manufacture and qualify vibration mounts for sea trials by the Navy and for commercial applications. PPMS also will design and analyze one mount for shock mitigation to verify the use of elastomeric composites in shock applications. The successful development of multi-performance composite mounts will reduce inventoried items and attendant logistics costs, reduce individual mount costs due to fewer fabricated parts, permit standardized installation and maintenance procedures and reduce associated costs, eliminate corrosion-induced failures of mounts, provide significantly longer service life and reduced maintenance costs, and provide significant weight savings and enhanced vibration and shock isolation performance.

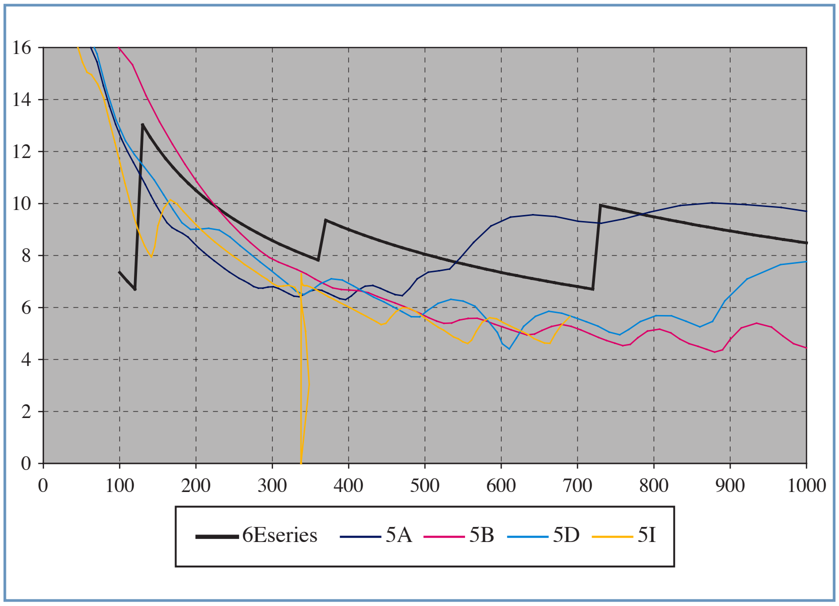


Figure 5. Comparison of multiweight performance of new designs versus existing six series mounts.

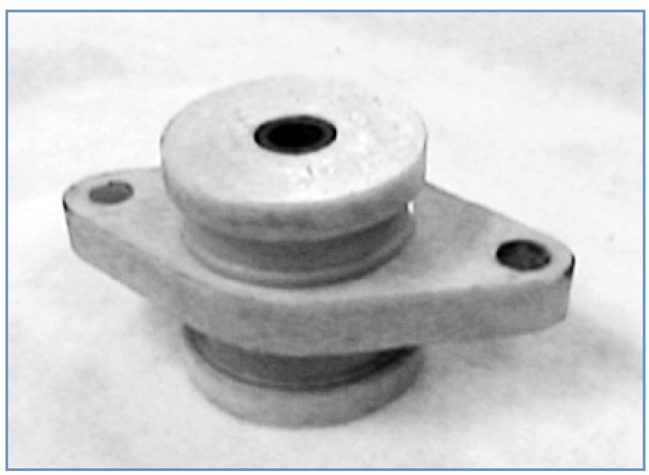


Figure 6. FRU vibration isolation mount designed and manufactured for naval applications.

Stanchions

Replacement of metal stanchions is the final area being pursued for application of urethane matrix composite materials. These components serve as the vertical structural element of most shipboard railing systems. Stanchion-supported horizontal cables provide a ship's crew with safety barriers along deck edges, platforms, and elevators.

While widely used, the current steel design of metal stanchions has several serious shortcomings. Considerable maintenance is required to prevent corrosion of the steel. In addition, the metal posts contribute significantly to a ship's radar cross-section, and are a source of electromagnetic interference when positioned near radar systems. Along an aircraft carrier's elevator, moving stanchions are designed to recess into the deck when the elevator is up and rise to provide a railing when the elevator is down. The current steel stanchions can be bent permanently when bumped by deck equipment, causing the elevator to become inoperable. A stanchion that returns to its undeformed position after a minor bump is highly desirable.

NSWCCD conducted an experimental effort to manufacture FRU stanchion components. The stanchions were filament-wound and exhibited large elastomeric global deformations, which would alleviate the elevator door deformation problem identified earlier. The cost of the stanchions that were made became an issue.

To address the high cost caused by traditional fiber layup techniques, a Phase I SBIR was initiated to determine if the urethane material could be used in a pultrusion process to manufacture stanchions with the appropriate structural and physical properties. The pultrusion process is the only manufacturing method that can reduce the acquisition cost of the composite polyurethane stanchions to a level of economic acceptability.

KaZak Composites successfully demonstrated a pultrudable configuration in their Phase I effort that met all of the design criteria for the application. This effort has been transitioned to a Phase II SBIR that began in the summer of 2000. The goals of this program are to develop a stanchion configuration with a bending stiffness, EI, large enough to replace the steel stanchion tube and meet the requirement to carry a 300-lb tip load with a small deflection. At a predesigned load, this circular cross section would buckle elastically and allow the tip to deflect up to 45 degrees from the vertical position. The cross section would unbuckle when unloaded by virtue of the strain-to-failure characteristics of the urethane matrix material, and return to its original position. The elastic buckling characteristic of the urethane stanchion is shown in Figure 7.

This same stanchion was cycled between 0 and 30 degrees deflection 25 more times, with little change in load versus displacement history. Permanent deformation at the end of the cycling series was about 1.5 in. The stanchion was loaded to bending "failure"at the completion of the 25-cycle series. A load was applied until a cracking sound was heard as the tube reached an angle of about 40 degrees when measured from root to tip. The actual angle between the bent portion and the stanchion was greater than 45 degrees because the hinge that forms at large displacement actually is out from the base of the stanchion by about 10 in. It is assumed that some internal delamination and debonding occurred (based on the popping noise that was heard at maximum deflection), but still the stanchion returned to approximately its initial horizontal orientation, and continued to carry significant load.

Two stanchions have been fabricated using the KaZak design and were installed on CVN73 in June 2001. They were taken off for minor repairs of the adhesive joint to the steel attachment fitting and were reinstalled in December 2001. In addition, Lakeshore Inc. has installed 4 stanchions on a Roll-On Roll-Off Discharge facility that they are manufacturing for the Army. This application is one where the stanchions are subject to bending damage from various obstacles. This in-service evaluation may lead to further implementatin on other components such as causeways and the modular warping tug.

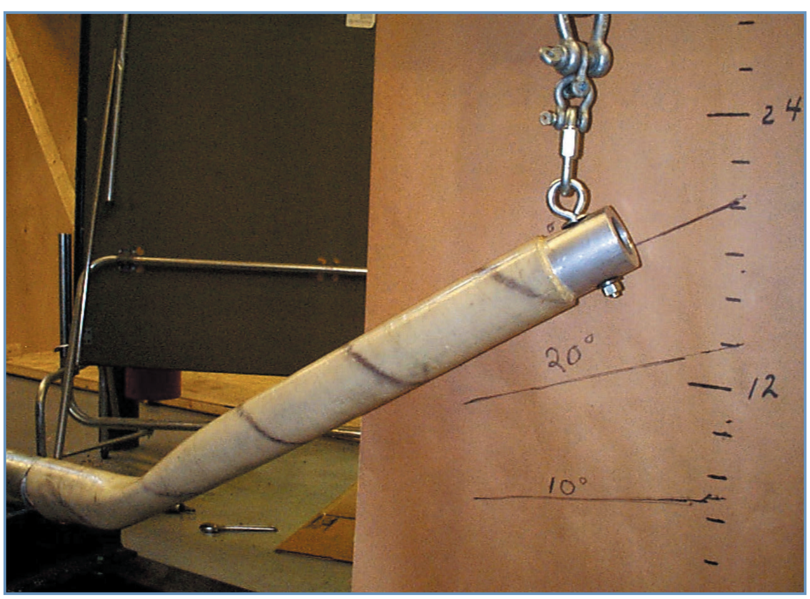


Figure 7. FRU stanchion deflected to 30 degrees by buckling at lower end.

Summary

NSWCCD has developed a novel composite system with mechanical properties significantly different from conventional thermoset composite systems. There are numerous composite applications that can be developed for naval applications that require these mechanical properties. By working closely with industry and through the transition of the manufacturing and mechanical property information, several applications have been developed that will be used for ship components. This development exemplifies the success that can occur with solid working relationships between government and industry.

Acknowledgements

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References

1. Crane, R.M., et al, "Filament Winding and Resin Transfer Molding of Large Strain to Failure Matrix Systems for Fabrication of Flexible High Damping Composite Structures," U.S. Patent 5,654,053 (5 Aug 1997).

2. Crane, R.M., and P.A.Coffin, "Flexible High Damping Structures," U.S. Patent 5,308,675 (3 May 1994).

3. Dupont Technical Publication AP-220.L100, Adiprene L-100, www.uniroyalchemical.com/adiprene.htm

4. Crane R.M., and C.P. Ratcliffe, "Graphite/Polyurethane Flexible Composites - Mechanical and Vibration Damping Properties," CARDIVNSWC-TR-601-93/02 (July 1993).

5. Chou, S.C., and E. DeLuca, "Dynamic Response of S-2 Glass Reinforced Plastic Structural Armor, A Progress Report," Army Research Laboratory Report ARL-SR-5 (1993).

6. Crane, R.M., et al, "Structural and Damping Characteristics of a Flexible Composite Structure," *Materials for Noise and Vibration Control*, ASME Winter Annual Meeting, NCA-Vol. 18, DE-Vol. 80 (1994).

7. Kerwin, E.M., Jr., "Damping of Flexural Waves by a Constrained Viscoelastic Layer," *Journal of Acoustical Society of America*, Vol. 31, No. 7 (1959).

8. Plunkett, R., and C.T. Lee, "Length Optimization for constrained Viscoelastic Layer damping," *Journal of Acoustical Society of America*, Vol. 48, No. 1(2) (1970).

9. Torvik, P.J., and D.Z. Strickland, "Damping Additions for Plates using Constrained Viscoelastic Layers," *Journal of Acoustical Society of America*, Vol. 51, No. 3(2) (1972).

10. Ungar, E.E., "Loss Factors of Viscoelastically Damped Beam Structures," *Journal of Acoustical Society of America*, Vol. 34, No. 8 (1962).

11. Ungar, E.E., "A Guide to Designing Highly Damped Structures using Layers of Viscoelastic Material," *Machine Design* (1963).

12. Crane, R.M., et al, "Tailorable Elastomeric Composite System for Absorbing High Energy Impact," U.S. Patent 6,053,644 (25 Apr 2000).

13. Slattery, K.J., et al, "Tailorable Elastomeric Composite Pneumatic Fender System for Absorbing High Energy Impact, and Manufacture," Navy Case 79,245 (16 Aug 1998).

14. Corona-Bittick , K., "Elastomeric Composite Bumpers," Production Products Manufacturing and Sales, Contract N00014-97-C-0117 (17 Feb 1999).

15. Steiner, K.V., and R.M. Crane, "An Evaluation of Elastomeric Matrix Composites for Crush-Energy Absorbing Structures," 29th ISATA Conference, Florence, Italy(June 1996).

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Corrosion Control For Submarine Trim and Drain Piping System

Richard A. Hays and David A. Shifler

Corrosion in the forward drain system piping on submarines has resulted in at-sea failures and has impacted ships' operations. Metallurgical analyses of pipe sections removed from service identified the failure mechanism to be poultice corrosion enhanced by the presence of sulfides and high flow rates or excessive turbulence. A variety of methods to mitigate the corrosion including water treatment, materials substitution, coatings, and cathodic protection were investigated. The most attractive corrosion control method from logistics and cost standpoints is to apply coatings to the inside diameters of the piping runs. A flexible extension for a standard commercial powder-coating gun was developed to apply coatings to internal piping surfaces. This extension allows application of heat-cured epoxy powder coatings to piping runs up to 6 ft in length that contain multiple short-radius elbows. Implementation of the coating process is estimated to result in cost savings of approximately $0.5M per year and ensure operational readiness of the Fleet.

Introduction

Routine wall thickness monitoring of submarine forward drain system piping identified unexpectedly high rates of wall loss in localized areas. In some cases, the localized corrosion actually penetrated the pipe wall (Figure 1). As a result, the Naval Sea Systems Command tasked NSWCCD to determine the degradation mechanism and develop a cost-effective method to correct the problem.

The drain system operates intermittently and carries graywater containing a relatively high level of organic solids. The lack of corrosion in similar systems, which carry only seawater, indicated that the operation and/or environment in the drain system contributed significantly to corrosion susceptibility. Accelerated corrosion mechanisms consistent with this observation included sulfide-induced corrosion and under-deposit (or poultice) corrosion. High flow rates or excessive turbulence may have exacerbated corrosion by removing naturally forming protective corrosion product layers.

The appearance of the corrosion product films indicated that the pitting primarily initiated on the bottom of horizontal piping runs where debris could readily accumulate. A ready source of organic material and the intermittent use of the system contributed to the accumulation of deposits, leading to putrification and generation of sulfides. Copper-nickel (Cu-Ni) alloys are susceptible to accelerated corrosion in seawater containing high sulfide, low pH concentrations, and high total organics.[1] Under-deposit attack or "poultice" corrosion may occur when a metal is locally covered by foreign, absorbent (organic or inorganic) materials.[2,3] In this case, attack can proceed even when the bulk of the system is dry due to retention of moisture in the poultice. The corrosion mechanism is similar to crevice corrosion and is caused by chemical attack and/or by galvanic interactions between the relatively noble area outside the deposit and the active area under the deposit. Identifying the degradation mechanisms led to an approach to mitigate the wall loss of the current copper-nickel piping.

Figure 1. Localized corrosion in forward drain system piping.

Approach

A multi-faceted approach was implemented to find and adapt or develop methods to control the corrosion in the drain piping system. Commercial practices to control corrosion in piping systems similar to the drain system from material and environmental perspectives were reviewed. Specific industries of interest included offshore oil, conventional and nuclear utilities, commercial maritime, and waste processing. The most promising corrosion control technique was selected after this review. Adaptation and process development of the selected technology for Navy applications followed. Once the process parameters for the corrosion mitigation method were optimized, land-based testing to verify effectiveness of this corrosion control technique in a simulated drain piping environment was implemented and compared with other possible control techniques.

Organic coatings were evaluated as a means to control the corrosion occurring in the drain system for three reasons. First, coatings have been used successfully to control corrosion and erosion in selected areas of other seawater handling systems on submarines and surface ships, as well as in many industrial applications. Second, submarine maintenance activities are experienced in applying coatings. The ability to perform the coating process in-house would permit the maintenance activities to control the process and schedule. Third, coating existing pipe sections would eliminate the cost and schedule concerns of new material procurement and result in the most cost-effective method to mitigate the corrosion (Figure 2). The primary obstacle to the use of organic coatings was the lack of ability to apply high quality coatings to complex piping runs such as the forward drain system that contain multiple elbows, bends, and components (Figure 3).

Results

Current commercial practices to mitigate corrosion in similar systems including water treatment, cathodic protection (CP), materials substitution, and coatings were investigated. Water treatment processes involve adding chemicals that promote more protective oxides, inhibit corrosion, or reduce the corrosivity of fluids running through the drain piping. Oxidizers, inhibitors, biocides, or chemicals that induce precipitation reactions in the environment were considered. Water treatment was rejected as a viable corrosion control method due to concerns regarding compatibility with non-metallic components, handling, storage, environmental discharge, and increased sailor burden.

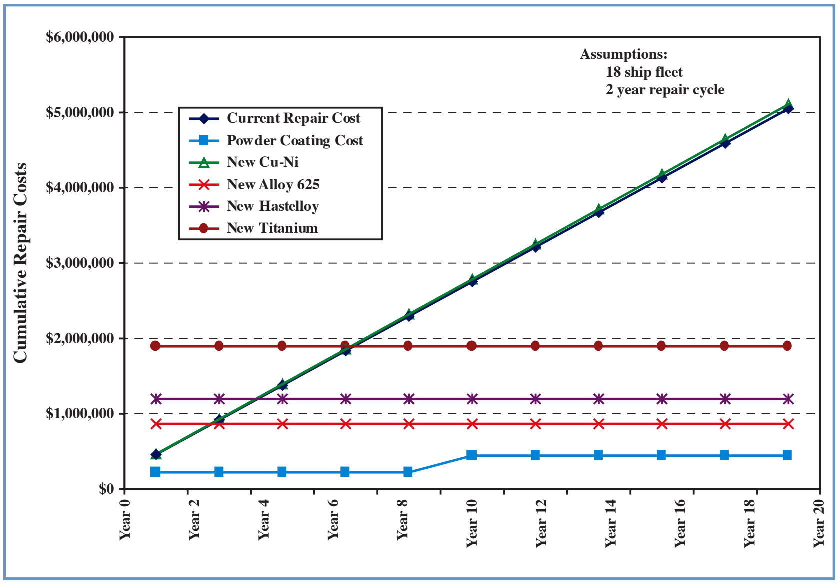

Figure 2. Cost analysis for various corrosion control methods.

Cathodic protection of suspect areas was considered but rejected. Sacrificial anodes could interfere with fluid flow in the pipe and possibly initiate erosion-related degradation at new sites. Both sacrificial and impressed current CP may have throwing power limitations and would be ineffective at any unwetted piping surfaces.

Materials substitution involves replacing the 70/30 Cu-Ni piping with a more corrosion-resistant piping material such as Alloy 625 or titanium. These corrosion-resistant materials have a higher procurement cost than 70/30 Cu-Ni piping and could introduce galvanic corrosion with other piping or piping system components. A cost analysis to introduce these alternative materials was conducted based on the costs of the piping and a constant installation labor cost (Figure 2). In addition to cost and galvanic corrosion concerns, long lead times for material procurement were a concern when using more corrosion-resistant piping materials.

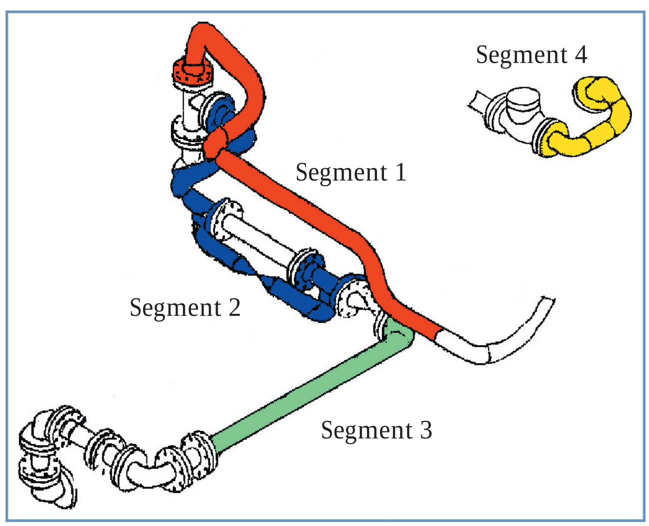

Figure 3. Isometric drawing of drain system (colored areas to be coated).

A survey of industrial pipe coating applicators showed that most internal diameter (ID) applications are performed on relatively large diameter, straight runs of new pipe prior to service. While two vendors provided samples of coatings on short pipe sections with elbows, the benefits of having an in-house capability and the uncertainty associated with the vendor's ability to apply coatings to longer, more complicated sections resulted in a decision to develop a process specifically for the drain system. Requirements for the process included:

- Ability to clean and prepare ID surfaces of complex piping runs up to 6 ft in length that contain multiple elbows and bends
- Application of coating system with proven service performance
- Ability to be performed at the maintenance activities with minimal investment in equipment
- Quality assurance procedures.

Given these requirements, the use of an electrostatically applied, heat-cured powder epoxy used for repair of valves, flanges, and other seawater system components was investigated for the drain piping application. Electrostatic application provides relatively uniform film coverage and buildup with the added benefit of the ability to provide this coverage to complex shapes.[4]

Cleaning of the internal diameters of the pipe sections was achieved by grit blasting with commercially available ID blast nozzles (Figure 4) using 80-grit aluminum oxide. Boroscopic examination was used to visually confirm cleanliness, and deformable tape was used to measure the surface profile. Blast pressures of 80 psi consistently provided adequate cleanliness and surface profiles in the range of 2 to 3 mils.

Initial tests of the powder epoxy application were performed using standard equipment on short runs (approximately 18 in. long) of 3-in.-diameter pipe containing a single, short-radius elbow. The standard spray gun has a rigid nozzle and cannot be inserted into the pipe beyond a bend; therefore, high airflow, powder feed rates, and electrostatic charge voltages were used in an attempt to ensure complete coverage. However, holidays and non-uniform coverage occurred in the vicinity of the elbow. Additional tests indicated that good coverage could be achieved when the electrode located in the tip of the applicator was proximate to the area of pipe to be coated. Therefore, a decision was made to design and build a flexible extension for the spray gun that could be inserted throughout the entire pipe assembly.

The prototype flexible extension was manufactured using 1-in.-diameter vinyl tubing as the powder carrier, because it was readily available and easily adapted to the existing spray gun. The extension was inserted easily through the most complex piping sections including piping Segments 2 and 4, and full coverage of the coating was achieved using lower airflows, powder feed rates, and electrostatic charge voltages. However, the vinyl tubing could not withstand the 400 °F application temperature. The current flexible extension (Figure 5) is constructed of flexible polytetrafluoroethlyene tubing capable of continuous operation at 500 °F and uses high voltage wire to reduce operator shock hazard. Components for the flexible extension can be procured for less than $500. Figure 6 shows the application of the coating to the piping Segment 2 assembly.

The coating application process is controlled by an Industrial Process Instruction, from initial pipe cleaning

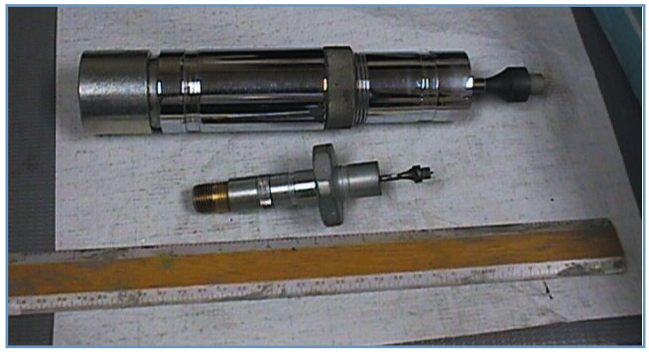

Figure 4. Pipe internal diameter grit-blasting nozzles.

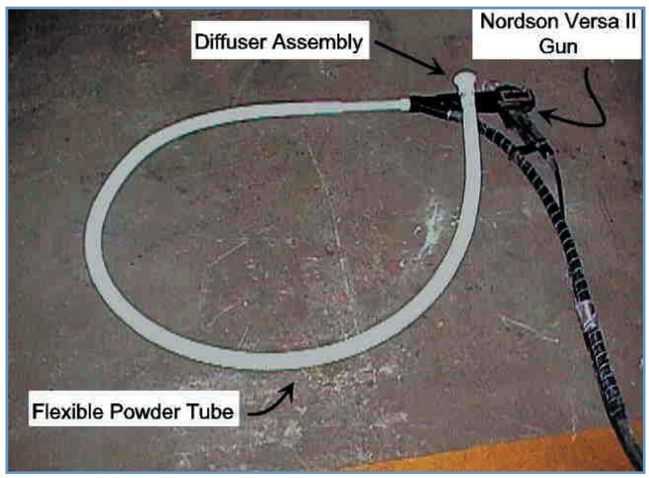

Figure 5. Flexible extension for powder spray gun.

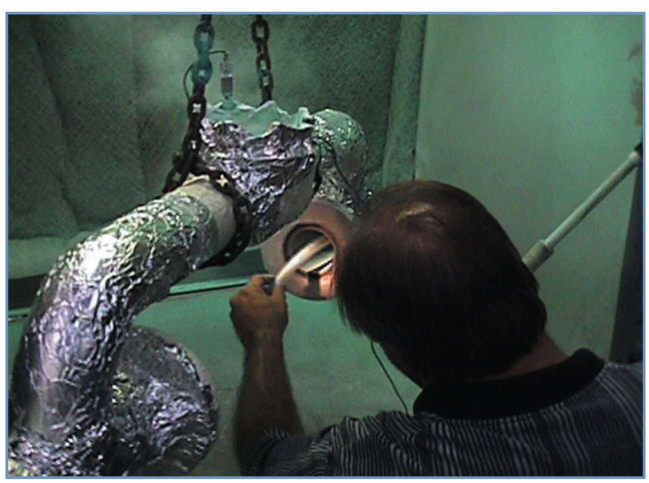

Figure 6. Coating of piping Segment 2 assembly with flexible extension.

through final quality assurance evaluations. This document provides a detailed description of the equipment, procedures, operator qualifications, safety, and occupational health requirements associated with coating trim and drain piping. Quality assurance is achieved through boroscopic examination of the pipe ID and by 100% inspection using a low voltage electrostatic holiday detector.

Summary

A procedure to coat the inside diameter of complex piping runs from a ship class forward drain system was developed to mitigate corrosion. To accomplish this, a unique, flexible extension for a powder-coating spray gun, capable of applying coatings around multiple piping elbows and bends, was designed and constructed enabling maintenance activities to perform the coating operation in-house. Currently, coated pipe sections are installed on three ships, and additional sections will be coated as they become available.

The use of coatings as opposed to other forms of corrosion control in this application is expected to result in savings of up to $4.5M over the next 20 years. Extending this technology to other systems and other ship classes has the potential to produce significantly greater maintenance cost savings.

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References

1. Efird, K.D., and T.S. Lee, *Corrosion*, Vol. 35, No. 79 (1979).

2. Hare, C.H., *Journal of Protective Coatings and Linings*, Vol. 15, No. 1, p. 67 (1998).

3. Fontana, M.G., and N.D. Greene, Corrosion Engineering, 2nd ed, McGraw-Hill, New York, NY, p. 39 (1978).

4. Munger, C.G., Corrosion Prevention by Protective Coatings, National Association of Corrosion Engineers, Houston, TX (1986).

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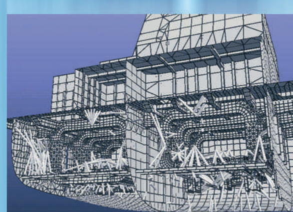
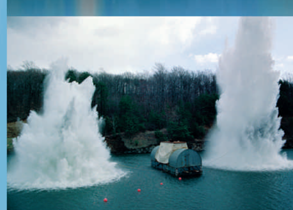
Vulnerability and Survivability

Overview Article Follows





TECHNICAL DIGEST

VULNERABILITY & SURVIVABILITY SYSTEMS

The Carderock Division provides the facilities and expertise to conduct full-spectrum RDT&E, design/acquisition support, life-cycle management, and in-service engineering of vulnerability and survivability systems for current and future surface ships, submarines, Marine Corps vehicles, and related applications which require improved survivability against weapons, shock hardened hulls and equipment, enhanced safety, improved ability to fight hurt, weight reduction, advanced hull forms, the ability to operate in shallow water in order to meet the changing threat, the ability to meet Congressionally mandated Live Fire Legislation, force protection, and affordability.

Vulnerability and Survivability Systems: An Overview

Fred J. Fisch

This paper presents an overview of ship protection principles and design features required to preserve hull integrity and system functioning after combat damage to maintain mission capability. Analysis methods to evaluate vulnerability-reduction design options, to assess the achievement of ship hardening design goals, and to support legislated Live Fire Test and Evaluation requirements are outlined also. Technical papers on recent achievements in vulnerability and survivability systems are presented, with a focus on technologies that have a significant impact on current acquisition programs and the Fleet. An extension of one key technology to non-military applications is also presented.

Introduction

Survivability of a combatant ship or submarine results from the integration of design features for reduced susceptibility and vulnerability and for post-hit recoverability. Susceptibility is the probability that the ship will be hit by a threat weapon. It encompasses active defense, countermeasures, and signature control features of the ship.

Vulnerability is the probability that the ship will lose some or all of its mission capabilities, or sink, when hit by a threat weapon. It focuses primarily on the immediate effects of the hit and how to minimize initial damage. Recoverability relates to the features of the ship designed to control and limit progressive damage, and to restore functional capability to the maximum possible extent. It encompasses time-based effects such as the spread of fires and smoke, flooding, and the progressive loss of function caused by these casualties, as well as damage control actions by the crew. The latter two are depicted graphically in Figure 1 as a survivability time line for a post-hit ship.

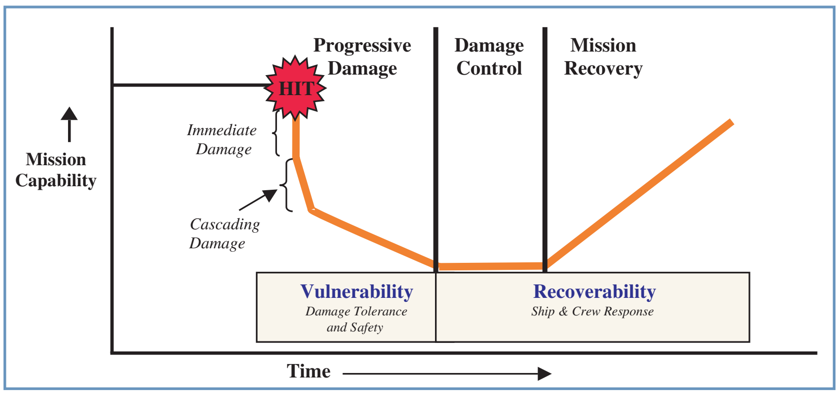


Figure 1. Ship Vulnerability Time Line

The survivability chain can be written as a probability equation in the following form:

$$S = 1 - P_h * P_{k/h} * (1 - P_{r/k}),$$

where S is the survival probability, P_h is the hit probability (susceptibility), $P_{k/h}$ is the kill probability given a hit (vulnerability), and $P_{r/k}$ is the probability of recovery given a kill (recoverability). $P_{k/h}$ and $P_{r/k}$ are explicit functions of time.

Traditionally, recoverability has been interpreted to mean damage control and restoration of critical functions. It also encompasses vulnerability reduction and hardening features. These are enabling factors for mission recoverability, because they enable containment and control of damage and set the stage for restoration of functions.

The remainder of this paper presents an overview of ship protection principles and general design features required to preserve hull integrity and system functioning after combat or accidental damage to maintain mission capability. The paper briefly addresses analysis methods to evaluate vulnerability reduction design options, to assess the achievement of ship-hardening design goals, and to support legislated Live Fire Test and Evaluation (LFT&E) requirements.

Elements of Ship Protection

Generally, the design of a survivable ship or submarine integrates features that make it difficult to detect, difficult to hit if detected, difficult to damage if hit, and easy to restore if damaged. The first two are functions of signature control, countermeasures, and active defenses and will not be addressed further in this paper. Signatures are addressed elsewhere in this Technical Digest. The latter two are the subject of this paper.

The objectives of ship and submarine protection are to preserve seaworthiness, mobility, and firepower. Vulnerability reduction design features that can be used to achieve these objectives are: compartmentation, arrangement and redundancy, armor, equipment hardening, firefighting and dewatering systems, and means to rapidly reconfigure distributed systems. These features build on and make use of developments in structures, materials, machinery, and damage control equipment and systems.

Compartmentation is subdividing the interior volume of the platform to limit flooding and maintain stability after damage, to retard the spread of fire and smoke, and to contain explosion blast pressure.

Navy buoyancy and stability standards require that surface combatant ships be able to withstand flooding from a hull opening equal to 15% of the ship's waterline length, located anywhere along the hull, without sinking or capsizing. This design standard, derived from extensive battle damage and accident experience, has recently been revalidated for modern ship designs through a series of hydrodynamic model tests.

Arrangement includes features such as redundancy and separation of vital systems, including damage control systems, isolation and separation of energetic materials and systems, and protection of critical components with less vital equipment. Redundant (parallel) components/systems should be separated to the maximum extent possible to minimize the likelihood of damage to all from a single hit. Conversely, series components/systems should be consolidated to reduce the total exposure, because damage to any one component kills the system.

The vulnerability impacts of alternative arrangement options are examined continually during the design cycle to obtain the best overall solution to meet the specified performance requirements within the context of the total platform design. Vulnerability analysis methods and computer codes developed by the Naval Surface Warfare Center, Carderock Division are used by engineers and analysts routinely in concert with cost impact data to support the assessment of design alternatives.

Structural protection features consist of ballistic armor, underwater protection systems, watertight bulkheads, blast- and fire-resistant bulkheads, decks, doors and hatches, damage tolerant primary structure, and hardened topside structures.

A method developed by the Carderock Division to increase the blast resistance of internal bulkheads with low cost and weight impact has been adopted as the Navy design standard for combatant ships. This concept is being incorporated into the DDG 51 Flight IIA (DDG 79 and beyond) and LPD-17 Class ships, and is being considered for other new designs. Figure 2 shows a successful full-scale test of a representative hull section with blast-hardened transverse bulkheads and box girders to preserve longitudinal strength. Watertight door concepts with increased blast resistance have been developed and tested also. This technology has found application in the civilian sector in support of the Federal Aviation Administration (FAA) Commercial Aircraft Hardening Program mandated by Congress as a result of the Pan Am 103 bombing. Carderock Division engineers recently designed, fabricated, tested, patented, and delivered an explosive containment device to the FAA for airport security.

Figure 2. Hardened Structure Test.

Figure 3. WINSTON S. CHURCHILL (DDG 81) Shock Trial

Equipment hardening increases the ruggedness of components against air blast and underwater explosion shock, heat from fire or nuclear thermal pulse, armoring against fragments, and protection against electromagnetic effects.

Carderock Division historically has supported Navy ship and submarine shock-hardening requirements through development of standards, test procedures, conducting shock tests of individual equipment, system assemblies and full ships, and development of shock isolation systems. Figure 3 shows the June 2001 shock trial of WINSTON S. CHURCHILL (DDG 81). The Division was responsible for a significant portion of this trial, including explosives operations and shock response instrumentation and analysis, and has participated in the planning and execution of every Navy shock trial since the 1960's.

It is not possible to make a combatant ship or submarine invulnerable to the damaging effects of modern weapons. Priority consideration should be given to design features that prevent catastrophic loss of the platform or critical functions and improve the probability of survival of each function against weapon hits. The overall goal is to provide balanced protection against the spectrum of threats specified for the design.

Analysis Methodology

Combatant ships and submarines are not only complex systems they are also system complexes. Consequently, their design is an iterative process that includes a series of design trade-offs and compromises to achieve platform performance and cost goals. Vulnerability analyses are conducted as the design progresses from early concept to the as-built platform to evaluate the benefit of vulnerability reduction design options, assess the achievement of hardening design goals, and support legislated LFT&E requirements.

These analysis tools range from low fidelity methods designed to conduct rapid comparisons to high fidelity physics-based computer codes employing finite difference (hydrocodes) and finite element methods. The latter are deterministic methods that require a high level of detail and are best employed for detailed analysis of specific problems rather than overall vulnerability assessments. The most widely employed tools are moderate-fidelity codes based on engineering level damage prediction algorithms. These codes are sufficiently sensitive to ship/submarine design features to allow analysis of design alternatives with a degree of accuracy appropriate for the level of design detail.

Carderock Division has a long history in the development and application of modeling and simulation-based vulnerability analysis methods to support platform design and operational assessments, and to assess the lethality of our own U.S. and allied nations weapons against their intended ship and submarine targets. Vulnerability analysis codes currently in use are the Ship Vulnerability Model (SVM) and the Fast SVM to support ship design, and the Submarine Vulnerability Evaluation Model (SUBVEM) to assess submarine vulnerability and the effectiveness of antisubmarine warfare weapons. A new explicit time-dependent vulnerability code, the Advanced Survivability Assessment Program (ASAP), is in the final stage of development. This code is designed to address all phases of the ship vulnerability time line of Figure 1, from initial weapon hit, through damage control, to recovery of some level of mission capability. These codes have been applied by Division engineers extensively to support Navy acquisition programs and to assess the effectiveness of joint service weapons. The antiship/antisubmarine weapons lethality data contained in the Joint Munitions Effectiveness Manuals (JMEMs) used by war fighters to plan attacks and to support munitions inventory requirements have been developed by Carderock Division weapons effects analysts.

Live Fire Test and Evaluation

The requirement for full system-level live fire testing of major systems was legislated by Congress in 1986 *(Title X U.S. Code Section 2366. Major systems and munitions programs: survivability testing and lethality testing required before full-scale production)*, commonly known as the "Live Fire Law." Navy ship and submarine acquisition programs come under its purview. While the law requires realistic testing of the system as configured for combat, against the threats it is expected to face, it also provides for live fire tests to be conducted by other means when such tests would be unreasonably expensive or impractical (the so called "waiver provision"). This generally applies in the case of ships and submarines. With the approval of the Secretary of Defense, a ship or submarine acquisition program can satisfy the live fire requirement through a combination of modeling and simulation-based analysis, component and surrogate tests, ship shock trials, and total ship survivability trials based on simulated damage.

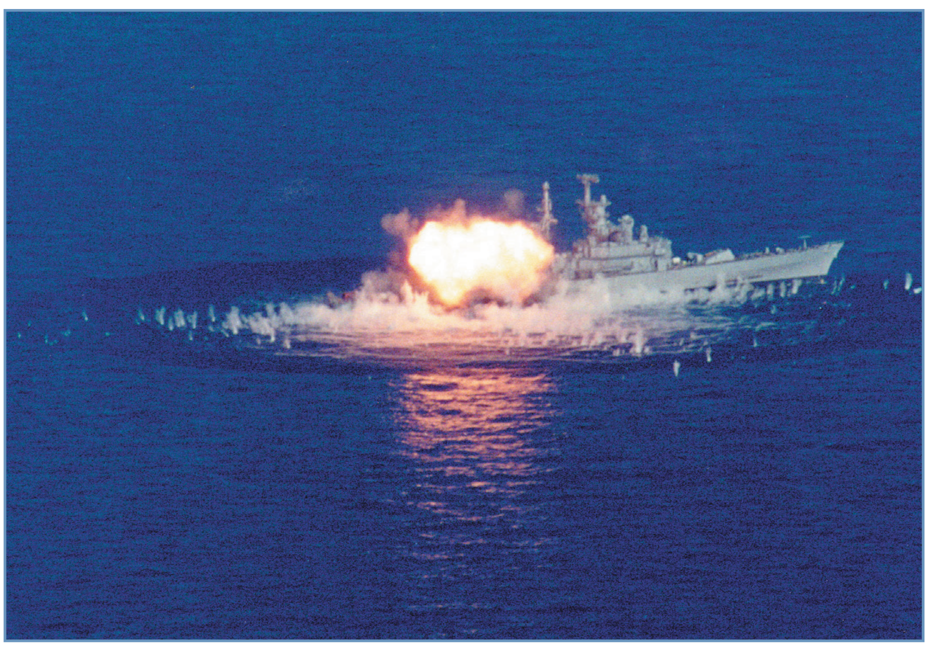


Figure 4. Surrogate Target Live Fire Test

The Division plays a major role in the Navy's ship and submarine LFT&E process. It conducts vulnerability analyses using appropriate modeling and simulation tools, prepares data and assessments for Program Office Vulnerability Assessment Reports, conducts component and surrogate tests, and plans and executes full shock trials and total ship survivability trials (TSSTs). The Division has supported LFT&E for every covered ship and submarine acquisition program since the law was passed. It was extensively involved in planning and executing the only two TSSTs performed by the Navy to date, both on DDG 51–Class ships. Similarly, the Division supports Navy weapon acquisition programs by conducting vulnerability assessments of target ships and submarines to compute weapon terminal effectiveness (lethality) estimates and by planning and executing tests against surrogate targets. Figure 4 shows a PEO-DD (x)/PMS 500 sponsored live fire test of a missile warhead against the Ex-RICHMOND K. TURNER (CG 20). This test was planned and executed under the direction of Division engineers with support from other Navy activities, and the Army Aberdeen Test Center.

The Way Ahead

Precision-guided munitions, reduced manning, and wide spread use of commercial off-the-shelf (COTS) equipment pose significant challenges for future development in this area. Acquisition and life cycle operating cost pressures will preclude using traditional approaches that result in parasitic protection, damage control, and recoverability systems. Attention will be focused on weapons effects protection fully integrated with structure and signature control. Damage tolerant, and potentially self-healing, structural systems will be explored. Dynamic armor systems with significantly enhanced performance over traditional passive systems are being researched, while efforts are underway to improve the weight efficiency of the latter through materials developments and structural integration. Robust, fault tolerant, rapidly reconfigurable distributed systems and automated damage control capabilities are being developed in response to reduced manning requirements. The potential application of nano-technologies to ship/submarine vulnerability/recoverability problems is an exciting new avenue to explore. A total systems approach is being pursued to ensure that future Navy ships and submarines are highly survivable against the threats they are expected to face in combat.

Technical Papers

The remainder of the Vulnerability and Survivability Section presents four papers that are illustrative of recent Division achievements related to vulnerability and survivability systems. They are examples of the wide spectrum of work at the Carderock Division in support of the Navy's efforts to provide survivable ships and submarines. The papers focus on technologies that have a significant impact on current Navy acquisition programs and the Fleet. The first paper addresses modeling and simulation applied to ship/submarine vulnerability assessment. The second describes advanced shock isolation technologies under development to protect COTS equipment. The third describes application of advanced control and network technologies to automate distributed system response to weapon effects damage. The final paper summarizes the Division's work in support of the FAA Commercial Aircraft Hardening Program including the patented Threat Containment Unit being deployed to U.S. and international airports.

Dr. Fred J. Fisch *earned his Ph.D. at Lehigh University in 1968. His academic areas of concentration were mechanical engineering and applied mechanics. Until his retirement in October 2001, he served as the Associate Director for Survivability and Live Fire Technology in the Survivability, Structures and Materials Directorate. He has over 30 years experience in the field of weapons effects and ship protection and has led numerous projects to develop and apply ship vulnerability assessment methods to support ship design and weapon lethality evaluations, and to develop and test structural hardening concepts. Dr. Fisch is a lecturer in the Department of Ocean Engineering at the Massachusetts Institute of Technology and is lecturer-in-charge of the MIT Professional summer course Weapons Effects and Ship/Submarine Survivability.*

Modeling and Simulation of Weapons Effects on Ships

Robert R. Wunderlick

This paper describes modeling and simulation tools to assess the effects of weapons on ships and the application of these tools in support of U.S. Navy ship design, operation, and acquisition. The major computer codes maintained (or under development) at NSWCCD are listed along with a summary of the wide application of these tools in support of U.S. Navy requirements. Applications include vulnerability assessments in support of ship acquisition programs and congressionally mandated Live Fire Test and Evaluation requirements, survivability benefits assessments for new and emerging technologies, weapons effects scenario data in support of Fleet training and Navy medical planning, lethality assessments for weapons development and weaponeering, and others. An overview of weapons effects and ship vulnerability modeling is presented, along with brief technical descriptions of major damage assessment models. Future plans are discussed that will provide robust analysis tools in support of the Navy's maturing ship survivability program and accommodate highly automated future ship systems that will result from the Navy's drive for reduced manning.

Introduction

Modern modeling and simulation techniques, applied to the effects of weapons on surface ships provide reliable tools to assess ship vulnerability and to quantify the survivability benefits of design features and new technologies. Damage and casualty estimates produced by such simulations provide valuable inputs for military planners and aid in increasing crew warfighting effectiveness. Robust simulations of weapons effects against ships have been applied to satisfy congressionally mandated Live Fire Test and Evaluation (LFT&E) requirements for Navy ship acquisition programs. Assessments of the effectiveness of weapons against ship targets provide design tools for weapon development and munitions effectiveness data for weaponeering.

Applications in Support of the Fleet

NSWCCD has a long history of development and application of computational tools for weapons effects simulation and ship vulnerability assessment dating back to the mid 1960's. It is dedicated to the continual upgrading of these tools in support of the Navy's maturing ship survivability design discipline. The major codes currently maintained and under development by the Division are listed in Table 1 in the approximate chronological order of their development.

These, and other analysis methods have been applied to support platform design and operational assessments, weapon development, and to measure the lethality of our weapons against foreign ship targets. Table 2 highlights selected applications in support of a wide variety of U.S. Navy technical requirements.

Ship Vulnerability Analytic Process

Many factors are involved in ship vulnerability analysis. Figure 1 highlights the influencing parameters common to most surface ship vulnerability assessments. The ship's physical and functional description, including signature

Table 1. Computation tools for weapons effects simulation

FSVM	Foreign Ship Vulnerability Model
SVM	Ship Vulnerability Model
BDE	Battle Damage Estimator
TSSM	Total Ship Survivability Model
ASAP	Advanced Survivability Assessment Program

Table 2. Applications of weapons effects modeling and simulation to support the Fleet.

Navy Requirement	Codes Used	Impacted Platforms/Weapon Systems/Technologies
Vulnerability Assessments to support ship acquisition programs	SVM, TSSM, ASAP	Most Recent: DDG 51, LPD 17, DD (X), Arsenal Ship, CVNX, JCC(X), T-ADC(X), Maritime Preposition Ship, New Coast Guard Medium Endurance Cutter
Technology Assessments - quantifying survivability benefits/assessing system vulnerabilities	SVM	• Electric Propulsion - notional DDG • ZEDS (Zonal Electric Distribution System) - CVNX • EMALS (Electromagnetic Aircraft Launching System) - CVNX • Advanced Armor Concepts - Arsenal Ship
Platform LFT&E Support	SVM, BDE, TSSM	DDG 51 FLT IIA, LPD 17, DD (X), CVNX
Weapon LFT&E Support	FSVM	Mk 48 ADCAP
Munitions Effectiveness/ Weaponeering (air approach weapons)	FSVM	Inputs to JCTG Munitions Effectiveness Manuals
Military Worth Studies	SVM	Survivable Naval Architecture Project - future frigates, destroyers, cruisers
Topside Hardening Studies	SVM	Assessment of the survivability benefits of topside armor and structural hardening options to support ship design and alteration studies - numerous ships/classes
Fleet Training/Total Ship Survivability	SVM, BDE/Flood/Fire	Weapons primary damage and secondary effects (flooding, fire spread, etc.) scenarios for crew damage control exercises - ship classes: CG 16, CG 26, CG 47 CGN 38, DD 963, DD 993, DDG 51, FFG 7, LHA 1, LHD 1, LPD 4, LSD 41
Total Ship Survivability Trials (TSST) - planning support	SVM, BDE	Predictions of weapons effects/ship damage in support of ship damage control and recovery exercises - DDG 51 FLT IIA, initial planning for LPD 17
Navy Medical Planning - crew casualty rates	SHIPDAM	Scenario based casualty rate predictions for naval forces afloat - medical planning support
Damage Tolerant Hull Structures	SVM, BDAM	Assessment of the survivability benefits of: Blast Hardened Bulkheads (BHB), damage tolerant hull girder concepts, hull protection systems, etc.
Insensitive Munitions (IM) and Magazine Safety	SVM, TSSM, BDAM	Vulnerability/survivability assessments of magazine protection/safety features, and benefits of reduced munitions sensitivity - VLS (Vertical Launch Systems)

characteristics, forms the basis to assess the ship's susceptibility to threats and response to weapons effects if a hit occurs. Threat characteristics determine the location and severity of weapons effects that the ship will experience. Analytical models simulating damage mechanisms are imposed on computerized models of ship structure, vital equipment, and functional descriptions of ship systems, to determine the likelihood of functional impairment to critical systems or ship structure and/or ship loss. Using a probabilistic approach, the results of these calculations generally are presented in the form of probability of kill (Pk) tables or graphs which may be used to assess ship vulnerability, quantify survivability benefits of a design feature, or measure the effectiveness of a weapon. Figure 2 depicts three multi-hit

Pk relationships; a baseline ship with three protection options, mission inactivation probabilities for a particular threat weapon, and the probabilities of losing C 3 Overall (level of combat readiness) for four threat weapons.

Weapons Effects Prediction and Vulnerability Analysis

Vulnerability analysis is centered on characterizing “loading” and “response”. Loading refers to the metrics that describe weapon damage mechanisms (e.g., blast is characterized by a pressure-time history at a certain ship location). Response refers to the response of equipment and structure to these damage mechanisms. Response can consider that a particular piece of equipment failed or survived, or that a structure remained elastic, was deformed, or failed.

The damage mechanisms are derived from the two major categories of conventional weapons, air delivered and underwater delivered. Air delivered weapons are designed with three major purposes - destroy mission essential topside equipment, inflict massive structural damage, or penetrate to vital spaces to destroy functional capabilities. Methodology is available to handle the damage mechanisms of each of these types of weapons. Many weapons are designed to spray a large number of high-velocity fragments against topside sensors to destroy topside equipment. Methodology has been fairly well defined to understand the effect of fragments on structure. However, the data for fragmentation patterns of threat weapons, as well as the vulnerability of topside sensors and other shipboard mission critical equipment to fragmentation, is unique for each threat/ship interaction that is considered. The Navy has a strong history of programming funds for the characterization of each. The data from these efforts is used to support vulnerability analysis. Figure 3 depicts a typical simulation to assess the Pk of a vital component from weapon fragmentation. A critical input parameter is the vulnerable area data for each vital component (depicted by the Pk/h matrix in the lower right side of Figure 3). These tables provide data on the vulnerability of equipment to specific fragment mass and velocity characteristics.

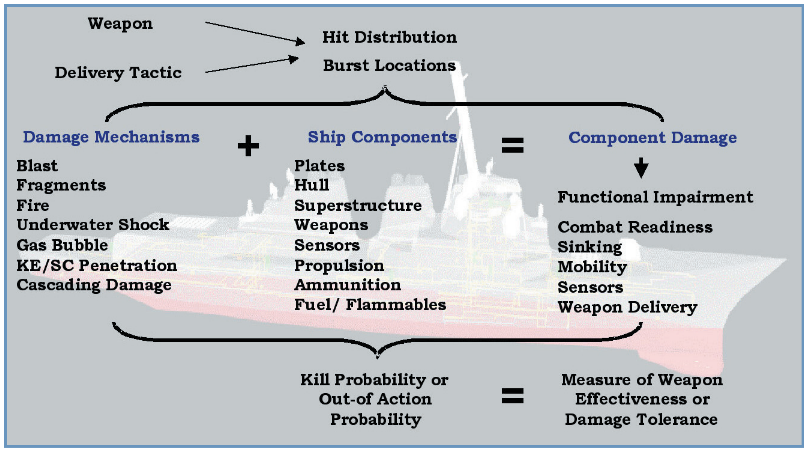


Figure 1. Principal factors used to assess vulnerability to weapons effects.

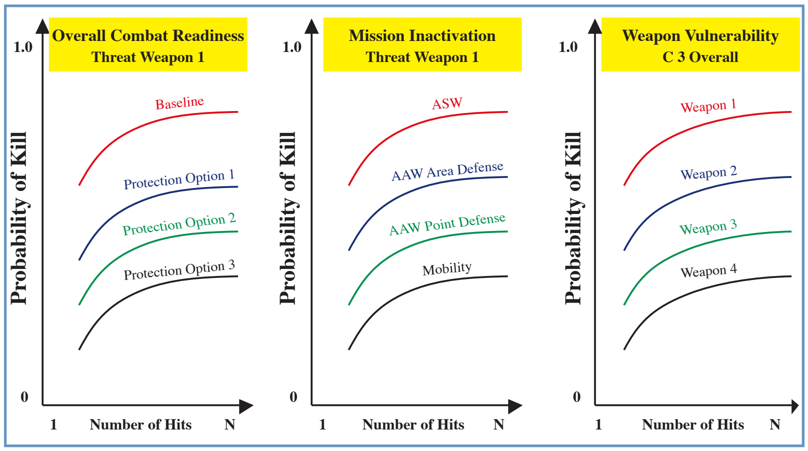


Figure 2. Various uses of kill probabilities produced by vulnerability analyses.

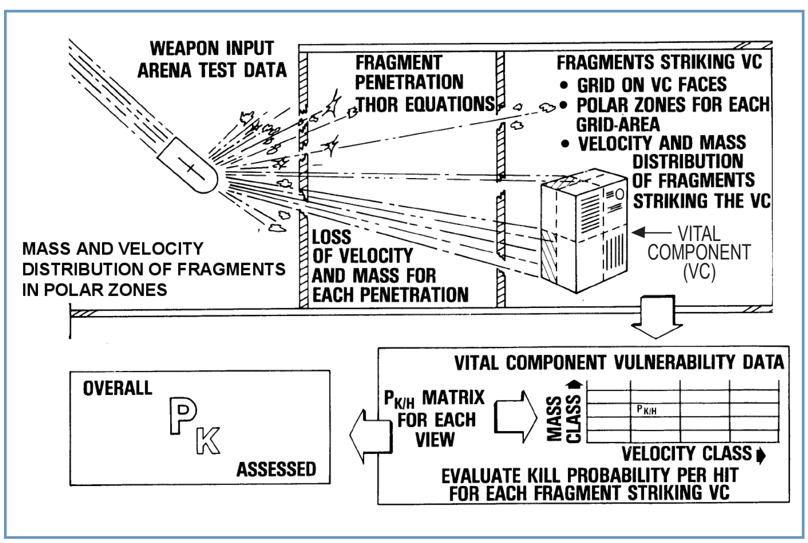


Figure 3. Assessment of fragment damage to equipment.

Weapons designed for massive structural damage rely on the creation of internal blast and fragmentation, usually with an emphasis on the blast. Research conducted in the last 30 years has led to the ability to accurately predict the response of a wide range of naval structures to internal blast, resulting in improved modeling techniques. The Blast Damage Assessment Model (BDAM) was developed as an initial answer to understanding the response of structures to internal blast. Originally developed as a stand-alone PC program, today elements of BDAM are incorporated into SVM, BDE, and TSSM. BDAM will be refined further for incorporation into ASAP. Figure 4 is a representation of the BDAM process, which straddles the technology between approximate tools (such as "damage radius" concepts) and detailed finite element analysis/hydrocode calculations. Based on real-time calculations of the blast pressures in ship compartments (accounting for venting between compartments and atmospheric venting), BDAM time steps through the individual motion of ship structural members, monitors deflections and failure criteria, and tests for structural failure.

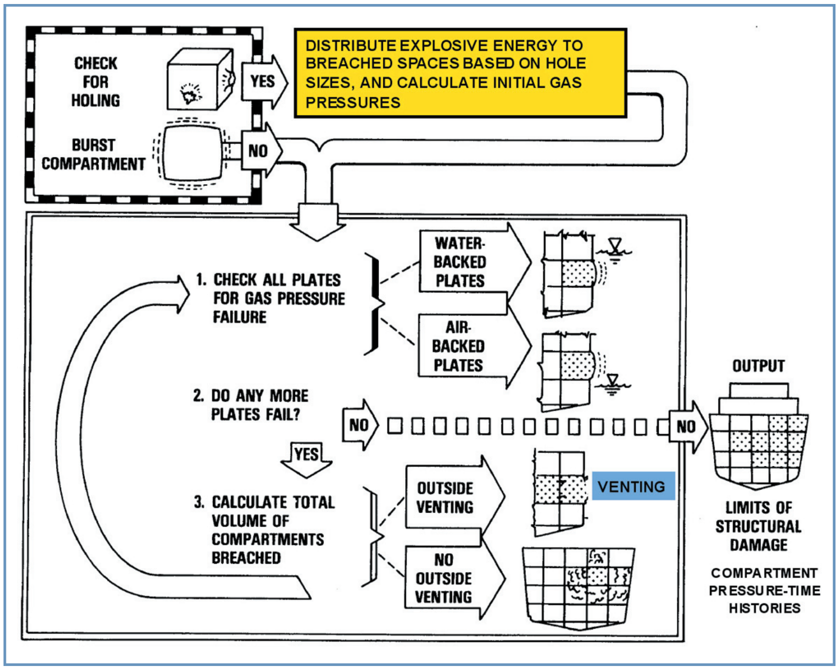


Figure 4. BDAM calculation of structural blast damage.

Use of Analysis Tools

The tools available to ship designers range from lower fidelity models for rapid analysis of total ship concepts to higher fidelity models that enable analysis of the impact of construction details on compartment level survivability.

The first important step to ensure a survivable ship design is to understand the appropriate tools to use for analysis. As an example, there are methods to calculate structural damage that could provide satisfactory results in terms of a ship's damage tolerance at the concept level design. Once the structural details and sub-compartmentation are added into the geometry, the same methodology applied to the same ship could provide results that indicate the ship no longer meets damage tolerance requirements.

The savvy analyst will try to use as many available tools as possible. With each tool comes a greater understanding of the inherent damage tolerance of a ship. Throughout a ship's design, each of the tools mentioned previously will be used to gain an understanding of the relative damage tolerance of the ship.

Pedigree of Models

There are a number of instances of good correlation to be cited for the prediction of the effects of weapons on ships in the Fleet today. As the Navy moves toward the use of new materials, commercial fabrication techniques and commercial off-the-shelf equipment, the sense of confidence in vulnerability predictions will decrease until research can be conducted to understand the effect of weapons in this regard.

Many of the underlying theories are empirical and lend themselves to a statistical approach for presentation of results. The probabilistic nature of weapons effects prediction is the main reason that the most proper implementation of a total ship survivability analysis is one of comparison vice a high confidence prediction of an actual damage state. However, an accurate representation of damage from a single event can be developed using a combination of assessment tools, lessons learned, and engineering judgement.

Verification, validation, and accreditation (VV&A) efforts have been completed for some codes and are underway for others. SVM is in the verification and validation process for accreditation in support of DDG 51 FLT IIA LFT&E. The overall ASAP VV&A strategy is being designed to support the DD (X) and LPD 17 acquisition programs and munitions effectiveness assessments (JTCG/ME) accreditation processes.

The Way Ahead

The objective of ASAP is to develop a survivability assessment and analysis computer model that predicts (as a function of time) the vulnerability and recoverability response of the ship, systems, and crew to weapons effects. ASAP is an explicit time-stepping code that simulates ship response to primary weapon effects damage, subsequent cascading (distributed system response to multiple simultaneous faults resulting in system shutdown) and progressive damage (spread of fire, smoke, flooding), damage control, and mission recovery efforts. ASAP will link together a series of physics-, empirical-, or doctrine-based analysis models to provide for time-dependent analysis. The drive to reduce manning will lead to ships with highly automated systems for ship control, monitoring, fire-fighting, and other damage control functions. ASAP will provide a rigorous analysis tool to assess the effectiveness of these systems and the survivability of future ships.

Summary

Navy ships may be sent in harm's way to conduct vital missions to support our national interests. Damage tolerance and the ability to fight hurt are combatant ship characteristics required by Department of Defense and Navy directives. The techniques used to make a ship more survivable impact every system on the ship, from enhanced structural design to hardened equipment to the basic architecture that forms the basis for ship-wide distributed systems. From a practical standpoint, cost versus performance trades must be conducted to maximize damage tolerance within budget constraints. The methods developed by NSWCCD will continue to ensure that U.S. Navy ship designers have the right tools to make the right trade-offs and thus provide the world's most survivable platforms.

Acknowledgements

The author would like to acknowledge Tom Carroll of Tom Carroll and Associates for his timely and insightful assistance in developing this paper.

Robert R. Wunderlick *received his B.S. in mechanical engineering in 1984 and his M.B.A in 2001, both from the University of Maryland. He is a senior project manager in the Survivability and Weapons Effects Department at NSWCCD. Since joining the Division in 1985, he has led numerous projects involving weapons effects analysis of foreign and U.S. ships, the development and application of vulnerability modeling tools, and the development and testing of ship protection systems. He has served as an assistant in the Safety and Survivability Office at the Chief of Naval Operations and is currently serving as a member of Tech Team 21.*

Intelligent Networks and Controllers for System Reconfiguration

Donald D. Dalessandro

The Carderock Division, under the sponsorship of the DD (X) Program Office, developed and demonstrated the concept of a highly survivable automated systems response for a fire main. The project was initiated to support the Navy's goal of reduced manning on the next-generation surface combatant and to provide improved response to a casualty. Its objective was to automate the system response to a casualty induced by an actual warhead explosion affecting a DDG 51–type fire main and the electrical and communication systems. The system employs advanced intelligent device controllers, a device-level distributed control network using the LonWorks® Protocol, survivable differential pressure sensors, compatible short protection circuitry for the communication system, and advanced electrical protection devices. The goal of the demonstration was to identify and isolate the damage from a casualty and to automatically reconfigure it such that maximum capability of the remaining system would be restored within 1 minute. The information gathered from the live ordnance testing provides design guidance for future improved systems response and reduced manning initiatives for the next-generation surface combatant. The paper describes the design of the test system, the results of the live warhead tests against it, and the lessons learned.

Introduction

In support of the DD (X) initiative to reduce manning on the next-generation surface combatant, NSWCCD conducted a series of machinery control system "live-fire ordnance" demonstrations of survivable advanced control and networking technologies. Commercial technology has been available for years to automate and control machinery systems for normal process control operations. The Navy is moving toward fully-automated systems that will isolate damage and reconfigure themselves following damage (i.e., with no crew involvement). Initial commercial efforts used central control methods for remote system control (e.g., valves, pumps) via a console operator for remote or automatic control. While this method improved system control over manual operation, it is vulnerable and represents a single point of failure. It is desirable to distribute the intelligence to the control point, such as a valve actuator, in order to produce survivable automated systems. Recognizing the benefits of distributed control for survivability, the Automated System Reconfiguration (ASR) Program was established by NAVSEA (SEA 05R) and (PMS 500) to demonstrate a survivable, highly distributed control system in an auxiliary system.

® LonWorks is a registered trademark of Echelon Corporation.

The program goal was to demonstrate advanced fluid system technologies that enable a shipboard auxiliary system to isolate a rupture automatically after being subjected to battle damage and to reconfigure the system automatically to maximize its remaining capability within 1 minute of the casualty event. The Division developed an automated distributed damage control system to accomplish this task. It operates independently on each device or control point and eliminates any reliance on a central control station that could be isolated from the problem by the damage event.

Approach

The overall system concept uses advanced microprocessors installed on each device, advanced sensors, and a distributed control network with sophisticated control algorithms. The DDG 51–Class fire main was used as a model to identify the functional requirements necessary to control the auxiliary system after it is damaged. The advanced microprocessors used are based on LonWorks® Network Technology by Echelon Corporation. In a LonWorks network, intelligent microprocessor-based control devices, called nodes, communicate with each other using a common communication protocol optimized for control. The nodes located on each device (e.g., valve actuator) contain an algorithm that determines the device's required response from data received by local sensors. Figure 1 is an example of a LonWorks control node installed in a valve actuator used in the test.

For this concept, differential pressure sensors were located at key isolation points at each butterfly valve to identify flow in the system that may be caused from a blast or fragmenting warhead. Figure 2 shows the differential pressure sensor installed in the test system. This test program used current state-of-the-art sensors to demonstrate the feasibility of the concept. Actual implementation in operational systems would integrate the sensor within the valve body. The distributed intelligent controller installed in the valve actuator continually monitors the local flow conditions using differential pressure to determine if fluid flow is present in the system.

Through communication with other devices adjacent to the valve, the local intelligent controller and its programmed algorithms identifies the location of the flow in the system and determines if it is from a rupture or a normal service load. Breaks, leaks, and normal service loads can provide similar input to the sensors. The logic developed for rupture isolation was required to identify the differences to eliminate false closing responses. The photographs in Figure 3 show the potential for leaks and full ruptures that can be caused by battle damage.

The valve actuator on each side of the rupture will independently command its valve to close when it is determined that the flow is caused by a rupture and not by an activated service load. Autonomous intelligent logic is embedded in each valve controller to prevent usable portions of the fire main from being isolated and allows the system to be reconfigured to restore its maximum usable service capability.

The project looked at two other major critical failure areas that could cripple an auxiliary control system to demonstrate the overall integrated casualty response capability. The first potential critical failure area is the control network. This system employed a three-ring-type network architecture using interconnecting routers that could inherently withstand single breaks in the wire and transform the ring topology into a bus topology (see Figure 4).

While this architecture and protocol can support a clean break in the network cable, shorted network cables could cause all network traffic on the damaged ring to be lost. Advanced low-cost circuitry was developed and integrated into each critical controller to isolate the short from the rest of the network. This circuitry was added to the system near the blast section, and an induced short on the network was generated to demonstrate the effectiveness of the circuitry.

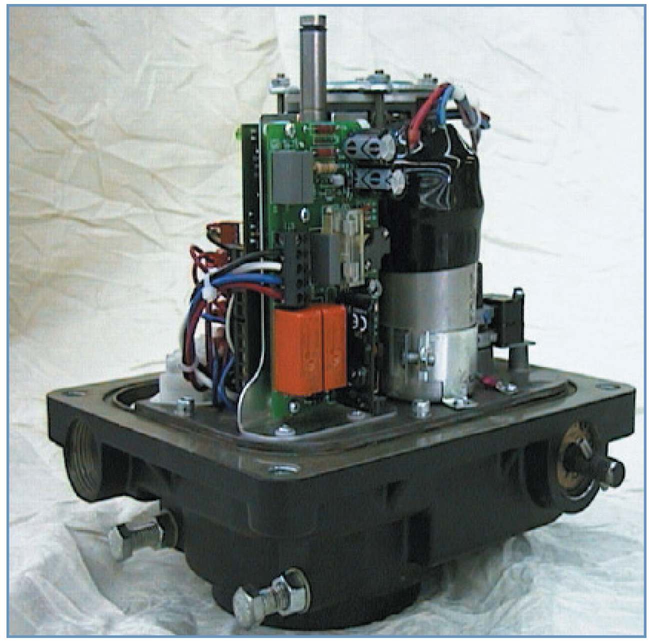


Figure 1. An integrated intelligent controller installed in an electric valve actuator.

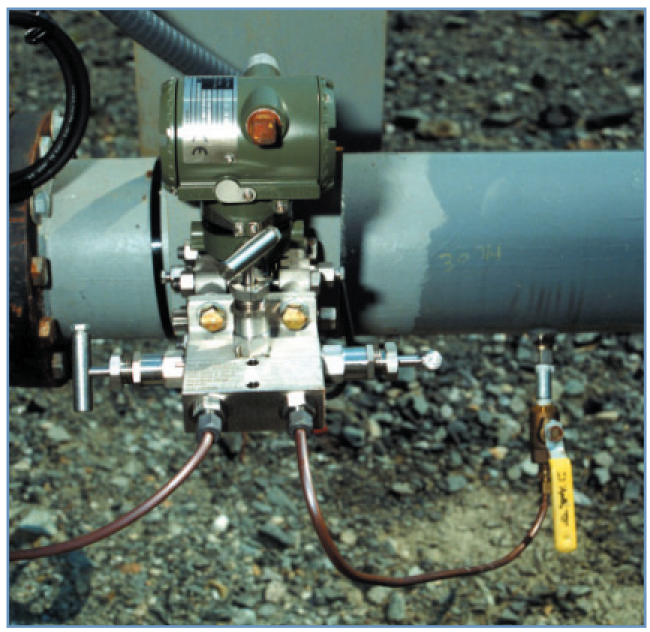


Figure 2. Differential pressure sensor installed next to an isolation valve.

Figure 3. Results of large-article test platform conducted at Aberdeen Proving Grounds.

The second potential critical failure for this type of control system is the reliability of the electrical system. A major goal of the ASR project was to demonstrate that the control system could accomplish its objectives once electrical services were restored with no anomalies and without any manual intervention. To accomplish this, the project supported joint testing with the Multifunction Monitor III (MFM III) development test program. The MFM III device uses a sophisticated algorithm to detect and isolate electrical faults in a zonal electrical distribution system. (see *An Intelligent Fault Detection Device* paper in this Digest.) The fluid control system and its controllers were subjected to a power interruption with the same duration (65 ms) that would be expected from a system with an MFM III.

Testing

The fluid system test platform was constructed at the Division's Briar Point Survivability Test Site at the Aberdeen Proving Grounds, Aberdeen, MD. Figure 5 is a photograph of the test site showing the fire main piping and the blast site.

The key design features of the test platform include a full-scale 6-in. fire main loop system, a copper nickel pipe test section, segregation gate valve to configure the system for Zebra (battle) condition, isolation butterfly valves and a composite ball valve, electric actuators, differential pressure sensors installed at each control valve, control nodes installed with each device, a distributed control network, two 1,000 gpm titanium fire pumps, representative service loads, and a 10,000-gallon supply tank. A schematic of the system is shown in Figure 6.

The fire main system was subjected to a series of blasts simulating various types of damage scenarios. C-4 explosives were wrapped around the pipe and detonated to examine a complete pipe rupture scenario. A 155-mm Howitzer round was detonated in line with the piping system to simulate damage from a fragmenting warhead. Three test scenarios were designed to manage fluid system damage in the fire main with and without normal service loads activated, and with and without damage to the supply pump. In each scenario, the system was required to

Figure 5. Aerial view of the fire main piping system and the test site.

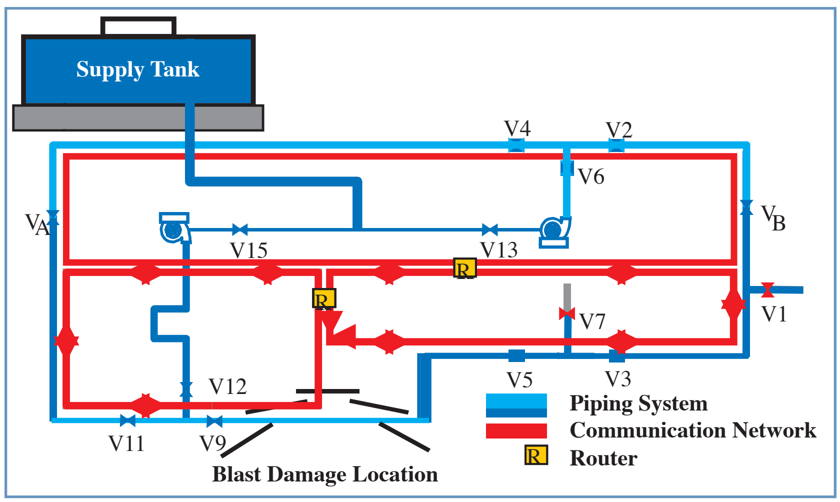


Figure 6. Fire main piping and control network.

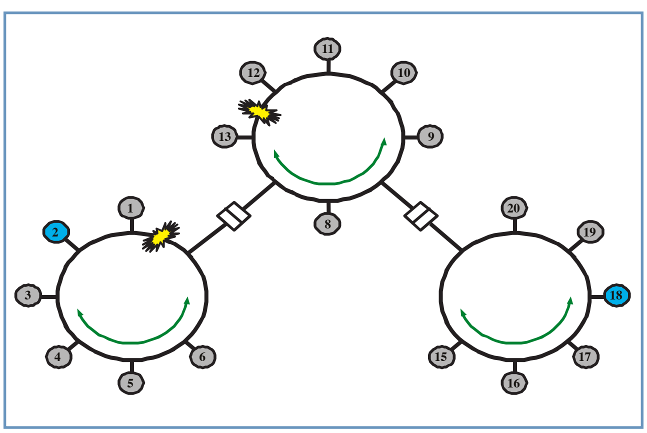


Figure 4. Network ring topology employed to enhance survivability characteristics.

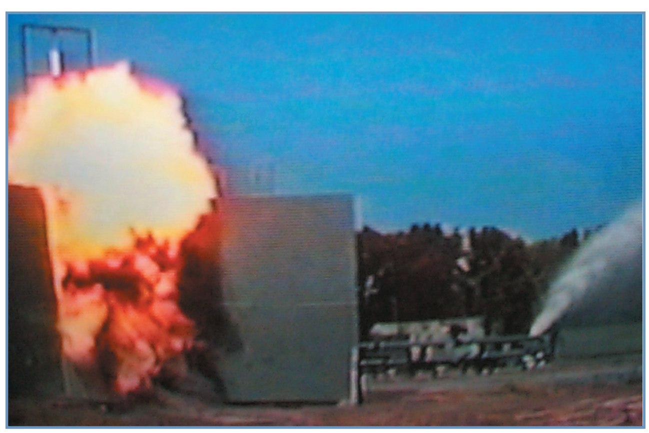


Figure 7. Automated fire main system demonstration with service loads activated.

identify the rupture automatically, isolate it, and reconfigure the system to maximum operating capability without any manual intervention. Shorts in the control network and power distribution interruptions were induced simultaneously to the fluid system ruptures to demonstrate the total system automated response to a realistic worst-case damage scenario. Figure 7 is a photograph of a C-4 explosion of the pipe that produced a complete rupture. The right side of the photo shows a simulated service load (such as a fire hose) which was used to confuse the logic that discriminates the actual rupture from a normal service load and isolates only the actual break location.

Test Results

The automated control system reacted to each damage scenario with no major anomalies. The system successfully isolated a rupture and reconfigured the firemain within the required 1 minute. Figure 8 shows the automated valve actuator response to the blast damage.

One service load was simulated outside of the isolation area and a second was simulated between the valves that isolate the rupture. Figure 9 shows the steps that occurred during the demonstration. Shortly after the rupture, only the valve closest to the rupture (on either side) autonomously closes as a result of information from its local sensors and adjacent valve.

Once the system has isolated the rupture, each valve independently determines if it should open to restore services that may have been isolated from the supply pumps. As shown in Figure 8, the valve that was used to segregate the system for the starboard and port configuration opens to restore services to available fireplugs. For this test, the complete system was isolated and restored within 54 seconds of the rupture. While system performance meets the objective, the overall time to reconfigure the system was driven by the valve closure stroke time set by the actuator manufacturer. Actuator stroke time could be shortened significantly to improve system response, but care must be taken to avoid additional damage caused by valve-induced water hammer.

Summary

During the demonstration, many risks were reduced and a number of lessons were learned. The new information is vital to the successful implementation of device level distributed control systems on next-generation ship platforms. The implementation of the device-level control was highly successful; however, limitations of the programming tools and system models were identified. Research continues to modify and upgrade this capability. The test program also identified hardware limitations when adding automa-

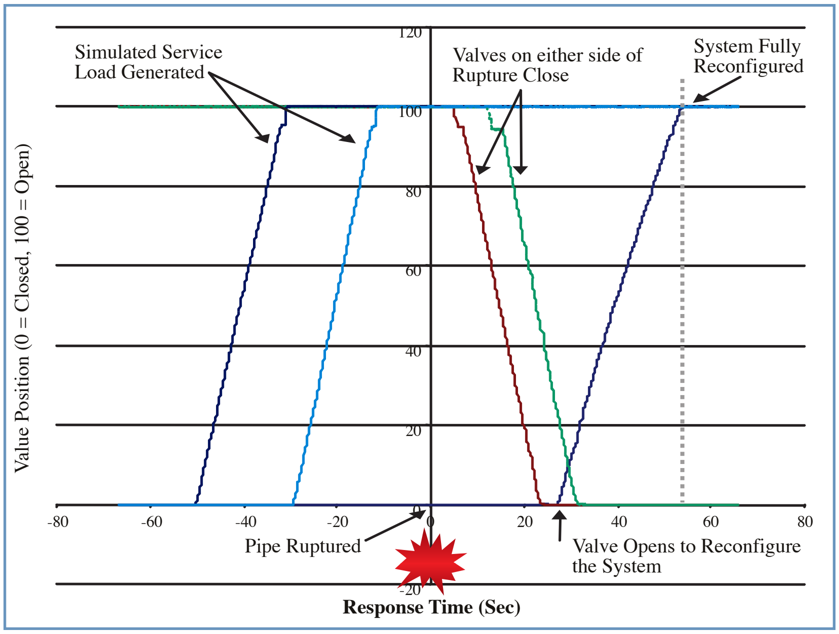


Figure 8. Automated isolation and reconfiguration response as a result of complete pipe rupture from a C-4 explosion.

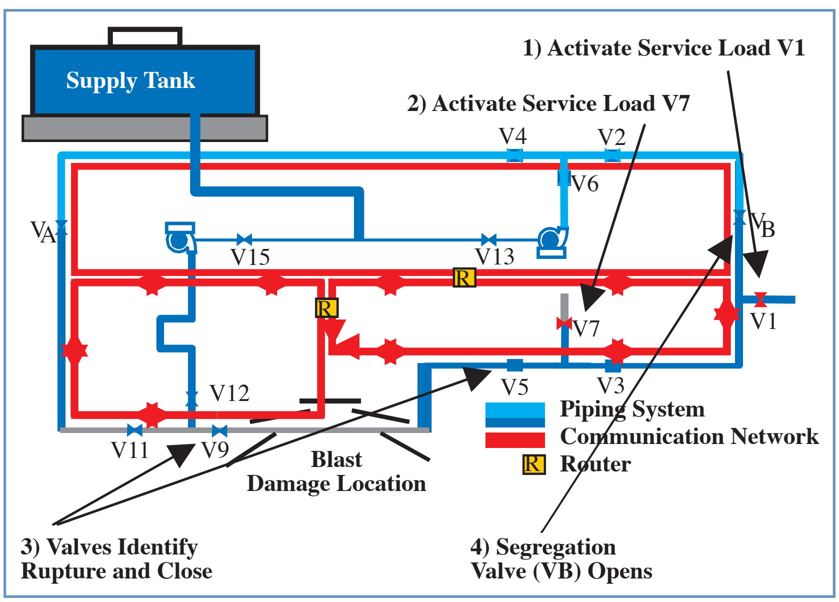


Figure 9. Location of activated valves during a detection, isolation, and reconfiguration demonstration.

tion to legacy devices. Valve, actuator, controller, and network hardware selection criteria have been developed to avoid problems that could occur in the automation system during a blast damage event. Survivable network architectures and topologies were investigated for this type of system, and other potential failure modes in the network were identified. The work conducted has led to research of new concepts in advanced reasoning using hierarchical control systems to interface with device-based distributed control systems that will be explored under ONR sponsorship.

NSWCCD has been exploiting pipe rupture detection and survivable distributed device-level control technology to develop a system to reduce the personnel required to manage battle damage and provide fight-through capability. Future shipbuilders will be able to use the technology, tools, and processes developed by the Navy to help meet their reduced-manning objectives.

Acknowledgments

The author wishes to acknowledge Mr. Brian Smale, NAVSEA (PMS 500) and Mr. Harry Skruch, NAVSEA (SEA 05R) for sponsoring this project.

Donald D. Dalessandro *is a senior engineer in the Advanced Auxiliary Automation and Controls Branch at NSWCCD in Philadelphia. He leads a group of engineers conducting advanced research to develop survivable automation for the next-generation combatants. His current work focuses on using advance device-level control and network systems technology for auxiliary systems. Mr. Dalessandro graduated from Penn State University in 1983 with a B.S. degree in aerospace engineering. He began his career with the Naval Air Propulsion Center, in Trenton, NJ, supporting the development of advanced gas turbine propulsion system technology. He has worked as both a contractor and a Navy employee to develop autonomous unmanned air vehicle systems and subsystems to test advanced Navy weapon systems.*

Commercial Aircraft Hardening

David T. Wilson

After the terrorist bombing of Pan Am 103 in 1988, the Federal Aviation Administration (FAA) was tasked by Congress to improve the safety and security of the nation's commercial air operations. Most of the effort to date has gone into detection of improvised explosive devices (IEDs) before they get onboard an aircraft. A smaller but significant effort has focused on determining the vulnerability of commercial aircraft to explosion effects and on a means to improve the resistance of the aircraft to IED explosions. Carderock Division has been a participant in the Aircraft Hardening Program since 1991, playing a key role as advisor to the FAA on explosive phenomenology, explosive testing, and hardening techniques. While drawing on the Navy's expertise, the FAA Program also has provided valuable data on how explosive loads can be modified by materials placed in close proximity to the explosive before it detonates. This paper details the history of the Division's involvement with the FAA Aircraft Hardening Program. It includes a description of some of the important discoveries made concerning the internal blast loads exerted on a structure when an IED detonates within baggage. Understanding these loads has allowed the FAA to develop specifications for hardened luggage containers to be used in wide-bodied aircraft and also to examine hardening measures for use in narrow-bodied aircraft cargo holds.

Introduction

The downing of Pan Am 103 in December 1988, with the loss of 270 lives in the air and on the ground, brought the problem of terrorist attacks on commercial aircraft to prominence. Beginning in 1990, the Federal Aviation Administration (FAA) has devoted significant effort to reducing the vulnerability of commercial aircraft to terrorist bombs. Most of the work has gone into improvements in explosive detection and luggage screening to keep improvised explosive devices (IEDs) off of airplanes. At the same time, a smaller effort has focused on three issues associated with hardening of commercial aircraft against the effects of the detonation of an IED onboard the airplane. First, methods have been developed to assess how vulnerable existing aircraft are to varying levels of threat bombs placed in different locations throughout the aircraft. The second effort focuses on developing technology that could be applied to future aircraft to improve their resistance to an IED explosion in the cargo holds. Lastly, the FAA is developing features that can be used with the current fleet of commercial aircraft to improve their survivability to the threat. These three efforts are managed within the FAA's Aircraft Hardening Program (AHP).

NSWCCD has been a partner with the FAA in the AHP since 1991. Our role has been to advise the FAA on the explosive effects that can be produced by the detonation of an IED inside an airplane, and to help perform tests to quantify these internal blast loads and the aircraft's structural response to these loads. The work performed under this partnership has varied widely but draws on the strengths of the Protection and Weapon Effects Department

Figure 1. Explosive testing of a pressurized B747 aircraft at Bruntingthorpe, England, in May 1997.

in the physics of internal explosions and fragment penetration, the design of structures to resist the dynamic loads produced by an internal explosion, and explosive testing methodology.

The vulnerability of aircraft to relatively small explosive charges placed in passenger luggage has been demonstrated dramatically through tests on retired aircraft. A test of a pressurized B747 is shown as an example in Figure 1. The damage from the explosion would have been much smaller on an unpressurized aircraft; once the damage exceeds a characteristic value, the forces exerted on the airframe by the pressurization are sufficient to expand the damage to a catastrophic level. The goal of the AHP is to prevent this damage.

The Aircraft Hardening Program

Hardening of commercial aircraft against bombs placed in passenger luggage can be accomplished in several different ways. The aircraft structure and systems can be hardened against the effects of a bomb in the cargo hold, or the luggage containers that normally hold the passenger baggage on wide-bodied airplanes can be hardened to contain the blast and fragments within the container. Changes to the aircraft structure and systems are cost prohibitive for existing aircraft, but could be included in new designs. The FAA focused on hardening the luggage containers in the aftermath of Pan Am 103. This option offered the best opportunity to improve the survivability of the existing aircraft fleet, because the terrorist threat is believed to be greatest on overseas flights, which are serviced almost exclusively by the wide-bodied aircraft that use the containers. The luggage containers, referred to as unit load devices (ULDs), are normally made as lightweight as possible.

One of the key questions that faced FAA investigators at the beginning of the AHP was what effect would luggage have on the internal blast loads produced by detonation of an IED. This information was needed to assess the vulnerability of the current fleet of commercial aircraft and to develop hardening features to reduce that vulnerability. Finite element and finite difference computer codes typically are used to perform detailed predictions of the response of structures to dynamic loads. However, they cannot accurately model the forces produced by the detonation of an explosive charge inside a suitcase that has been placed in a luggage container in the cargo hold of a wide-bodied aircraft. The complex and highly variable combination of materials and geometry of a piece of passenger luggage could not be duplicated with any degree of accuracy, so an experimental approach was devised.

NSWCCD designed a fixture that replicates the interior geometry of the most common type of ULD, with positions for up to 14 pressure transducers and other instrumentation on the interior of the fixture. The fixture was used to measure the internal blast pressures that would be exerted on the walls of a ULD when an IED is detonated inside it. Tests were conducted with bare explosive charges and with explosive charges placed in a suitcase and surrounded by different amounts of other luggage. Luggage used in the tests was actual lost luggage from international flights, obtained by the FAA from the airlines.

The results of the tests were startling: the quasi-static phase (QSP) pressure produced by an explosive charge in a suitcase in a stack of luggage could be reduced by as much as 90%, depending on the amount of luggage in the container and the position of the charge in the luggage stack. This attenuation is achieved through two mechanisms. First, as the incandescent post-detonation gases expand outward, heat from the gases is absorbed by the luggage surrounding the charge. This reduces the energy of the gases directly. The second mechanism is subtler. The gases produced by detonation of an explosive are capable of undergoing further combustion reactions with any available atmospheric oxygen (high explosives typically produce 40% to 60% of their energy output through post-detonation combustion). As the gases cool, they drop below the temperature necessary to sustain combustion. This reduces the total energy produced and keeps pressures on the walls of the container much lower.

As can be seen in Figure 2, the attenuation of the QSP pressure is greater when the charge is in the middle of a luggage stack than when the charge is in the top bag of the stack. This would be expected because some of the gases would move up into the free volume of the container and undergo combustion. When the charge is in the middle of the stack, the gases have to travel through more luggage to reach available oxygen. The ability of the clothing, shoes, and personal items to quickly absorb the heat energy of the gases was not expected. In fact, earlier tests on individual suitcases had indicated that the suitcase material and contents were capable of adding energy to the event through their own combustion.

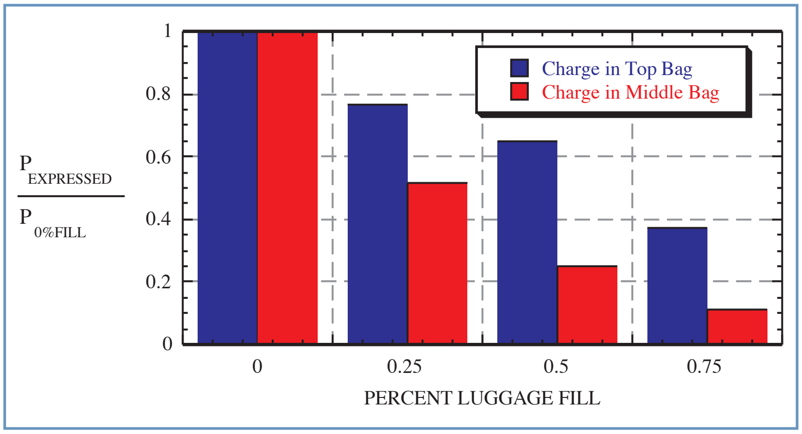


Figure 2. Expressed QSP pressure from explosions in luggage as a function of expressed QSP pressure in an empty fixture.

The pressure reductions are very important in terms of designing a hardened unit load device (HULD). Using data from the luggage tests in the rigid fixture, we were able to help the FAA develop an explosive loading for the walls of an HULD. The loading was incorporated into an overall draft specification for HULDs written by the FAA. The intent of the specification is to allow the development of prototype containers by industrial firms with expertise in the aircraft cargo container business or by composite materials manufacturers, even though they lack experience with explosive loads and weapon effects.

The FAA specification uses the data, coupled with knowledge of how the containers are loaded by the airlines, to define a wall loading for the HULD that would result in designs with acceptable weights. With up to 32 containers on a wide-bodied aircraft, a HULD needs to be as lightweight as possible to be economically acceptable to the airline industry. While protection against the threat is paramount, it is important to remember that hardened containers will fly many thousands of flights without a threat being present.

The results of the luggage tests are useful to the Navy as well as the FAA. By working with the FAA on the unusual aspects of their detonation conditions (i.e., a bomb inside a randomly filled suitcase, surrounded by other suitcases, inside a unit load device in the cargo hold of an aircraft), we have obtained a relatively large data set on attenuation of internal blast pressures by a surrounding media. The data complements our research into magazine protection sponsored by ONR and the DD (X) Program Office (PMS 500). The Navy-sponsored research focuses on using water surrounds to mitigate any internal blast loading from stowed munitions attacked by a threat weapon. Key insights into the mechanisms of the blast mitigation have been uncovered by comparing the reduction in internal blast loading obtained when an explosive charge is surrounded by luggage to the reduction obtained when an explosive charge is surrounded by water.

Another part of the specification deals with failure of the container due to shock holing. This phenomenon occurs when an explosive charge is placed close to a wall or panel. When the charge is detonated, the shock wave and near-field gas expansion produces an impulsive local load on the portion of the wall or panel nearest to the explosive charge. We have extensive experience with shock holing of steel plates when analyzing the effects of threat warheads on surface ships. We applied that experience to write a shock-holing requirement for the HULD specification. In addition, NSWCCD has performed over 70 tests of different materials used on existing ULDs and those proposed for use in HULDs. Many of the tests involved polymer composites, and this data has been used by the Division to help gain an insight into the performance of composite materials under weapon effects loads.

Threat Containment Unit

A good example of the quick response that NSWCCD has been able to provide the FAA was evidenced in 1997. The FAA was deploying advanced explosive detection equipment at major U.S. airports and needed an explosive containment device to provide a place to safely hold luggage suspected of containing a bomb until bomb technicians could be summoned to the scene. This eliminated the need to close off large portions of the airport. NSWCCD was tasked to survey the commercially available explosive containment units that met the FAA's requirements, which included:

- The ability to contain the effects of a specified size explosive detonated inside the container.
- A door and interior large enough to accommodate a piece of luggage 20 in. x 28 in. x 48 in.
- The ability to be deployed easily to different parts of the airport, including passing through a 36-in. door.
- Light enough in weight to be moved by one person.

Figure 3. NSWCCD-designed explosive containment device, pre-test (top) and during test (bottom).

Several commercially available units met one or two of the criteria above, but none fully satisfied the FAA criteria. The FAA tasked NSWCCD to develop a container to comply with their requirements.

Expertise in the design of blast-resistant structures developed to improve the survivability of surface combatants enabled us to design and successfully test a prototype within 28 days. The same tools used to predict the response of ship structure to internal blast loading were applied to the design of the container shell. Experience gained on Navy programs to design blast-resistant watertight doors was used to obtain a robust door to load luggage into the container. Figure 3 shows a prototype container before and during its test. Improvements have been made to the original prototype to make it more accessible to police bomb technicians and the robots they use to disarm suspect IED's. Two units have been deployed to airports, and an Interagency Agreement was signed recently to produce another ten units.

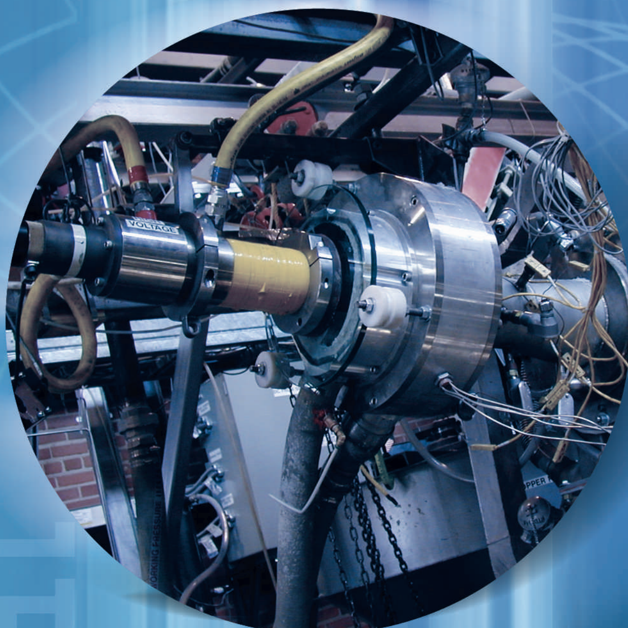
Summary

NSWCCD has partnered with the FAA on the Aircraft Hardening Program to significantly improve understanding of the weapon effects associated with bomb detonation onboard a commercial aircraft. The data generated will not only improve public safety during travel, but will improve the survivability of the Navy's surface combatants. We will continue to support the FAA with analysis and explosive testing as the program moves forward to study other aspects of aircraft vulnerability to the terrorist threat.

Acknowledgements

The author wishes to acknowledge the sponsorship and support of the FAA's Aircraft Hardening Program at the William J. Hughes Technical Center in Atlantic City, especially Mr. Nelson Carey, Mr. Ken Hacker, and Mr. Howard Fleisher, as well as Mr. Roger Cotterill of the FAA's Security Equipment Integrated Product Team.

David T. Wilson *has been at the Naval Surface Warfare Center, Carderock Division (NSWCCD) since 1982, working extensively in vulnerability reduction of surface ships. Mr. Wilson holds B.S. and M.S. degrees in civil engineering. His most recent work has involved live fire testing of decommissioned surface combatants and introduction of a blast-hardened transverse bulkhead design into the DDG 51 FLT IIA and LPD 17. He is working on the Integrated Magazine Protection Systems Program, which is aimed at preventing catastrophic ship loss due to an attack on a surface combatant's magazines.*



Environmental Quality Systems

Overview Article Follows

TECHNICAL DIGEST

ENVIRONMENTAL QUALITY SYSTEMS

The Navy is continuing its substantial investment at the Naval Surface Warfare Center, Carderock Division to design, engineer, test and evaluate military mission compatible, efficient, and cost-effective shipboard environmental systems to allow ships to train and operate unrestricted by environmental constraints, to minimize waste generation, to eliminate the use of harmful chemical compounds, and to destroy or appropriately treat wastes on board ship. The Carderock Division provides the core technical expertise necessary to equip Navy ships with procedures, equipment and systems that are best suited and/or designed to meet the unique requirements within the constraints of the warship environment (e.g., space, weight, stealth, noise, logistics, manning, etc.). The engineers and scientists at the Carderock Division utilize internal and external Navy resources to expertly integrate the latest commercially and university developed technology into products for today's ships and the environmentally sound Fleet of the future.

Environmental Quality Systems: An Overview

Thomas D. Judy and Craig S. Alig

This paper describes pollution prevention and abatement technologies being developed and implemented into the Fleet as part of the Carderock Division's Environmental Quality Systems programs. The projects within this program provide the Navy with operationally superior materials, procedures, processes, and systems for pollution control that will enable ships of the 21st century to be environmentally sound to ensure that Navy ships can operate unrestricted on the world's navigable waters. The potential impact of the developing Uniform National Discharge Standards on ships of the future is discussed. The technical papers in this program are introduced and their relation to current and future technology development is presented. These technologies will help to maintain Fleet readiness through the application of affordable and reliable technology, while allowing unrestricted ship operations worldwide, even as environmental regulations become more stringent.

Introduction

The focus of efforts in the Environmental Quality Program at NSWCCD is to provide the Fleet with self-sufficient, environmentally sound ships and submarines for the 21st century. Environmentally sound vessels comply with existing and anticipated environmental laws and regulations, thus allowing unrestricted worldwide operations. All Navy vessels must have unrestricted access to navigable waters and ports worldwide as a prerequisite to implement U.S. national defense and foreign policy. Navy responsibilities increasingly encompass forward presence, peacekeeping, humanitarian, and other-than-war duties that require prolonged operations in littoral and other environmentally sensitive waters (e.g., the "special areas" designated by the International Maritime Organization). Therefore, the Navy must be able to routinely operate in areas where waste discharges are severely restricted and where other environmental regulations may interfere with their mission. Environmental laws and regulations include the implementation of major international agreements such as the Montreal Protocol on Substances that Deplete the Ozone Layer and the International Convention for the Prevention of Pollution from Ships (MARPOL). Additionally, there are foreign host country requirements and individual port rules as well as national, state, and local laws and regulations. These environmental requirements impose restrictions on solid, liquid, and gaseous emissions from Navy ships and submarines. Additional requirements focus on other emerging environmental issues; for example, protected marine mammals can have significant impacts on Fleet readiness by restricting training and testing operations. Figure 1 illustrates the long history of the Shipboard Environmental Quality Program, which has been and will continue to provide the Fleet with the tools needed to accomplish its unique military mission.

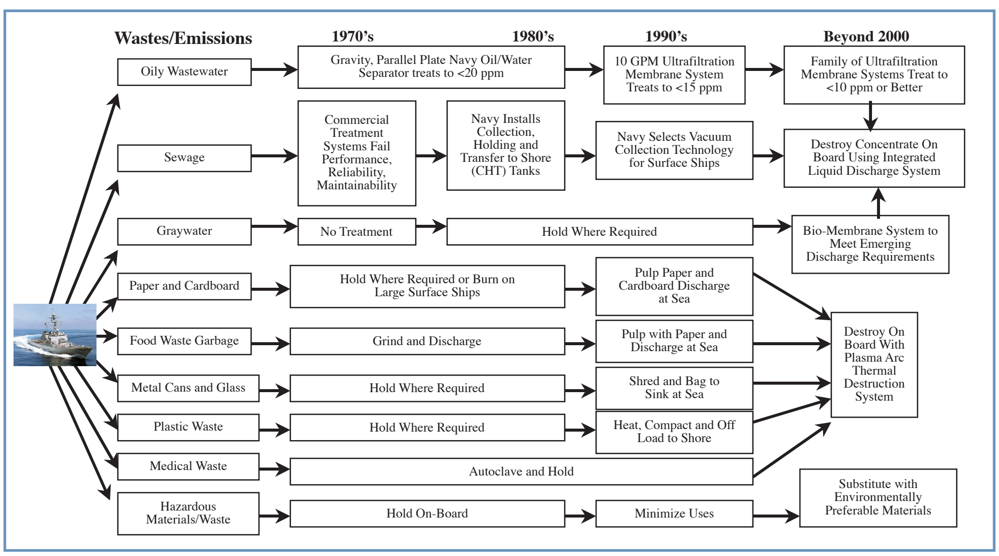


Figure 1. Evolution of pollution control for ships.

Environmental Quality Systems Primer

The development work in Environmental Quality (EQ) is aimed at providing the Fleet with increased operational capability and enabling Navy ships to comply with environmental laws and regulations. EQ initiatives address all phases of the development process for ship pollution abatement systems including (1) research and development; (2) test, evaluation, and Fleet implementation; and (3) in-service and life-cycle engineering. Many diverse technologies are being investigated for application to ship operating and maintenance activities. These technologies can be grouped into the following four major thrust areas: solid waste management, liquid waste management, pollution prevention/material safety, and in-service and life-cycle engineering.

In the solid waste management area, Congress directed the Navy to install shipboard solid waste processing equipment as a step toward meeting the intent of MARPOL Annex V. Food/paper/cardboard pulpers, metal and glass shredders, and plastic waste processors have been developed, procured, and installed on much of the surface Fleet. For the relatively small quantity of difficult-to-handle solid waste that is not effectively managed by the current equipment, incinerators using currently available commercial technology are being modified to meet the unique requirements of a warship. For future applications, when the discharge of processed solid waste into the marine environment may be prohibited, advanced thermal destruction technology using ultra-high temperature plasma is being developed and evaluated for shipboard use.

The second EQ thrust area involves the management of liquid wastes including oily wastes, blackwater (sewage), and graywater (showers, laundry, galleys, etc). Oily waste technologies include oil/water separators, ultrafiltration membrane polishing systems, improved oil content monitors, and modeling of compensated fuel/ballast systems. The latter shows promise to control the unintended discharge of fuel when refueling, increase the operating range of a ship, and decrease the frequency of refueling by reducing water hide-out in the fuel tanks. Treatment technologies for graywater and blackwater include membrane bioreactors, electrochemical oxidation, ultraviolet light disinfection, and thermal destruction of concentrates and sludges.

The third EQ thrust area is pollution prevention and material safety. Pollution prevention (P2) technologies (source reduction) are developed and implemented for shipboard and shoreside applications. In the P2 afloat program, commercial off-the-shelf technologies are being tested and evaluated to reduce ship hazardous material offloads. Shoreside efforts concentrate on ship maintenance, repair, and deactivation activities. These include coatings removal and application technologies, reduced fume cutting technologies, and hazardous material treatment technologies. The goal of efforts in the material safety area is the reduction and management of hazardous materials used for ship and submarine system maintenance and for general housekeeping.

The fourth EQ thrust area is in-service and life-cycle engineering. This includes efforts to improve the reliability, maintainability, and safety of shipboard pollution abatement systems. These efforts include conducting inspections, and analyzing and trending the system component inspection data. The information obtained from the analyses and trending is used to correct design details by way of alterations to existing systems. Often, design details must be adjusted on a ship-by-ship basis to maximize the effectiveness of the overall system. A parallel path for the use of this information is feedback to the Navy's EQ research programs for the development of new applications and advanced state-of-the-art systems. Engineering services are provided for sanitary wastewater systems, oil pollution abatement systems, solid waste equipment, and solid waste incinerators. This in-service engineering process is maintained for these systems throughout the life cycle of the ship.

The diversity of the Environmental Quality Program is illustrated further by the following efforts, which are outside of the four main thrust areas. One such project addresses the elimination of ozone-depleting substances by finding alternative ozone friendly refrigerants to retrofit in existing shipboard air conditioning plants, and by developing new air conditioning and refrigeration plants that use ozone-friendly refrigerants. Another effort is investigating the effects of distant underwater explosions on bottlenose dolphins and Right whales. Studies are also being conducted to identify Navy ship operational processes and procedures that could contribute to the introduction of non-indigenous species transported in ballast water and to identify potential prevention and treatment options. Environmentally friendly biological fouling control is being addressed for hull coatings, heat exchangers, and seawater piping. As a final example, an automated underwater hull-cleaning vehicle that captures debris from hull cleaning operations is being developed.

Total Ownership Cost

The Chief of Naval Research has identified Total Ownership Cost Reduction as one of the 12 approved Future Naval Capabilities. Affordable Environmental Compliance, which leads to unrestricted worldwide operations, is one of the enabling capabilities for Total Ownership Cost Reduction. Environmental compliance results in tangible and intangible costs. For example, Congress directed the Navy to install shipboard solid waste processing equipment on a very aggressive schedule to eliminate the discharge of plastics waste at sea and as a step toward meeting the intent of MARPOL Annex V (which prohibits solid waste discharges from ships in environmentally sensitive "special areas" such as the North Sea). The development, procurement, and installation of this interim solution for the Fleet will cost approximately $750M.

Other examples of tangible costs are:

- Delays, mitigation measures, and litigation associated with protecting marine mammals and endangered species during at-sea operations and testing (e.g., postponement of the 1994 shock trial for DDG 53 cost $3.7M)

- Increased ship propulsive fuel consumption and more frequent dry dockings due to the banning of underwater removal of hull biofouling in certain ports (underwater hull cleaning saves $20 to 60M/year in fuel costs)

- Off-loading of ships' solid and liquid wastes to private contractors who are in a position to demand maximum fees (the Fleet paid $70M for shoreside liquid waste disposal worldwide in FY95)

Examples of intangible costs include:

- Inability to fully support the Navy's "Forward...From the Sea" strategy and the JCS Joint Vision 2020 that require the Navy to carryout war fighting and operations other than war without violating the environmental regulations of beneficiary nations

- Inability to conduct realistic, Navy, joint, and NATO training exercises

- Reduced ship speed, range, and maneuverability attributable to the attachment of marine organisms to underwater portions of the hull

Future Environmental Quality Emphasis

The emphasis of future Environmental Quality efforts will focus on ensuring that naval operations are unrestricted in littoral and other environmentally sensitive waters and on the reduction of Total Ownership Cost by affordable onboard treatment or destruction of ship-generated wastes. For example, research is underway to combine all shipboard liquid waste treatment systems into an integrated liquid discharge system (ILDS). The ILDS will include thermal destruction technology to treat low volume liquid waste residues including waste oil from oil/water separators, oily concentrate from oily waste membrane ultrafiltration systems, and concentrate from the membrane bioreactor treatment of graywater or sanitary waste. In the papers that follow, two of the technologies that would provide concentrated waste to the ILDS are described, the membrane bioreactor for sewage and graywater and the ultrafiltration membrane system for oily bilgewater. The ILDS concept will allow Navy ships to operate anywhere and visit any port unencumbered by liquid waste environmental regulations.

Even with the addition of solid waste equipment (plastic processors, pulpers, and shredders), large Navy ships have a significant need for thermal destruction technology to process waste that is not managed effectively. Commercial incinerator technology is being investigated for shipboard use. Another thermal destruction technology is ultra-high temperature plasma arc, which has the potential for extremely fast and more complete destruction of complex organic molecules. The development of plasma-arc technology for shipboard use is discussed in one of the technical papers that follow.

Uniform National Discharge Standards

The lack of uniformity in state and local regulations governing incidental discharges from vessels of the armed forces has presented significant operational problems for the Navy. Uniform National Discharge Standards (UNDS) being developed cooperatively by the Department of Defense and the Environmental Protection Agency will provide standard provisions to regulate non-sewage incidental discharges. These standards will have a significant impact on future Environmental Quality efforts. The purpose of UNDS is to enhance operational flexibility of vessels of the Armed Forces, advance Navy development of environmentally sound ships, and stimulate development of innovative pollution control technology. Specific discharges have been identified (Phase I) and performance standards for marine pollution control devices are being established (Phase II). Three of the discharges that were identified in Phase I as requiring control are addressed in the following papers, oily bilgewater, graywater, and compensating fuel ballast. It is anticipated that the UNDS and international regulations will necessitate the redesign/update of some existing pollution control devices and the development and integration of new technologies.

Technical Papers

The five technical papers that follow illustrate the range of technical development that is conducted under the Environmental Quality umbrella. The first paper addresses the treatment of bilgewater to reduce the concentration of oil in discharges to less than 15 ppm. A first-stage density separator is used in combination with ultrafiltration membrane technology. The second paper is aimed at non-oily, liquid discharges including sewage and graywater. Aerobic biological pre-treatment is combined with ultrafiltration membranes and ultraviolet light disinfection to satisfy anticipated effluent discharge requirements without the use of toxic chemicals as disinfectants. The third paper addresses the pollution caused by the overboard discharge of fuel during refueling of compensated fuel/ballast ships.

This paper illustrates how computational fluid dynamics, structural modeling, and scaled physical modeling can be used to address environmental issues and enhance military operations at the same time. The fourth paper describes the plasma-arc thermal destruction technology that is designed to convert shipboard solid waste into gas and an easily storable, benign, solid product resulting in a waste volume reduction of 75 to 1. The final paper illustrates the technical issues associated with the in-service and life-cycle engineering of shipboard pollution abatement systems, in particular the integration of new, large capacity oil/water separators.

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__Craig S. Alig__ is an environmental engineer and department head in the Environmental Quality Department at NSWCCD. He has B.S. and M.S. degrees in agricultural engineering from Penn State University and a M.S. degree in engineering administration from George Washington University. Mr. Alig has led numerous projects to control and treat wastewater, solid waste, hazardous waste, and oily waste for the Navy, Coast Guard, Marine Corps, Department of Commerce, and others. In his present position, he directs research and development, test and evaluation, life-cycle management, and in-service engineering for the Environmental Quality Program at the Carderock Division.

Development of Ultrafiltration Membrane Systems to Treat Navy Bilgewater

Lawrence P. Murphy

Advanced oily waste ultrafiltration membrane systems are being developed for the shipboard treatment of bilgewater. Three membrane systems: 5, 10, and 50 gpm are in various stages of development with the10 gpm system in the most advanced developmental stages. All three are two-stage systems that use a density/ gravity separator and ultrafiltration membranes. The development of the 50 and 5 gpm oily waste ultrafiltration membrane system designs are discussed in this paper and include lessons learned from the 10 gpm system. Completion of this research and development effort will provide the Fleet with a solution to treat bilgewater.

Introduction

The first bilgewater treatment systems were developed and implemented in the 1970's and 1980's. They were based on density separation and used coalescing parallel-plates to separate oil droplets from water. The two most common systems are the Navy 10NP and the similar C50 separator. The 10NP, 10 gallons per minute (gpm) oil/water separator (OWS) (Figure 1) was designed for destroyers and cruisers. The 50 gpm, C50 OWS was designed to treat bilgewater on aircraft carriers and large amphibious ships, which typically have higher generation rates. The parallel-plate systems work well on "wet-bilge" ships, with large quantities of water and relatively low concentrations of oil and contaminants (e.g., detergents, dirt, corrosion products). Improved ship design and bilgewater management practices resulted in "dry-bilge" ships, with less water, resulting in higher overall concentrations of oil and contaminants. The higher concentrations of oil and contaminants impedes the ability of the parallel-plate OWS to reliably produce discharges with less than 15 ppm oil content. Therefore, a secondary treatment device is required to consistently meet the 15 ppm limit.

Ultrafiltration Oily Waste Membrane Systems

Deployment of DDG 51–Class ships in the 1990s brought the dry-bilge/parallel-plate separator issue to the forefront. The DDG 51–Class design significantly decreased bilgewater generation rates through the selection of a gas turbine propulsion plant, reverse-osmosis potable-water plant, and other waste minimization/segregation designs. Significantly less bilgewater (500 gpd) was generated, but the concentrations of oil and contaminants were higher and were difficult to treat with the parallel-plate OWS.

The Division identified the problem and began to develop secondary treatment systems that would consis-

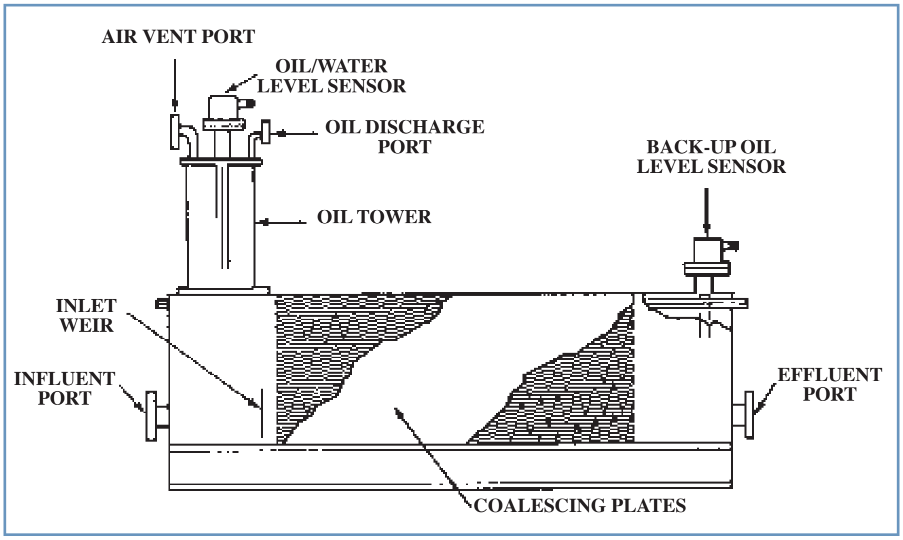

Figure 1. Navy 10NP oil/water separator.

tently produce a discharge with less than 15 ppm oil content. Laboratory evaluations and a small-scale shipboard evaluation established ceramic, ultrafiltration, and cross-flow membranes as the leading candidate technology to provide reliable secondary treatment of parallel-plate OWS effluent. Ultrafiltration technology physically separates oil and water. The semi-permeable membranes allow water molecules to pass through the membrane, but the larger oil droplets are retained within the membrane. The two technologies work well together; the density separator removes large oil droplets, and the membrane removes the remaining emulsified oil.

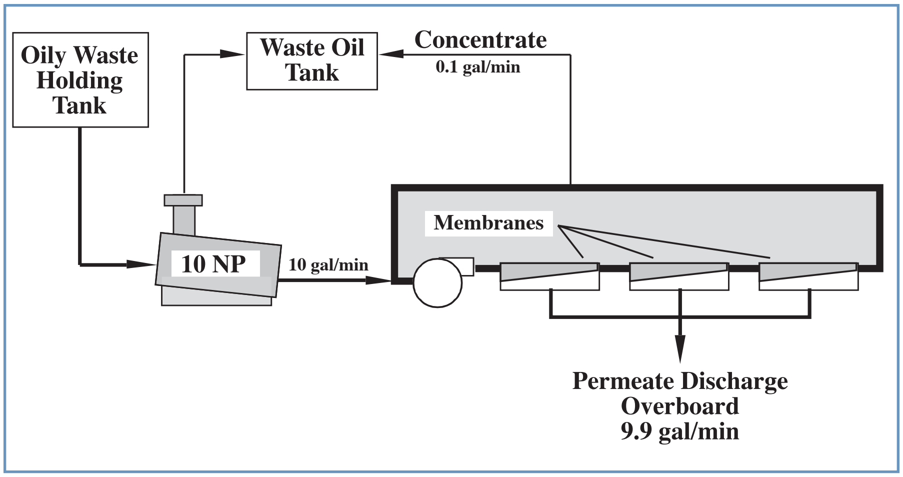

Figure 2. Prototype 10 gpm oily waste membrane system schematic.

Based on the results of small-scale tests, a full-scale prototype 10 gpm oily waste membrane system (OWMS-10) was developed and evaluated aboard USS CARNEY (DDG 64) in 1996. The full-scale prototype performed secondary treatment of the Navy 10NP parallel-plate OWS effluent as shown in Figure 2. The successful prototype OWMS-10 evaluation aboard USS CARNEY demonstrated an average effluent that contained less than 5 ppm oil, a 100:1 volume reduction factor (ratio of bilgewater processed to concentrated waste stored in waste oil tank for disposal ashore), and a membrane replacement/cleaning cycle of 15 months or greater. System design and component selection were two major reasons for the successful evaluation aboard CARNEY. With the exception of the ceramic membranes, all components in the prototype OWMS-10 are standard marine equipment: pumps, piping, temperature and pressure sensors, and a programmable logic controller (PLC). The PLC allows fully automatic operation of the system. Figure 3 shows the prototype OWMS-10 installed aboard USS CARNEY.

As a result of the successful evaluation aboard USS CARNEY, an engineering development model (EDM) OWMS-10 was installed aboard USS RUSHMORE (LSD 47), Figure 4. Performance specifications were developed for the DDG 89 and follow (the remaining 12 ships in the class) and the LPD 17–Class (7 ships). The DDG 89 and follow oily waste membrane systems have been procured, and first-article tests are complete. LPD 17 is currently procuring OWMS-10 systems. The ceramic ultrafiltration, cross-flow membrane technology has transitioned from small-scale test and evaluation to full-scale, 10 gpm shipboard systems.

Figure 3. Prototype 10 gpm oily waste membrane system installed aboard USS CARNEY (DDG 64).

Oily Waste Membrane Systems Status

As the OWMS-10 system transitions to the Fleet, research and development efforts are focused on two additional oily waste membrane systems that will provide bilgewater treatment solutions to meet current and future Fleet requirements. A 50 gpm oily waste membrane system (OWMS-50) and a 5 gpm Navy integrated membrane system (NIMS-5) will be developed and transitioned to the Fleet. The NIMS-5 combines density separation and ceramic ultrafiltration membrane technology in a single system.

Figure 4. Engineering development model 10 gpm oily waste membrane system.

50 GPM Ultrafiltration Oily Waste Membrane System

The move from a 10 to a 50 gpm membrane system appears to be a simple scaling problem (add five times as many membranes). However, the addition of multiple membrane modules significantly increases the number of design parameters and, potentially, the overall system complexity. The ceramic membranes are the most expensive (and only consumable) components in the system; therefore, optimization studies are required to achieve the most cost-effective system design. Several critical design parameters and analytical methods to evaluate each were identified during small-scale tests and development of the OWMS-10. These design tools were used in the development of the OWMS-50 system.

Design Studies

The critical parameters identified for ultrafiltration oily waste membrane systems are membrane flux rate, transmembrane pressure, and cross-flow velocity. Membrane flux rate is the permeate flow rate divided by membrane surface area; typical units are gallons per square foot per day (gfd). Transmembrane pressure is the average differential pressure across the membrane surface. (Concentrate pressure varies along the length of the membrane surface due to cross-flow velocity, but the permeate pressure is essentially uniform along the length of the membrane.) Cross-flow velocity is the average concentrate flow velocity tangential to the surface of the membrane. While each of these parameters is important independently, they are all interdependent (i.e., a change in cross-flow velocity impacts transmembrane pressure; a change in flux or the number of membranes impacts cross-flow velocity). Therefore, the system must be analyzed as a whole to determine the cumulative system performance. This requires an iterative process when solving for optimum membrane configurations. A design optimization program, developed during the OWMS-10 design, was upgraded to analyze the multiple configurations of a 50 gpm system. The design optimization program evaluates the multiple system configurations and identifies designs that best meet the Navy's performance requirements for a 50 gpm membrane system.

- Membrane replacement/cleaning intervals (greater than 6 months)
- Size and weight (able to back-fit in a machinery space)
- Power consumption no more than 75 kW.

Membrane flux studies conducted by the Division indicate a critical flux rate for ceramic membranes to treat oily waste. Flux rates that exceed 60 gfd appear to cause accelerated fouling of membranes. The quantity of bilgewater a given membrane is able to process, before requiring replacement or cleaning, is dependent on how fast water permeates through the membrane. Bilgewater that is permeated too fast through an insufficient area severely reduces the total quantity of bilgewater a membrane can process. Bilgewater generation rates require that the membrane process at a rate of 50 gpm. The dense-pack membrane modules selected for the OWMS-50 each contain 120 ft^2 of surface area. Therefore, a minimum of 10 membrane modules is required for the OWMS-50 to maintain a flux rate below 60 gfd. The design optimization program analyzed the 50 gpm membrane system using up to 20 membranes in hundreds of configurations. The optimization indicated that 12 membrane modules would provide the necessary membrane life and result in a membrane flux of 50 gfd at a 50 gpm design flow rate.

The amount of pressure required to produce a unit flow increases as a membrane fouls. Therefore, the more transmembrane pressure a system can produce, the longer the membranes will last (as long as maximum membrane pressures are not exceeded). There are several ways to configure 12 membranes in a system, depending on the arrangement of membranes in parallel and series. The OWMS-10 uses three membranes arranged in series, which is described as a 1 x 3 (number of parallel paths x number of membranes in series). In the OWMS-50, 12 membranes could be installed in multiple configurations (12 x 1, 6 x 2, 4 x 3, 3 x 4, etc). An increase in the number of membranes in parallel allows an increase in transmembrane pressure, at the penalty of increased recirculation pump flow. The design optimization program was used to determine the trade-off of membranes in series versus membranes in parallel. Results indicated the 6 x 2 membrane configuration would provide the best combination of membrane life and power consumption requirements.

During small-scale and OWMS-10 evaluations, it was found that a cross-flow velocity of 10 feet per second was necessary to process bilgewater with ceramic ultrafiltration membranes. This cross-flow velocity provides the required membrane replacement/cleaning interval, without excessive power consumption. Each of the six parallel flow paths require 300 gpm when applied to the dense-pack membrane modules selected for the OWMS-50, for a cumulative concentrate flow rate of 1800 gpm. The cross-flow velocity was the only variable held constant while using the design optimization program, but an additional computational fluid dynamics (CFD) study was required to ensure equal flow distribution was obtained through each of the six parallel legs of the concentrate header. Results of the CFD study identified multiple header configurations that deliver equal flow distribution. The concentrate header used in the prototype OWMS-50 provides equal flow rate to each of the legs, without sacrificing manufacturability.

OWMS-50 Prototype System

The appropriate design parameters were implemented in the OWMS-50 design after the studies were completed. Figure 5 is a schematic of the prototype OWMS-50, which operates similarly to the OWMS-10. The 6 x 2 membrane configuration provides a system that meets the Navy requirements to process bilgewater for 6 months before membrane replacement/cleaning. Figure 6 shows the prototype OWMS-50 installed in the oily waste test and evaluation laboratory at NSWCCD, prior to shipboard evaluation. A performance specification is being developed to transition the system to the Fleet based on the prototype system's design. Lessons learned during the shipboard evaluation will be incorporated into the performance specification.

5 GPM Navy Integrated Membrane System

During the development and transition of the OWMS-10, it was recognized that future ships would have dryer bilges, a fact that requires future bilgewater treatment systems to address further concentrated waste, but at a lower capacity. To meet this need, the Division is developing a 5 gpm Navy integrated membrane system (NIMS-5) that combines a "bulk" oil separator and ultrafiltration membrane system. The shipboard evaluation of the OWMS-10 identified the need for the Navy 10NP, as a preprocessor, to remove the "bulk" oil prior to operation of the membrane system. The NIMS-5 is following this process approach, but the "bulk" oil separator is being selected on its ability to be integrated with a membrane system. The two technologies combined in one system will produce a smaller, simpler, and less expensive system.

A survey was conducted to identify candidate commercial "bulk" oil separators. Each separator was rated for integration with a membrane system, including maintenance requirements, separation efficiency, size, etc. Two commercial separators, a centrifugal separator and parallel-plate separator, were selected for a laboratory evaluation simulating various bilgewater conditions. Figure 7 is a plot of separator efficiency versus oil droplet size being processed. Laboratory tests of the bulk oil separators identified the cen-

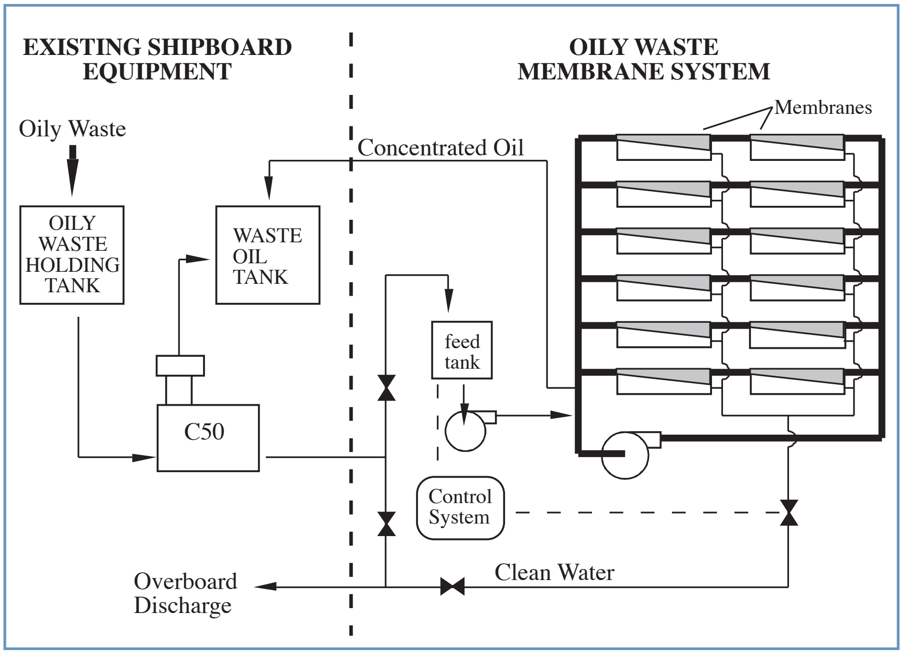

Figure 5. Prototype 50 gpm oily waste membrane system schematic.

Figure 6. Laboratory checkout of the prototype 50 gpm oily waste membrane system.

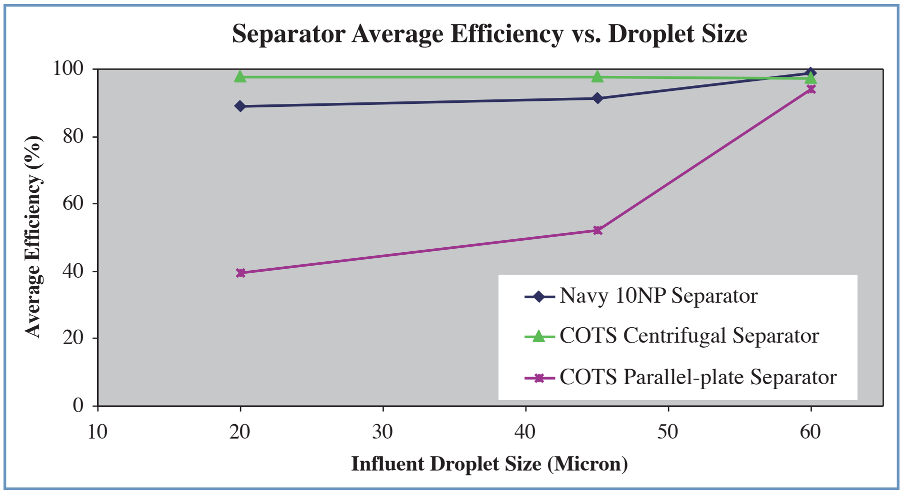

Figure 7. Bulk oil separator laboratory test data.

trifugal separator as a good candidate for the NIMS-5, with a very small footprint and excellent separation efficiency. The centrifugal separator is being evaluated aboard ship to determine its maintenance requirements.

In addition to the new “bulk” oil separator, the NIMS-5 is targeting reduced maintenance and increased automation by evaluating two additional components. A sliding shoe feed pump, which has performed well in Navy oily waste transfer systems, is being evaluated as a potential feed pump. An automated strainer is being evaluated to eliminate the maintenance-intensive manually cleaned strainers. Both components are being evaluated on board ship with the centrifugal separator to demonstrate their effectiveness at reducing maintenance and increasing automation.

A prototype NIMS-5 is being designed. Optimization of the membrane design portion of the NIMS-5 is being conducted using the OWMS-10 and OWMS-50 design optimization program. A prototype system will be developed and evaluated after completion of the study, and a performance specification will be produced to transition the system to the Fleet.

Summary

The ultrafiltration membrane system project has identified a reliable treatment technology for the shipboard treatment of bilgewater. Ultrafiltration membrane systems will be transitioned into several classes of new construction ships, DDG 89 and follow-on and LPD 17. Lessons learned from the development of the 5, 10, and 50 gallon per minute systems are being incorporated into performance specifications, which will provide a fleet-wide oily waste treatment solution.

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The Membrane Bioreactor: A Promising Technology for Shipboard Sewage and Graywater Treatment

James E. Higgins

Fleet operators around the world are looking for a more economical and environmentally friendly way to handle non-oily wastewater from their showers, laundries, galleys and toilets. National and international laws require ships to collect and hold sewage when operating within 3 nautical miles of shore. The in-port costs of non-oily wastewater disposal are a substantial burden to the Fleet. This paper describes the status of efforts to develop shipboard non-oily wastewater treatment. The challenge is to develop treatment systems that meet shipboard requirements for affordability, compactness, low manning/maintenance, high reliability, safety, noise, vibration and shock, and will meet anticipated discharge requirements.

Introduction

Large Navy ships, such as aircraft carriers and some amphibious support vessels, generate up to 350,000 gal/day of non-oily wastewater (combined sewage and graywater). Graywater is waste from hotel and commissary activities aboard ship, including showers, sinks, galley, scullery and laundry equipment, and comprises 50% to 90% of the non-oily wastewater produced by the ship. Federal law prohibits the discharge of raw sewage from ships within 3 nautical miles (nm) of shore.

Many Navy ships are equipped with a Type III Marine Sanitation Device (MSD),[1] known as a collection, holding, and transfer (CHT) system. CHT systems are designed to collect and transfer graywater and sewage to shore receiving facilities (or barges) while in port, to hold sewage and discharge graywater overboard while transiting navigable waters, and to discharge sewage and graywater overboard when the ship is beyond 3 nm. Sewage holding times vary from ship to ship, but tankage typically is sized to provide 12-hr holding capacity. Certain locations like the Panama Canal, which can take up to 10 to 15 hr to navigate, put significant strains on the ship's force, requiring toilets to be secured for extended periods until passage is complete. Furthermore, increasing needs for littoral operations by the Fleet result in CHT tanks that are insufficiently sized on many ships. In addition to capacity problems for ships underway, the current practice on many ships is to avoid the overboard discharge of graywater in any port due to local regulations that vary widely. This policy results in greater volumes of wastewater that must be offloaded to shore, a costly process, especially in foreign ports. Ships occasionally use paper plates for meals overseas due to the significant costs of waste disposal. Along with escalating costs, foreign waste haulers may be unreliable, placing additional burden on the ship.

Vacuum collection, holding, and transfer (VCHT) systems are shipboard wastewater systems that use low volume, freshwater flush sewage collection. The VCHT systems are for sewage only; graywater is collected using a gravity system and plumbed to tanks. The VCHT system uses 1 to 2 pints of freshwater per toilet flush, whereas the CHT system uses 5 to 7 gallons of seawater per flush. The lower volume, higher concentration VCHT sewage represents less waste generated and results in reduced onboard tankage required. VCHT systems are installed on an increasing number of ship classes, including DD 963, DDG 51, MHC 51, and PC 1, and are planned for the LPD 17 and CVN 77.

An alternative to shipboard holding tanks, and one that would reduce offload costs, is the use of onboard wastewater treatment systems. Conventional land-based biological wastewater treatment plants rely on large aeration tanks with settling/clarification tanks and long (>20 hr) hydraulic retention times (HRT) to remove suspended solids and oxidize organic matter. These systems require frequent attention, including such operations as concentrated sludge wasting and periodic chemical additions, and occupy significant space. As a result, conventional biological systems are not well suited for shipboard applications where space and manning are limited.

A Type II Marine Sanitation Device that has been used by the Navy is installed on the LHA-1–Class ships. A Type II MSD is defined as a "flow-through and discharge" device that produces an overboard effluent with a fecal coliform (FC) count of not more than 200 colonies/100 mL, and a total suspended solids (TSS) level of not more than 150 mg/L. The unit installed onboard the LHAs is a thermally accelerated, extended aeration sewage treatment system. After treatment and prior to discharge, the plant effluent is disinfected with chlorine to destroy any remaining pathogenic organisms. The influent box of the plant receives the raw sewage where it is passed through a comminutor and into an aeration tank. In the aeration tank, the sewage is mixed with air and heated to facilitate microbial treatment. The liquid is then fed to the sedimentation tank where sludge is allowed to settle out and is returned to the aeration tank. The clear liquid flows to the chlorination effluent holding tank where any remaining pathogenic organisms are destroyed. The effluent is ready for discharge at this point. The system is designed to achieve maximum effluent discharge standards of 150 mg/L TSS and 200 colonies/100 mL FC. The system works best when operated continuously. The Navy has had trouble maintaining the system and operating it as required while achieving and maintaining consistently high effluent quality. This can probably be attributed to a lack of continuous system operation. A biological system cannot simply be turned on when entering coastal waters and immediately achieve proper sewage treatment conditions; it takes some time for a sufficient quantity of the bacteria that are necessary for aerobic conditioning to develop. This fact is amplified if the system has lapsed into a septic, non-aerobic condition, or has been inactive.

However, short-term aerobic biological pre-treatment is attractive when coupled with membrane ultrafiltration systems. Membranes reject a high percentage of suspended solids and bacteria, and bio-conditioning stimulates microbial activity that consumes the majority of the organic content in the wastewater. If these systems can be designed to operate effectively at shorter HRT (e.g., <15 hr), they offer major potential for shipboard non-oily wastewater treatment. This paper describes the research and development efforts to demonstrate and validate the membrane-bioreactor (MBR) concept, using in-tank, hydrophilic, ultrafiltration membranes.

Membrane-Bioreactor Concept

Membranes are thin barriers or films of material that allow certain substances to pass, while rejecting other material. Membrane throughput, or flux (Equation (1)), is controlled by the driving force (positive or negative pressure) and is reduced over time by the fouling rate. Membranes provide a straightforward and relatively simple means to separate and concentrate waste streams (up to 98% by volume), decrease waste volumes, and substantially increase shipboard waste holding time.

$$J20 = Q\mu / A \qquad (1)$$

Where J20 = membrane flux Q = permeate flow rate
μ = absolute viscosity
A = membrane surface area.

The combination of membranes with biological wastewater treatment has been reported in the literature for over 30 years.[2] Many of the initial limitations of membrane separation have been overcome, making the MBR process a viable alternative to many conventional processes in biological wastewater treatment. The MBR is similar to a conventional activated sludge system, but instead of conventional final clarifiers, the MBR uses membrane filtration to separate the solids from the liquid effluent. The MBR process maintains higher biomass concentrations and uses smaller aeration tanks than conventional systems, while achieving comparable treatment. The nearly complete conversion of influent organic matter to carbon dioxide and water is accomplished by maintaining a highly concentrated, healthy biomass and retaining the high molecular weight compounds with the membranes.

As a result of the high biomass concentration, a high oxygen demand must be satisfied in aerobic MBR systems to ensure continuous biosynthesis and cell growth. Maintaining a low ratio of food (influent waste) to microorganisms in the reactor results in minimum sludge generation and wastage, reduced plant size, and retention of waste-specific microorganisms. Figure 1 shows the standard in-tank MBR configuration with ultraviolet (UV) post-treatment to ensure disinfection of the effluent. The compact nature of this design makes it attractive for shipboard application, where space and operations personnel are limited.

Membrane effluent quality can be reflected in many standard parameters that measure biological, chemical, and physical changes in the wastewater. There are three principal parameters used to regulate wastewater effluent[1] 5-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), and FC bacteria. The determination of BOD_5 involves the measurement of dissolved oxygen used by microorganisms in the biochemical oxidation of organic matter. This measurement provides an indication of the amount of organic matter, or food for the microbes, present in the wastewater. The TSS measurement represents the non-filterable fraction of the total solids in the wastewater. It is determined by passing a known volume of liquid through a filter with 1.2-μm nominal pore size, then evaporating the filtrate at 104°C and weighing the residue. FC bacteria, found naturally in high concentrations in sewage, are used as an indicator for less numerous pathogenic organisms that are more difficult to isolate and identify and that may be present in the wastewater. The number of FC bacteria present can be determined by involving successive dilutions followed by detection of gas formation or by filtration and growth in a nutrient medium.[3]

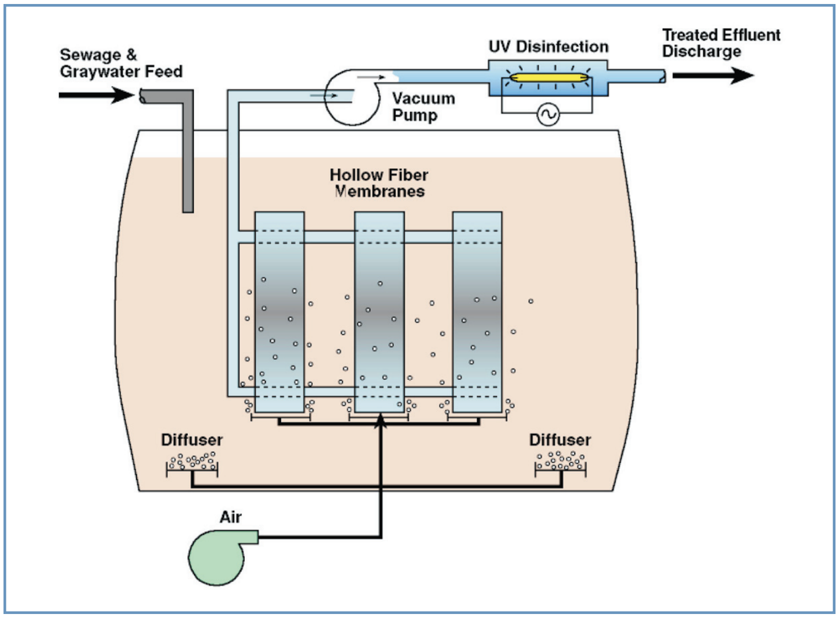

Figure 1. Submerged membrane bioreactor.

Description of Membranes

The membranes used in the MBR treatment systems evaluated are an in-tank design, meaning they are immersed in the bioreactor. There are several manufacturers of these membranes worldwide. Each manufacturer's membrane design includes unique features, but all can be grouped into two general categories: hollow fibers and flat sheets.

Hollow-fiber membranes are constructed of hydrophilic polymeric material and are arranged in a compact bundle of flexible fibers. As shown in Figure 1, the hollow fibers are connected to a common header pipe that is plumbed to a vacuum source located outside of the bioreactor. The pump is used to create a pressure differential across the membranes, inducing flow through the membrane walls. The clean permeate flows to the header pipe and out of the bioreactor. Coarse-bubble aeration is used under the membrane bundle to provide the oxygen necessary for survival of the biomass and the scouring required to keep the hollow fibers from clogging with solids. Hollow-fiber membrane modules have large surface area-to-displacement volume ratios (approximately 300:1 ft^{-1}) and, coupled with a relatively low driving pressure, provide good resistance to clogging. The hollow-fiber membrane is the most common type used in MBR processes.[4,5]

The other principal type of in-tank membrane used in the MBR is the flat sheet or panel. Membrane panels are arranged vertically in a rectangular box configuration, with a small gap between each panel. Similar to the hollow-fiber membranes, coarse bubble aeration is used to scour the panels. During operation, the aerated waste rises between the panels, causing a circulation of sludge within the tank. Each panel is connected to a common permeate collection header, and permeate is drawn out by a vacuum source, similar to the hollow-fiber membrane system. The flat sheet membrane module has a smaller surface area-to-displacement volume ratio (approximately 50:1 ft^{-}) than the hollow-fiber membrane module.[6]

Navy System Development and Demonstration

In-tank membranes were tested successfully on a small scale, processing a combined conventional (gravity-collected, freshwater flush) sewage and graywater mixture. Based on the tests, a 75-person, shipboard-scale MBR was designed, fabricated, and demonstrated pierside at Norfolk Naval Base. The design and fabrication effort was conducted in collaboration with industry experts. The Aerated Membrane Treatment System (AMTS) used hollow-fiber membrane modules, and treated non-oily wastewater from various Navy ships over several months. The system was sized to process 2.3 gal/min of waste generated from ships equipped with gravity-collected graywater and vacuum-collected sewage systems. The system was designed to meet the effluent quality goals shown in Table 1, and to provide at least a 15-day holding capacity for a 75-person vessel. The AMTS was installed on a 12-meter-long mobile trailer (Figures 2 and 3) and consisted of a collection tank, an equalization/bioreactor tank with separate compartments for equalization, bioreactor and membranes, and associated system equipment.

Table 1. Effluent quality thresholds for combined sewage and graywater treatment.

Water Quality Parameter	Effluent Water Quality Threshold*
Biochemical Oxygen Demand (BOD5)	< 50 mg/L
Total Suspended Solids (TSS)	<100 mg/L
Fecal Coliform (FC)	<200 colony forming units/100 mL

*Effluent quality thresholds must be met at a 90% success rate with 95% confidence.

The purpose of the demonstration was to evaluate the performance of an automated system using ship-generated wastewater. A process flow schematic is shown in Figure 4. Suitable hoses were connected from the ship to the 3000-gallon collection tank inlet. Wastewater was transferred from the collection tank to an equalization compartment based on tank level sensors. As the system processed the waste, wastewater feed was transferred from the equalization compartment to the bioreactor to maintain a steady level. The recirculation pump transferred conditioned waste from the bioreactor to the membrane compartment for filtration. The bioreactor and membrane compartments were designed to allow waste to spill over a weir from the membrane compartment into the bioreactor to maintain a steady level in the two compartments and a well-mixed biomass. A permeate pump was used to draw permeate from the membranes and pump it through a UV disinfection chamber for FC reduction. The effluent was directed to the pier sewer. Sample connections were located at various points to monitor the characteristics and condition of the feed, biomass, and effluent streams.

Figure 2. AMTS (in-tank membrane system) pier-side demonstration system trailer.

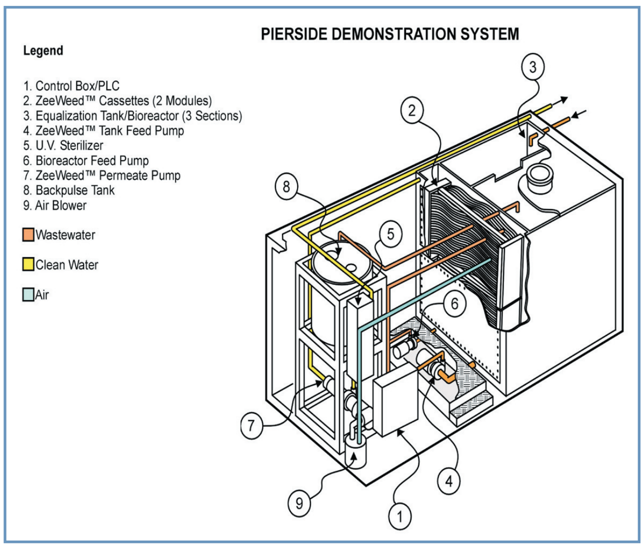

Figure 3. Expanded diagram of AMTS showing major treatment equipment.

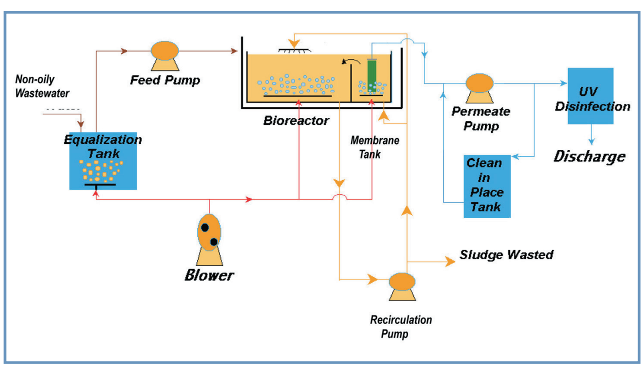

Figure 4. AMTS process.

The AMTS was initially operated pierside from May through October 1999. The demonstration was conducted in four phases: setup (5 to 7 May), startup (8 to 15 May), debugging (16 May to 8 July), and processing (9 July to 20 October). The system processed wastewater for a total of 1805 hr at 2.3 gal/min. The membrane resistance trend at the end of the test indicated that the membranes could process approximately another 5000 hr after the test, for a total service of 401 days, before any chemical cleaning (restoration) of the membranes would be required. The effluent quality goal to satisfy the limits in Table 1 was met throughout the demonstration for TSS and FC. The system did not meet the effluent quality goal for BOD_5 90% of the time with 95% confidence throughout the demonstration, primarily due to foaming and associated aeration rate limitations. However, sequential improvements made to the foam control system over the course of the demonstration resulted in increasingly higher quality effluent. Figures 5 through 7 show the three effluent quality parameters versus time for the system after the startup and debugging phases. The effluent quality threshold for BOD_5 was met during the last 42 days of the evaluation. Overall, the pierside system demonstrated an ability to process shipboard sanitary wastewater and meet effluent quality goals.[7]

Follow-on advanced development is ongoing at the Naval Surface Warfare Center, Carderock Division. The advanced development, or demonstration/validation (DEM/VAL) program, addresses shipboard design requirements (e.g., electromagnetic interference, shock, vibration, and noise) not considered in the design of the AMTS. The DEM/VAL program is aimed at forward fit shipboard applications and includes laboratory and shipboard tests. Recent laboratory tests evaluated several commercial in-tank membranes installed in separate, 1000 gal/day MBRs. Side-by-side tests evaluated the performance of hollow-fiber membranes and flat sheet membranes under identical operating conditions. Based on the laboratory evaluation, a 75-person capacity developmental graywater treatment system was designed, fabricated and installed on USS BONHOMME RICHARD (LHD 6). The system has been operated since June 2001, and will be operated continuously through September 2002. In addition, a combined graywater/blackwater prototype system is being developed for evaluation in the laboratory. The product of these evaluations will be an acquisition package including a system performance specification that will enable the Navy to acquire wastewater treatment systems for future ships.

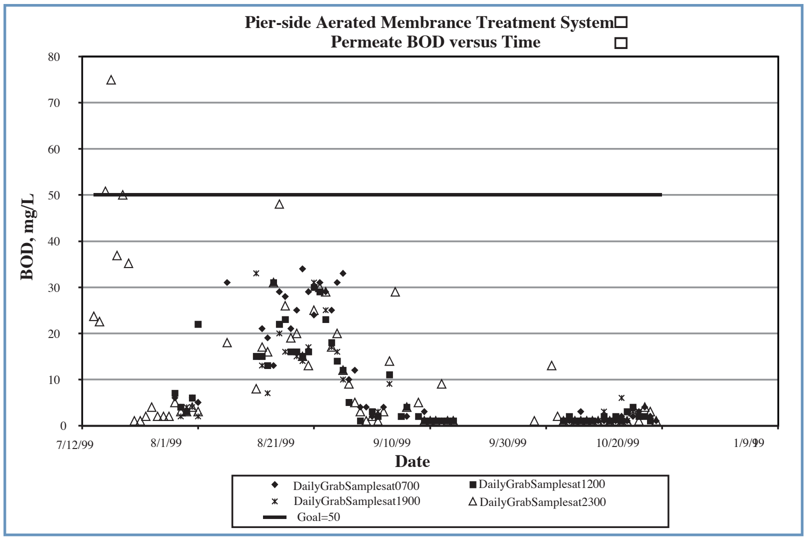

Figure 5. Effluent quality data, BOD5.

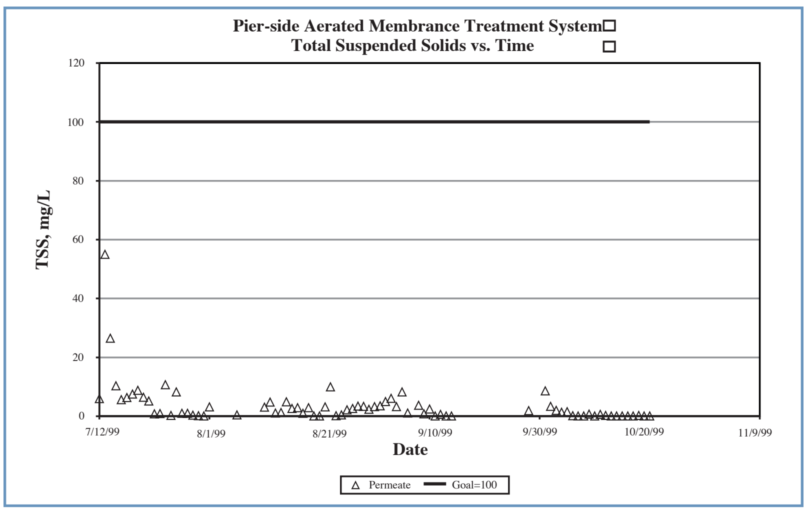

Figure 6. Effluent quality data, TSS.

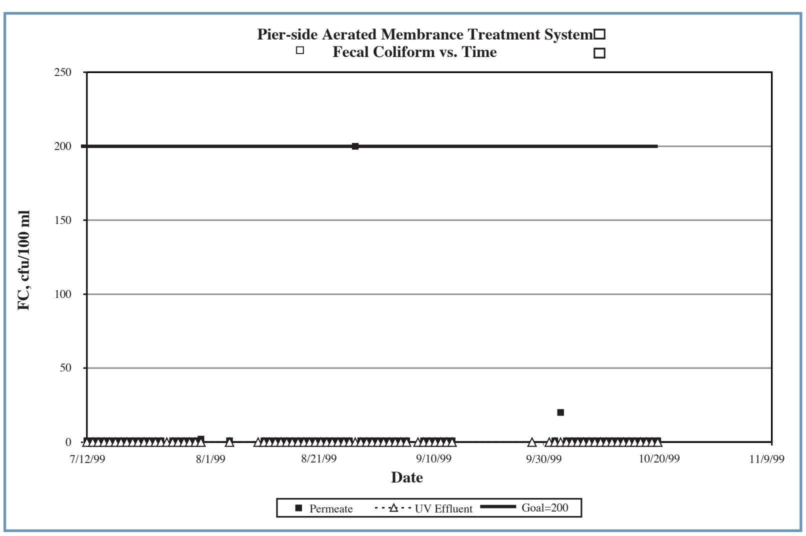

Figure 7. Effluent quality data, FC.

Summary

Membrane bioreactors are an appropriate technology for Navy shipboard wastewater treatment applications because they require a small footprint and little operator attention. Several important factors should be considered when evaluating these systems.

- Pretreatment and screening needs, which are based on the incoming waste characteristics
- Maintenance procedures, which will establish the manpower required
- Aeration requirements and aeration capacity available
- Energy consumption and annual maintenance costs

The pier-side demonstration system was designed to meet unique Navy shipboard challenges and requirements. The in-tank MBR system was evaluated on a small scale initially, using graywater mixtures developed from land-based laundry and galley sources. The bench-scale tests were transitioned to a pier-side demonstration of the AMTS, processing actual shipboard non-oily wastewater. The MBR consistently satisfied effluent goals for TSS and FC, and once modifications were installed to address biomass aeration limitation issues, the BOD_5 goal was met.

Recent laboratory tests applied lessons learned from the pier-side demonstration to develop a 75-person capacity, shipboard graywater treatment system. A system performance specification, with the goal to provide the Navy with a wastewater treatment solution that is technically sound, highly reliable, and cost-effective, is being developed.

Acknowledgments

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References

1. *Environmental compliance afloat*, OPNAVINST 5090.1B, Chapter 19 (1 Nov 1994).

2. Papers presented at the 1st International Meeting on Membrane Bioreactors for Wastewater Treatment, School of Water Sciences, Cranfield University (Mar 1997).

3. Wastewater Engineering - Treatment, Disposal and Reuse, 3rd Ed., Metcalf & Eddy, Inc., revised by Tchobanoglous, G., and F. L. Burton, Irwin McGraw-Hill, New York (1991).

4. *ZeeWeed-230 module*, Zenon Environmental Inc., Burlington, Ontario, Canada.

5. "*Instruction manual for the LHE 234 hollow fiber membrane element*," Mitsubishi-Rayon Co., LTD, Membrane Products Department, Tokyo, Japan.

6. *Kubota submerged membrane unit – submerged type membrane separation device*, and *Submerged membrane process for domestic sewage treatment*, Kubota Corp., Environmental Engineering Division, Membrane System Department, Tokyo, Japan.

7. Adema, C. M., et al, *Membrane biological non-oily wastewater treatment system for ships*, Paper presented at the United States-Japanese Natural Resources (USJR) Conference, Tokyo, Japan (May 2000).

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Compensated Fuel/Ballast Ships: Minimizing Overboard Discharge of Fuel and Maximizing Fuel Capacity During Refueling

Raymond F. Schmitt

Solutions are being developed for problems encountered during the refueling of compensated fuel/ballast ships - pollution caused by overboard discharge of fuel and reduced fuel capacity due to water hideout. A computational fluid dynamics model, developed to propose and evaluate structural modifications to fuel tanks, has predicted and simulated a refueling phenomenon that leads to excessive mixing of fuel and water. This phenomenon has been confirmed in physical model refueling tests. These tests have also disclosed the relationship between fuel tank piping configurations and tank level indicator (TLI) location, which affects the refueling problems directly. This paper discusses the refueling phenomenon and its adverse effects, and reviews the crucial nature of TLI location, its role in the cessation of refueling, and the subsequent impact on the overboard discharge of fuel and water hideout.

Introduction

The U.S. Navy has three classes of compensated fuel/ballast ships: DD 963, CG 47, and DDG 51. The fuel tanks of these vessels are kept full of varying amounts of fuel oil and seawater at all times to enable them to maintain trim and seakeeping characteristics. After refueling, the tanks are essentially full of fuel. As the fuel is used, quantities of seawater are pumped into the tanks from the ship's firemain. During refueling, the compensating water is discharged overboard as the fuel tanks are filled with fuel. The concentration of fuel oil in the discharged compensating water is of concern to the Navy. Local, national, and international regulations impose strict requirements on the overboard discharge of oily waste, and these requirements are becoming more rigorous with time. Their overall effect is to potentially limit the operations of compensated ships by placing severe restrictions on their refueling.

The ideal condition during refueling would be consistently stratified and quiescent fuel and water layers. However, the internal structure of the fuel tank encourages mixing because it is a complex array of transverse and longitudinal bulkheads or "floors" that separate the tank into several bays; see the schematic of the DDG 51–Class Tank 5-300-2-F in Figure [1]. The flowing fuel and water streams proceed through a variety of openings throughout the tank including 6-in. limber holes, 15-in. by 18-in. and 15in.- by 23-in. manholes, and large openings in the longitudinal stiffeners. Downstream of each of the openings, mixing is intensified with the consequent entrainment of fuel droplets in the water phase, often followed by their discharge overboard. In addition, the compensated ship's fuel capacity is reduced significantly, because the fuel tank's internal structure encourages water hideout where water is trapped and retained in the lower sections of the tank after refueling.

The Naval Sea Systems Command sponsors the Compensated Fuel/Ballast Ships project. The project was initiated to ensure that refueling restrictions caused by overboard discharge of fuel do not encumber ships' operations and to maximize fuel capacity. These objectives can be accomplished by developing modifications for existing ships and design guidelines for future ships. Modifications may entail alterations in internal tank structure or piping configuration, or both. Design guidelines will convey the modifications to future compensated ship classes to enable their designs to be optimized with respect to environmental compliance and fuel capacity. The operational return on investment to the Fleet is significant. Environmental compliance during refueling ensures that the operational envelope of compensated ships is enhanced and uncompromised. Increased fuel capacity, due to the reduction of water hideout, increases the operational envelope even more by permitting the ship to operate over greater distances.

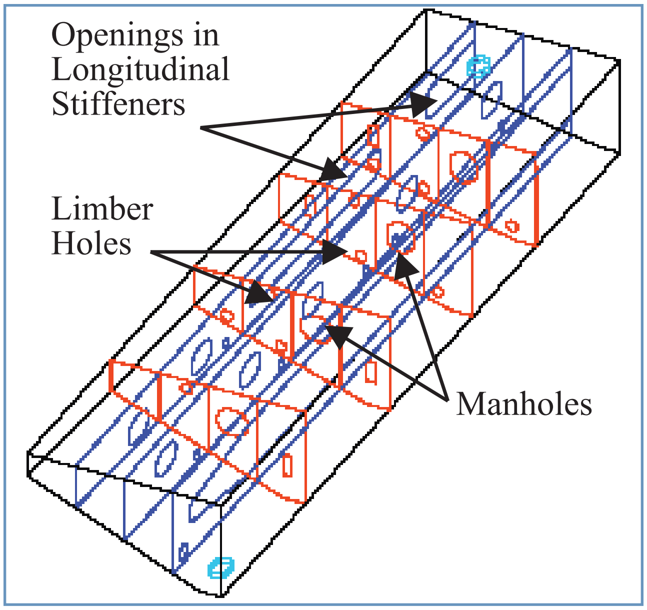

Figure 1. Complex internal structure of a compensated ship's fuel/ballast tank, DDG 51 Class Tank 5-300-2-F.

Approach

A synergistic approach is being used to meet the project's objectives. Computational Fluid Dynamics (CFD) modeling is used to simulate refueling operations. Potential tank modifications are developed using the results of the model, and the efficacy of these modifications is evaluated with additional CFD refueling simulations. Stress analyses, using finite-element models, and fatigue analyses are conducted on the proposed modifications to ensure that structural integrity is not compromised because these tanks are in the bottom of the ship and are its structural foundation. The CFD modeling and the stress and fatigue analyses have been conducted within separate program areas at the Division. CFD modeling is performed in the Hull Forms and Propulsors Branch of the Resistance and Powering Department, and structural analyses are performed in the Design and Applications Branch of the Structures and Composites Department. Finally, a series of physical model tests are conducted to obtain empirical data and validate, refine, and optimize the CFD model.

The project has concentrated on the DDG 51–Class, which is the newest of the compensated ship classes and the only one in which ships are currently being built. Accordingly, recommended tank and piping modifications may be implemented in these ships while still under construction. All of the project's efforts have focused on Tank 5-300-2-F, which is the last fuel storage tank of the mid-port tank group. It is 38 ft long x 9 ft wide x 4 ft 7 in. deep at the centerline, decreasing to 1 ft deep outboard. The long and shallow geometry combined with the internal structure virtually eliminates the possibility of fuel/water stratification, while the potential for mixing and water hideout is intensified. Therefore, Tank 5-300-2-F essentially presents the worst possible scenario. Modifications found effective in that tank also are effective in larger, deeper tanks where fuel/water mixing is not as severe. CFD modeling, and 1/2- and 1/8-scale physical model tests yielded significant information on fuel/water mixing, tank filling characteristics, the effects of piping configurations, and other elements of the refueling process. That information is reviewed in the following sections.

Computational Fluid Dynamics Modeling

Computational modeling began with basic refueling simulations in two bays of a compensated fuel/ballast tank,[1] proceeded to an eight-bay tank, and finally to Tank 5-300-2-F.[2] All modeling was performed at the underway-refueling flow rate of 1000 gpm. The simulations used a homogenous multiphase (HMP) model that solves a single set of momentum equations for both fluids, separate volume fraction equations for each fluid, and a mass conservation equation for the combination of fluids. The HMP model presupposes that each fluid moves with the same velocity in each computational subvolume, among other assumptions. Therefore, it does not afford accurate treatment of oil/water entrainment or model the actual two-fluid behavior found in the refueling of a compensated fuel/ballast tank. However, it was considered to be accurate enough to study both the bulk flow of fluid through the tank and water hideout by providing indications of where and when mixing would occur.

Animations of the refueling simulations of Tank 5-300-2-F showed a series of what were characterized as buoyant flow events occurring through the manholes in the tank floors and the openings in the longitudinal stiffeners. Identification of the buoyant flow event is a distinctive and extremely important accomplishment of the computational model, because it is considered to be a major cause of fuel/water mixing during refueling. Characterization and analyses of buoyant flow events lead directly to the location and design of tank modifications to reduce or eliminate fuel/water mixing, the entrainment of fuel droplets in compensating water, and the discharge of fuel overboard. This results in environmental compliance for compensated fuel/ballast ships. A buoyant flow event is shown in the center bay of a longitudinal tank section in Figure 2.

The buoyant flow occurs during refueling when fuel enters at the top of the tank and fills it from the top down, displacing the compensating water. When the fuel level in a tank bay drops below the upper edge of a manhole or other opening, buoyancy forces drive the fuel to the deckover (the top of the tank) in the receiving bay, which is filled predominantly with water. The fuel jet strikes the deckover and caroms off, forming a recirculation zone downstream of the manhole or opening. The fuel/water interface breaks down at the jet and the recirculation zone. Fuel is entrained in the compensating water and discharged overboard. A detailed example of a buoyant flow event, including the impinging fuel jet at the deckover and the recirculation zone, is shown in Figure 3.

The computational model has been improved and refined toward the ultimate goal of predicting the concentration of fuel in the overboard discharge of compensating water. CFD refueling simulations are now conducted using a single-fluid scalar transport (SFST) model that directly addresses two-fluid mixing and settling, and includes turbulence. None of these could be included comprehensively in the earlier HMP simulations.

Figure 2. A buoyant flow event in a longitudinal section of Tank 5-300-2-F during a CFD refueling simulation at 1000 gpm.

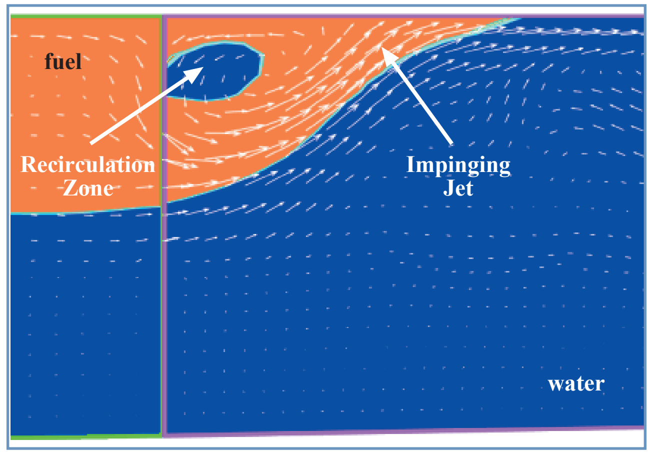

Figure 3. A buoyant flow event including the impinging jet and the recirculation zone.

While the computational model affords a detailed examination of fuel and water flows during refueling, including buoyant flow events and water hideout, it also provides the capability to develop, simulate, and evaluate the effectiveness of the potential tank modifications to minimize or eliminate the problem areas. In this particular case, adding openings at the tops of the floors allows fuel to flow uniformly across the top of the tank, minimizing buoyant flow events. Adding the same kinds of openings at the bottoms of the floors facilitates the flow of water toward the tank's discharge, thereby reducing water hideout. Semi-circular openings, 12 in. in diameter, were proposed originally, but were rejected because they presented potential structural problems. Alternatively, smaller openings of various sizes and shapes have been assessed, and it appears that 6-in.-diameter circular holes reduce the intensity of buoyant flow events without attendant structural disadvantages. The positive effects of the openings on buoyant flow events may be seen in Figure 4, which shows the same longitudinal section of Tank 5-300-2-F (Figure 2), taken from a CFD refueling simulation at 1000 gpm using the SFST model. However, the 6-in. holes at the bottoms of the floors and stiffeners do not have the same success in reducing water hideout. Their effects are still being studied, and additional modifications may be required.

Figure 4. The positive effect (of adding 6 in. holes) in limiting a buoyant flow event in Tank 5-300-2-F during an SFST CFD refueling simulation at 1000 gpm.

Efforts to optimize the CFD model continue. An entrainment model is being developed to encompass the physical processes that occur at the fuel/water interface. It will include both the entrainment of fuel into compensating water and the entrainment of water into fuel, along with the coalescence of fuel droplets and their settling into a stratified fuel layer. The development of the entrainment model will rely particularly on qualitative information and empirical data from physical model experiments, beginning with small-scale model tests and proceeding to full-scale refueling tests. All of these tests use models based on all or part of Tank 5-300-2-F.

Physical Model Tests

Small-scale model tests, conducted in a specially designed facility at the Division's Philadelphia site, are the first step in the progression of physical model tests necessary to provide information vital to the refinement and validation of the computational model. These tests are conducted in two formats: a 1/2-scale, two-bay model based on two bays of Tank 5-300-2-F, and a 1/8-scale model based on the entire tank. The 1/2-scale tests investigate the physics of two-phase flow and interfacial mixing, while the 1/8-scale studies supply information on tank filling and the location of the fuel/water interface in each of the tank's bays.

A tank floor containing a manhole separates the bays of the 1/2-scale model. Several different phases of the refueling evolution are isolated and studied, including the inlet jet, fuel breakover through the manhole and the exit flow. High-resolution photography is used to characterize and measure the spatial and size distributions of fuel droplets in the areas of interest. Particle imaging velocimetry is used to provide a two-dimensional map of the flow field, showing velocities, velocity gradients, and fuel droplet diffusion and advection. The studies of fuel breakover confirmed the existence of the buoyant flow event identified in CFD simulations. Figure 5 shows a buoyant flow event, similar to those shown in Figures 2 and 3, in a 1/2-scale model experiment conducted at the same inlet flow velocity found in refueling at 1000 gpm. The tank floor in that particular experiment was not modified with the circular flow holes. As these studies continue, the empirical information developed will continually enhance the effectiveness and predictive capability of the computational model.

The 1/8-scale tests study tank filling and its collateral results, overboard discharge of fuel and water hideout. The tests are conducted at a flow rate scaled to a refueling rate of 1000 gpm, with scaling based on the Froude number (the ratio of the inertia force to the force of gravity). The 1/8-scale model is similar to the shipboard tank except it has a flat bottom that does not reflect the hull curvature found in Tank 5-300-2-F. Piping configurations and the tank level indicator location are examined in these tests because they are considered crucial to the overboard discharge and water hideout problems. The piping configurations examined include inlet and exit bellmouth, or point-to-point inlet to exit; inlet bellmouth and diffuser exit, or point-to-diffuser; and inlet bellmouth and shortened diffuser exit, or point-to-shortened diffuser. The bellmouth is the flared opening on an inlet or exit pipe. The diffuser exit is a pipe, running the length of the tank, with evenly spaced holes along its bottom to discharge the compensating water. Point-to-point piping was installed originally in Tank 5-300-2-F in earlier hulls of the DDG 51–Class. It was replaced by point-to-diffuser piping in DDG 51 through DDG 67–Classes. While not installed aboard ship, the point-to-shortened diffuser configuration represents a promising alternative.

The point-to-point configuration is shown in Figure 6. The point-to-diffuser is shown in Figure 7, with the inboard longitudinal floor removed to afford a better view of the diffuser exit. The point-to-shortened diffuser is similar to the point-to-diffuser, except that the diffuser exit runs from Frame 314 to 338 rather than the length of the tank. The TLI in Tank 5-300-2-F is located in Bay 300CL. In actual operations, refueling is stopped when the fuel/water interface reaches the high-high-alarm setpoint (HHAS) on the TLI. The location of the TLI has a direct effect on the HHAS and, thus, on the amount of water hideout and whether fuel is discharged overboard when the HHAS has been reached. The HHAS was scaled to a similar location in the 1/8-scale tests. An interface probe was installed in each bay of the model, allowing filling to be mapped across the entire tank. Overboard discharge of fuel was postulated to have occurred when the fuel/water interface reached a pre-determined location in the exit bay for each configuration, based on visual observation and effluent sampling. Several test replications were run for each configuration to ensure statistical validity.

The results of the point-to-point tests showed that the HHAS was reached in 171 seconds. Overboard discharge of fuel had begun; yet water remained in 47% of the tank, essentially a refueling "worst case." In the point-to-diffuser tests, the HHAS was reached in 94 seconds. Fuel had not been discharged from the tank, but water hideout was extremely high at 71%. The point-to-shortened diffuser configuration provided better results. The HHAS was reached in 170 seconds and no fuel was discharged. However, water hideout still was a significant 47%. Therefore, the tests showed that the existing TLI location is inappropriate for any of these piping arrangements. The

Figure 5. A buoyant flow event in a 1/2-scale model test.

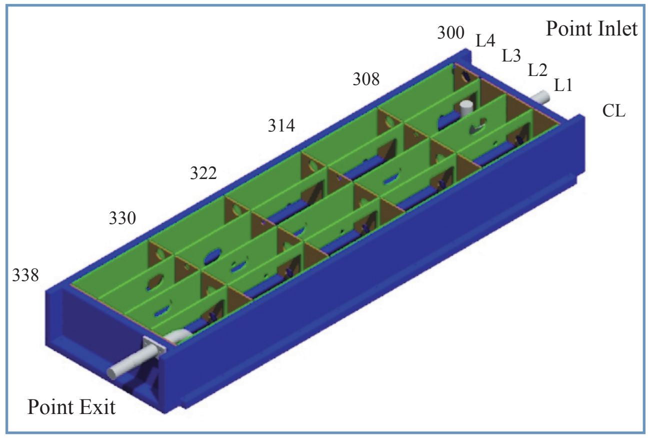

Figure 6. The 1/8-scale model with point-to-point piping configuration.

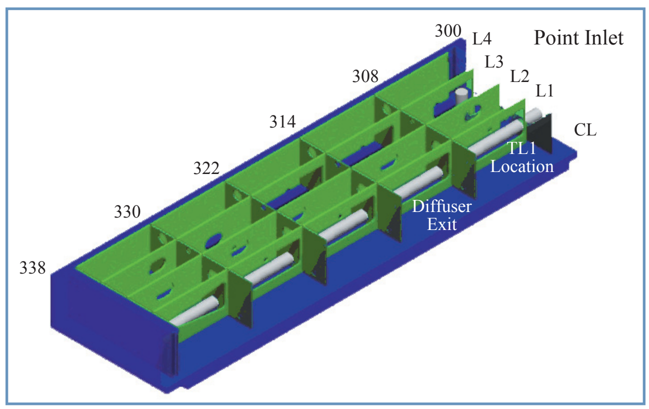

Figure 7. The 1/8-scale model with point-to-diffuser piping configuration.

TLI location should be dependent on the specific piping configuration; i.e., ideally as close to the exit bay as is structurally possible and operationally suitable. A TLI nearer to the exit bay will detect a fuel/water interface location more closely approximating the interface location in the exit bay. Therefore, the HHAS on the TLI would present a more suitable point to stop refueling and to minimize both water hideout and the potential for overboard discharge of fuel.

Further 1/8-scale model tests are underway to optimize the relationship of the piping configuration and the tank level indicator location. A sequential filling configuration was developed to increase the effective distance from inlet to exit and stop the short-circuiting of fuel to the exit bay, thereby fostering uniform filling of the tank. This results in a reduction in water hideout and elimination of fuel discharge. The most promising tank and piping modifications developed from the 1/8-scale model tests will be evaluated in full scale along with TLI locations and technologies. The results will be used to optimize the computational model and provide recommendations to modify existing compensated fuel/ballast ships and design guidelines for future ships to ensure that water hideout and overboard discharge of fuel are eliminated.

Acknowledgments

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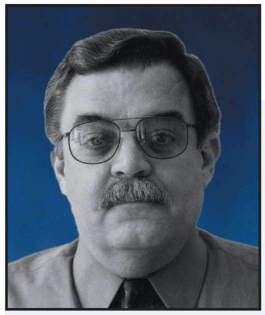
References

1. Chang, P., et al, "Transient, Two-Fluid Flow Through Two Compartments of a Compensated Fuel/Ballast Tank," Third CFX International Users Conference, Chesham, Buckinghamshire, England, UK (Oct 1996).

2. Caplan, I. L., and P. A. Chang, "Mathematical Modeling of Hydrodynamics in Compensated Ballast Tanks to Minimize Overboard Discharge of Fuel," International Conference on Waste Water Treatment Technologies for Ships, Oldenburg, Germany (Nov 1998).



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Plasma-Arc Thermal Destruction Technology for Shipboard Solid Waste

Eugene E. Nolting and Jon W. Cofield

Solid trash represents the most conspicuous and highest volume of waste generated aboard warships. Thermal destruction, which greatly reduces waste volume by transforming combustible materials into gas, has long been considered the preferred method of solid waste management. While thermal destruction technology has several forms, earlier Navy-sponsored studies concluded that ultra-high temperature plasma arcs have the best potential to meet the Navy shipboard requirements. Plasma-arc thermal destruction employs an electric current to heat gas to approximately five times the operating temperature of conventional incinerator systems. These ultra-high temperatures promote extremely fast and more complete destruction of the complex organic molecules that form the waste. This paper describes the underlying technologies used in the design of a shipboard plasma-arc waste destruction system.

Introduction

When at sea, a Navy warship serves as home and workplace for the men and women of the crew. Almost every activity performed on a ship generates solid wastes, which represent the most visible and largest volume of the shipboard waste streams. The solid wastes generated are similar in composition to those created in cities, but unlike municipal rubbish there is no space to bury the waste material, and there is limited space to store and process it aboard ship. An aircraft carrier generates several tons of solid waste daily. Figure 1 is a photograph illustrating a typical 1-day production of non-food solid waste. Historically, much of the shipboard solid waste has been discharged overboard as the principal method of waste management. However, because of international interest in preserving the quality of the world's waters, the practice of at-sea discharge has become unacceptable. Each ship's Commanding Officer is responsible for meeting applicable environmental statutes, regulations, Executive Orders, Department of Defense Directives, Navy Instructions, and Status of Forces Agreements. In order to meet the challenge, the Navy's Forward From the Sea doctrine requires Navy warships to operate anywhere and anytime with unrestricted access to all operational areas, including littoral waters.[1] Complete autonomy of operation requires that new technologies be developed for the environmentally sound treatment of shipboard-generated solid wastes.

The practice has been to develop specialized equipment designed to treat the various components of the solid waste stream. Pulpers are used to grind food, paper, and cardboard waste for diffuse discharge at sea. Plastic waste processors are employed to heat and compress plastic materials for shipboard storage and later disposal ashore. Shredders process glass and metal wastes for submergence. Earlier Navy-sponsored studies concluded that thermal destruction is the best technological approach to develop a single onboard system to process the wide variety of ship-generated solid waste.[2] By building a centralized system to process the full spectrum of waste materials, manning requirements and operating costs are reduced. The interest in thermal destruction is primarily because it transforms the combustible materials into gas; these items constitute about 90% by volume of the solid waste stream. Of the many forms of thermal destruction technology, Navy-spon-

Figure 1. Photograph of tri-wall boxes used to contain the daily solid waste typically generated by a NIMITZ–Class aircraft carrier.

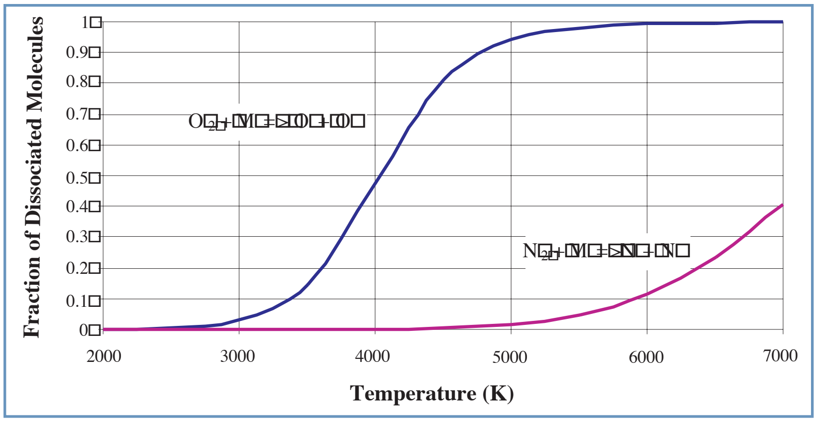

Figure 2. Molecular dissociation as a function of air temperature at atmospheric pressure.

sored studies have found that the use of ultra-high temperature plasmas has the best potential to treat the large variety of shipboard solid waste in a single compact system.[3,4] However, several technology issues were identified that need resolution before a plasma-based waste destruction system can be deployed onboard a warship.

Plasma arcs have been used for a variety of industrial applications for well over 100 years.[5] Plasmas' high sensible energy content (enthalpy) makes them particularly attractive for thermal destruction. Typically, the plasmas of interest are created by forming an arc discharge in gas flowing between two electrodes by applying a sufficiently high voltage. Average gas discharge temperatures are characteristically in the 5,000 to 10,000°C range. For comparison, conventional incinerators are operated at temperatures of 900 to 1,200°C. These much higher temperatures cause much faster chemical reactions with rates that can be several orders of magnitude greater than those of standard incineration. The extremely fast chemical kinetics can be used to implement an appreciably more compact design of the thermal destruction hardware. Ultra-high operating temperatures also cause a more complete breakdown of complex organic molecules down to the atomic level, leading to cleaner destruction products. In addition, the plasma arc's higher temperatures create new chemical pathways not available to more conventional thermal destruction methods. Figure 2 shows that disassociation of molecular oxygen to atomic oxygen starts to occur at temperatures above about 2800 K (2527°C), and only atomic oxygen remains above approximately 5500 K (5227°C).[6,7] Note that most of the oxygen will be dissociated in the primary operating range for the plasma-fired eductor, which enables thermal processes not possible in conventional incineration. Atomic oxygen, which is very chemically reactive, greatly enhances the thermal destruction process; other highly reactive radicals, such as OH, are produced as well. Finally, the use of plasma as the primary heat source makes the thermal destruction process less dependent on the waste's chemical energy for gasification. Effects due to variations in waste material heat content (e.g., plastic versus moisture-laden paper) can be minimized because the plasma inputs an independent minimum energy into the thermal destruction process.

While plasma technology has been used successfully for several commercial applications, it has never been deployed in the marine environment on a moving platform. The approach used to develop a Navy system has been to create a design that provides the inherent benefits of ultra-high temperature waste destruction while being compatible with the ship's mission requirements. These mission constraints include: restrictions on system size and weight, low total ownership costs, reduced manning requirements both in number and skill level of operators, high reliability and availability, equipment operational safety, tolerance to mechanical shock and vibration, minimal electromagnetic interference (EMI), and rapid start-up and shutdown of equipment. Addressing these issues has led to a new design for the plasma-arc equipment that greatly reduces its size and avoids the use of heavy refractory materials that are common in commercial equipment. Refractory materials, such as alumina, are susceptible to thermal shock and require extensive heat up and cool down times to preserve their life; they are also vulnerable to damage during maintenance. Refractory liners on current Navy incinerators represent their largest maintenance cost. A plasma-arc waste destruction system based on a novel design is being built for technical evaluation as part of the Navy's Advanced Technology Demonstration Program.[8-13]

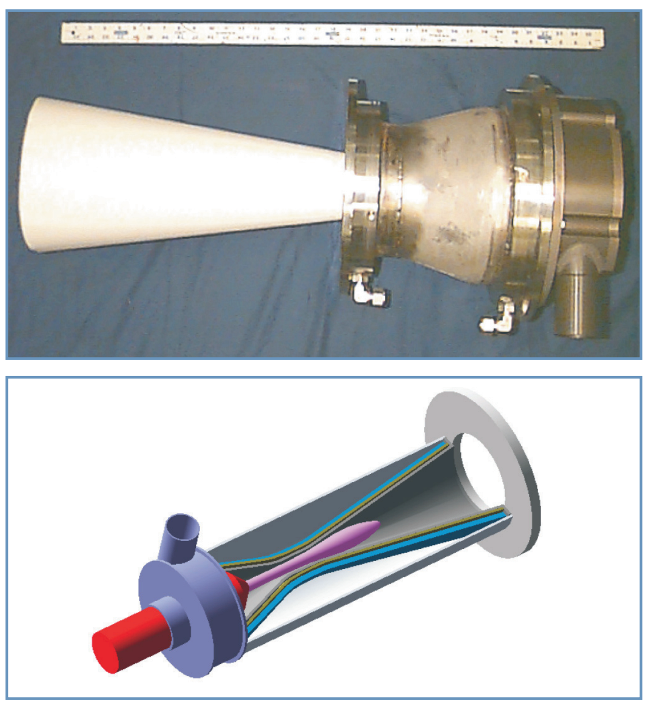

Figure 3. The pre-prototypical PFE is shown in the photograph with its internal structure illustrated in the drawing.

The Navy has patented a design for the first-stage of a two-stage burner for combustible waste.[14] Figure 3 shows the plasma-fired eductor (PFE), which employs ultra-high temperature plasma to gasify the organic based waste as it passes through it and the pre-prototypical eductor used to quantitatively evaluate the concept. The PFE is used to determine operating parameters for several liner geometries, feed rates, feed compositions, and torch powers, all of which are being included in the Advanced Technology Demonstration PFE hardware design. The eductor is designed to force small combustible particles to directly interact with the ultra-high temperature plasma plume so that they rapidly undergo destruction. The waste particles are sized to limit the thermal transfer time required to bring their entire mass up to gasification temperatures; pyrolysis, the breakdown of combustible material's chemical bonds by thermal energy, occurs rapidly above approximately 350°C. The PFE's nominal dimensions are 0.8 m long with a 0.2 m diameter. The unit shown is represents a volume of approximately 1/300 that of conventional plasma systems with similar throughput.

Process Requirements

The design of any thermal destruction system is critically dependent on the quantity and characteristics of wastes to be processed. Shipboard waste, like municipal garbage, comes in a variety of forms. For the purposes of classification of shipboard waste, its chemical energy or heating value and its physical form are the primary characteristics of interest. In terms of chemical energy, waste material can be roughly placed into three categories: high heat value waste (e.g., plastics), intermediate heat value waste (e.g., paper and cardboard), and low heat value wastes (e.g., high moisture content food). For reference, plastic has about three times the chemical energy per unit mass compared to paper. The physical form of the material also is critically important. While a pound of paper sheets and a pound of wood have approximately the same chemical energy, their substantially different forms impact the design of a system that must accommodate both.

Table 1 lists shipboard combustible waste composition. The items listed are based on shipboard solid waste survey data gathered by the Navy and represent the amount and variety of waste materials that must be treated daily. The values are for the 95th percentile waste generation rate for an aircraft carrier with a crew of 5500. Large day-to-day excursions are to be expected from these compositional values depending on the ship's operating area and phase of deployment cycle. The thermal destruction system must be designed to adjust easily to these variations. The process rate listed in the table assumes two thermal destruction units each with a 150-kG/hr throughput operated 18 hr per day. The choice of two units was made to improve system reliability and increase equipment availability; it also allows better matching of the equipment capacity to the waste production rate. Designing the system to handle the high end of the waste production guarantees that very few days will exceed the capacity of the equipment. An average 75% duty cycle provides time for preventative maintenance and clean up of the ship spaces. The equipment can operate for longer periods when necessary.

Table 1. Daily process rates of combustible waste for a single eductor unit.

Waste Component (As Received)	Process Rate (kg/day)	Weight (%)
Food (except Non-pulpable items)	690.3	25.6
Paper	1074.9	39.9
Non-Food-Contaminated Plastic	99.5	3.7
Light Cardboard	127.6	4.7
Heavy Cardboard	478.5	17.8
Food-Contaminated Plastic	158.5	5.9
Wax-Coated Cardboard	31.9	1.2
Wax Paper	22.2	0.8
Kimwipes	11.1	0.4
Total	2694	100

An additional complication is that the waste does not arrive at a constant rate throughout the day. Ship surveys show that no waste is delivered for several hours, followed by a sudden influx of material. Ship management practices could modify the waste delivery rate, but the plasma waste destruction system being developed has been designed with waste storage buffers to reduce shipboard impact.

Plasma-Fired Eductor Operation

Details of thermal destruction chemistry for solid waste are highly complex with literally hundreds of reactions, and the production of many chemical species are possible. The reactions depend on temperature, oxygen levels present, chemical composition of the waste, local conditions (i.e., conditions at each point throughout the reaction volume), etc. As a starting point, it is useful to look at the complete combustion reaction under equilibrium conditions to estimate the amount of air required and quantities of products produced by the thermal destruction process. Paper, cardboard, and food, which comprise most of the combustible waste, can be represented as cellulose ($C_6H_{10}O_5$). For the combustion of 1 mole of cellulose, the chemical reaction can be written as[15]

$$C_6H_{10}O_5 + 6\ (O_2 + 3.76\ N_2) \Rightarrow 6\ CO_2 + 5\ H_2O + 22.6\ N_2. \qquad (1)$$

This equation states that 6 moles* of air, composed of 21% oxygen (by volume) and 79% nitrogen, are required to completely convert the cellulose into carbon dioxide and water vapor. This represents the minimum amount of air needed for complete combustion and is called the theoretical air or stoichiometric air. In reality, because of the statistical nature of the combustion process, excess oxygen is required to ensure complete burnout of the fuel. Two-stage combustion is a common technique used to improve the efficiency of the combustion process, and it has been employed in the plasma system's design. The plasma-fired eductor uses air as the plasma torch gas and as the carrier gas for the waste to simplify shipboard logistics. During the eductor's operation, the amount of air, actually the oxygen, is controlled to be on the order of 30% of the theoretical air indicated in Equation (1). This produces a fuel-rich environment, and the thermal energy added by the plasma torch produces significant quantities of carbon monoxide, hydrogen, and char (carbon). These products are converted in the second stage to carbon dioxide and water vapor by the addition of excess air. However, because the fuel gases and char are easy to oxidize, the amount of excess air is greatly reduced over typical single-stage combustion. This has important system implications, because the size is a function of the gas volumes that are processed.

The reaction rates for the chemical pathways available must be included to quantitatively estimate the operation of the plasma-fired eductor and the secondary combustion chamber. From chemical kinetics, the rate equation for a single chemical reaction can be expressed as a first-order differential equation in terms of the reactants concentrations, C_i,

$$-dC_A/dt = k\ C_A{}^a\ C_B{}^b. \qquad (2)$$

In Equation (2), time is represented by the variable, t, and the negative sign indicates that the loss rate of reactant A is proportional to the concentrations of each reactant raised to the number of moles of the reactant in the reaction equation. In Equation (1), 1 mole of reactant A (cellulose) reacts with 6 moles of reactant B (oxygen) to produce carbon dioxide and water vapor; Equation (1) indicates that the nitrogen does not contribute to the chemical process. From statistical physics, it can be shown that the rate constant, k, has a general analytical form

$$k = A\ T^n \exp\ (-E_a/RT), \qquad (3)$$

where, A is the pre-exponential factor, E_a is the activation energy for the reactant of interest, and R is the universal gas constant. The absolute temperature, T, appears in the exponential term and is also raised to the nth power ($-2 < n < .5$), the value dependent upon the geometry of the molecule. For most cases, the value of k is dominated by the exponential term.[16]

As previously stated, the plasma-fired eductor operates at temperatures on the order of five times higher than conventional incinerators. Because of the exponential relationship of Equation (3), the typical decomposition rate for cellulose into carbon monoxide, hydrogen, and methane is roughly 10,000 times faster at 5000°C. New chemistry models had to be developed to predict destruction rates because this temperature is well beyond the range typically used to analyze conventional combustion systems.. This chemistry model has been installed in a computational fluid dynamics (CFD) software package so that the local reaction rates can be followed as the particles transit the eductor. Figure 4 is the result from a CFD model for a specific pre-prototypical eductor geometry. Comparison of the theoretical analyses results compared well with the data collected.

The plasma torch offers two significant advantages for safety of operation. First, for the throughput rates required, less than 20 grams of waste material and gaseous product are in the eductor and secondary combustion chamber at any given time. Therefore, little chemical energy is available for uncontrolled release. Second, the system can be quickly started up or shutdown, which is achievable by turning on or shutting off the feed system and the torch power. Figure 5 is a three-photograph sequence of the eductor gasification during startup of the feed system showing gases burning at the output of the eductor. The circular shape of the flame's image is caused by the aperture of the viewing port. Time evolves left to right and covers a total period of 19 ms. In the first frame only the torch is on, which is faintly visible; full operational conditions are shown in the third frame.

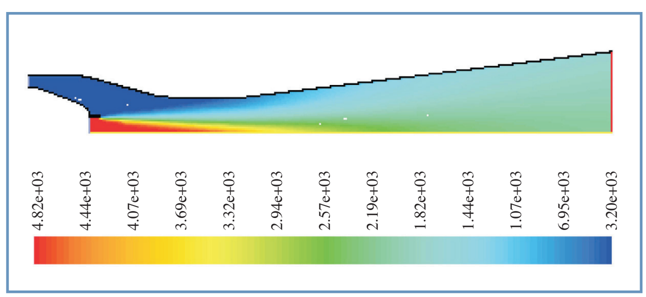

Figure 4. Computational fluid dynamics result indicating the temperature distribution for one of the pre-prototypical plasma-fired eductor geometries tested.

* The mole is the SI (Systeme Internationale) unit for the amount of a substance. One mole of an element that exists as single atoms weighs as many grams as its atomic number. Each mole contains Avogadro's number of atoms (6.022045 x 1023). For elements in the gaseous state at standard conditions, each mole has a volume of 22.4 liters. Ref: Dictionary of Chemistry, NTC Publishing, Lincolnwood, IL, 1996.

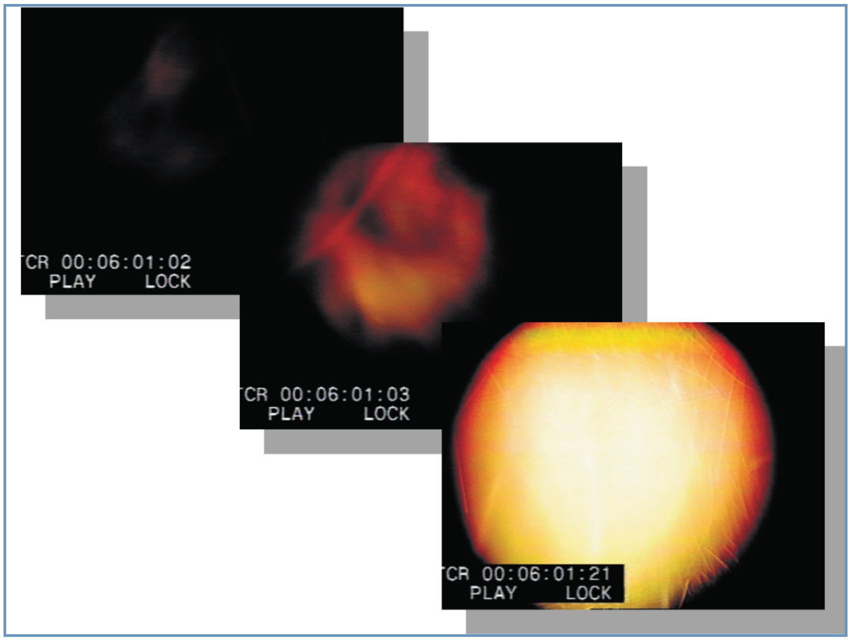

Figure 5. Plasma-fired eductor during startup.

Eductor Liner Studies

Most commercial plasma units are lined with thick layers of refractory materials to serve as a protective liner and insulator. However, refractory materials increase the size and weight of the units. It was determined early in the shipboard plasma-arc waste destruction system development program that using a refractory liner in shipboard plasma design was too great a penalty in terms of operational performance. However, there was concern about the heat losses and liner lifetime associated with the use of metal walls.

The liners are exposed to a severe environment because of the near proximity of the torch plume and material undergoing thermal processing. The temperatures of the liner walls are allowed to reach 900°C and can be maintained with "backside" cooling, because the walls are not required to provide structural integrity. Tests showed that there is little direct radiation energy coupling between the plasma plume and the liner wall. Heat loss through the eductor liner walls, which is on the order of 7 kW or less, occurs primarily during waste destruction. To date, tests have exposed the liners to frequent thermal cycling, which represents a harsher environment than they will see during normal operation. Furthermore, the noncombustible ash particles present an opportunity for erosion as they travel through the eductor at velocities of about 8 ms. The higher operating temperatures inhibit the condensation of acids on the surface to reduce corrosion and reduce the size of a "cool" boundary layer formed next to the wall that may act as a low temperature pathway for the particles to travel.

Two types of liner materials have been tested, 310 stainless steel and thermal-barrier-coated (TBC) Inconel 738 LC. The Inconel was coated with a NiCoCrAlY bond coat and a ZrO_2/$2CaOSiO_2$ topcoat liner layer. The Inconel liner can be operated up to about 1200°C for a short time. Liner temperatures were measured with thermal couples mounted on the liner's outside surface. Other materials (310 stainless steel, Inconel 625, spray-formed 50 Ni/50 Cr, and the TBC Inconel 738) were tested by placing polished coupons at the exit of the eductor where they were exposed to the hot exhaust gases and normal impingement of ash particles. These coupons were examined after several hours of operation.

The coupons and liners were inspected visually after exposure. Optical and scanning electron microscopy (SEM) were used on the samples also. Cross-sections were mounted, polished, and etched with equal parts of nitric, hydrochloric, and water. Secondary electron images were made using SEM to examine the sample's surface characteristics, and back-scattered electron images were used to determine the distribution of elements in the sample.

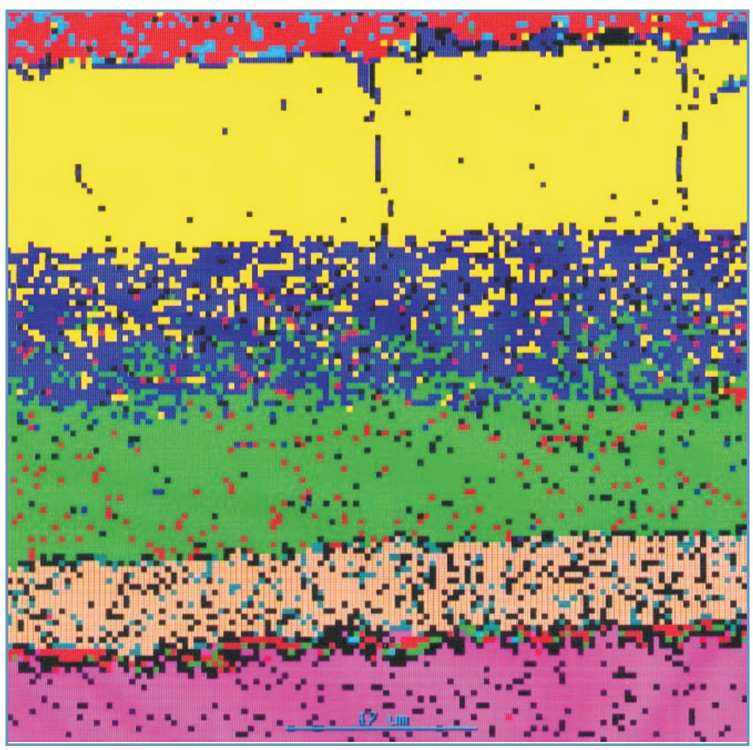

Figure 6. False color X-ray map of thermal-barrier-coated liner.

Energy dispersive spectrometry identified the elements in a sample surface, and X-ray maps were made to more precisely map the elemental distribution of the samples. Figure 6 shows a false color image of a liner cross-section made by superimposing X-ray maps of individual elements. Note that some cracks are visible in the dicalcium silicate layer that is directly exposed to the high temperature environment. Finally, X-ray diffraction was used to find the compounds formed by the elements deposited on the inside surface of the liner.

Metallographic examination of the sample materials indicated that some degradation due to the harsh environment. The analyses also indicated a relatively thin layer of noncombustible material had accumulated on the liner's inside surface, which appeared to provide a partially protective coating. The damage was light enough that a lifetime of 3000 hr still should be achievable and should be sufficient for one deployment cycle. The design of the liner hardware will render it easily changed at sea if needed. Demonstration of the long operating life for the liners is an important step in the development of the plasma-arc technology for waste destruction.

Conclusions

Thermal destruction of combustible waste is a simple concept, yet the development of a shipboard plasma-arc waste destruction system requires a detailed understanding of the many aspects of basic combustion, materials, chemistry, and the engineering sciences. The design of equipment to treat the wide varieties of forms and chemical composition of waste requires a robust process. We have brought together expertise from NSWCCD, industry, and academia to address technical issues that are unique to the ultra-high temperature combustion and marine environment.

A plasma-arc waste destruction system based on the two-stage eductor combustion is being built as part of the Navy's Advanced Technology Demonstration (ATD) Program. The ATD will demonstrate all the technologies necessary to deploy a plasma-arc waste destruction system aboard a warship. Upon completion of the ATD, an engineering design model (EDM) will be constructed and located at NSWCCD. A second EDM will be built for test and evaluation at sea. The plasma-arc technology should be used to treat waste generated on privately owned vessels, particularly cruise liners that have high waste generation rates, or for island communities where the opportunity for waste disposal is limited.

Acknowledgments

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References

1. Forward…From the Sea, Letter signed by the Secretary of Navy, John H. Dalton (9 Nov 1994).

2. Shipboard Pollution Control, U.S. Navy Compliance with MARPOL Annex V, Committee on Shipboard Pollution Control, Naval Studies Board, National Research Council, National Academy Press, Washington, DC (1996).

3. *U.S. navy ship solid waste management plan for MARPOL annex V Sspecial areas.* U.S. Navy Report to Congress (Nov 1996).

4. Chopra, H., *High temperature controlled thermal destruction of surrogate solid waste*. Master of Science Thesis, University of Maryland (May 1993).

5. Counts, D.A., et al, *Thermal plasma waste remediation technology: historical perspective and current trends*," Naval Research Laboratory Report 6170-99-8335 (1999).

6. Hansen, C.F., *Approximations for the thermodynamic and transport properties of high-temperature air*. National Advisory Committee for Aeronautics, Technical Note 4150, Washington, DC (Mar 1958).

7. Niessen, W.R., Combustion and Incineration Processes, Applications in Environmental Engineering, Marcel Dekker, Inc., New York, NY (1994).

8. Richard, R.V., et al, *Navy shipboard plasma-arc waste destruction system (PAWDS) baseline conceptual design*, Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA (May 1997).

9. Nolting, E.E., *Navy shipboard plasma-arc system development program*, Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA (May 1997).

10. Talmy, I.G., et al, *Occurrence and suppression of thermite reaction in slags from destruction of navy shipboard wastes,*" Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA (May 1997).

11. Uhm, H.S., et al, *Air torch modeling for thermal destruction,* Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA (May 1997).

12. Peterson, S.H., et al, *Slag formation from navy solid waste with a plasma-arc torch destruction system,*" Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA (May 1997).

13. Nolting, E.E., and Cofield, J.W., *Development of a shipboard plasma- arc waste destruction system*, Proceedings of the American Society of Naval Engineers Marine Environmental Symposium (Oct 1999).

14. U.S. Patent 5,960,026, Naval Surface Warfare Center, Carderock Division (28 Sep 1999).

15. Keating, E.L., Applied Combustion, Marcel Dekker, Inc., New York, p. 111 (1993).

16. Metz, C.R., Physical Chemistry, McGraw-Hill Book Company, New York, NY, p. 197 (1976).

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Shipboard Integration of Large Capacity Oil Pollution Abatement Systems

Stephen J. Hopko

Shipboard integration of large-capacity oil pollution abatement (OPA) systems is discussed in this paper and points to the need for in-service engineering early in the design phase of shipboard equipment. Equipment operational constraints and configuration variations onboard different ships may impede the development of generic systems that would integrate all required components and subsystems. Therefore, the design must be evaluated on a ship-by-ship basis to maximize the effectiveness of the overall system. A brief primer on Navy OPA systems is provided, followed by a specific application engineering solution case study. The case study looks at a specific integration issue related to the installation of multiple, large-capacity oil/water separator systems onboard two aircraft carriers. The case study also demonstrates the success of in-service engineering in incorporating original equipment manufacturer design changes by considering how the design departures will interface with other OPA system components.

Introduction

The process of reducing the oil content of shipboard-generated bilgewater to acceptable overboard discharge levels and the intricacies involved with monitoring of the associated overboard stream, are quite complex. The transfer of existing oil pollution abatement (OPA) technology from small and moderately sized vessels to larger ships poses a variety of technical challenges that must be met. Changes and variations to the oil/water separator (OWS) system must be integrated into larger ships to meet the additional processing demands associated with these vessels. Other factors need to be considered, including the fact that the larger-capacity OWS systems (Figure 1) being installed onboard aircraft carriers and amphibious ships are larger and substantially more complex than the traditional gravity separation systems installed on smaller combatants and auxiliary craft.

One of the many roles of in-service engineering (ISE) is to ensure that environmental systems or equipment supplied by the original equipment manufacturers (OEMs) are operational, effective, and reliable once they are integrated onboard Navy ships. A number of ISE functions cover a broad spectrum - test and evaluation; laboratory analysis; system design, integration, and installation; integrated logistics support (ILS) development; and operational certification and training. In-service engineering agents (ISEAs) routinely visit and remain in contact with many ships to observe and discuss their OPA related systems and equipment. Hence, the ISEA is able to see the "big picture" and understand the OPA system nuances from the theoretical, technical operation, and end user perspectives.

An OPA System Primer

The OWS is a principal component of a typical OPA system. It removes oil from bilge and oily wastewater and lowers the oil content to an acceptable overboard discharge

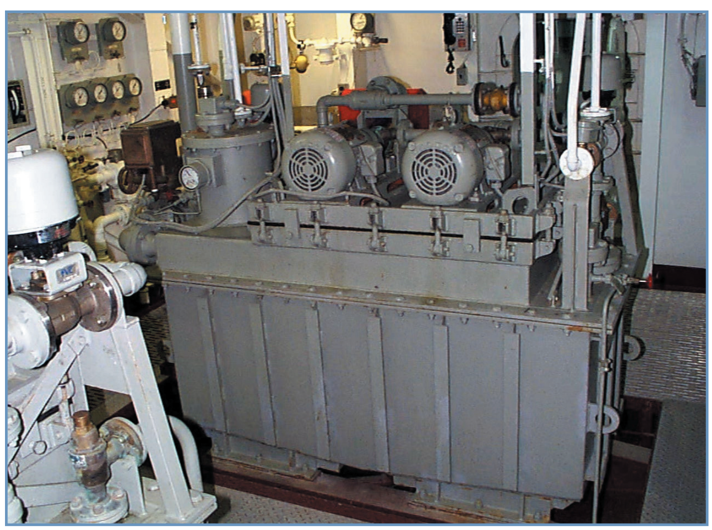

Figure 1. Model C-50 oil/water separator installed on USS HARRY S. TRUMAN (CVN 75).

level of 15 ppm or less under most conditions.[1] Nearly all Navy OWS systems are Navy Model 10NP units, which incorporate gravity-assist, parallel-plate/coalescence technology. The design and basic operating principle of the OWS are shown in Figure 2.

Shipboard-generated oily waste is collected in an oily waste holding tank (OWHT) and processed through the OWS. As the oily wastewater enters the separator, the bulk oil immediately rises into the oil tower. The smaller microscopic oil droplets that are not immediately separated pass between 1/4-in.-spaced, corrugated parallel plates under laminar flow conditions. These oleophilic (oil attracting) plates are a key element of the OWS design. The microscopic oil droplets need to rise no more than 1/4 in. to coalesce into larger oil droplets on the underside surface of a plate. These larger oil droplets roll up the underside of the corrugated plates toward weep holes at the peaks of each plate. The holes allow clear passage of the larger oil droplets to the top interior of the OWS tank via the vertically aligned weep holes. There, a slight incline forces the accumulated oil to creep toward the oil tower for automatic and periodic discharge to a waste oil tank (WOT). An oil content monitor (OCM) continuously monitors the OWS effluent via slipstream sampling under near isokinetic conditions. The OCM determines whether to discharge acceptable effluent overboard or recirculate unacceptable effluent back to the OWHT to hold until it can be processed through the OWS again. The decision is implemented by sending a signal to energize or de-energize a diverter valve located at the OWS exit. The OWS serves as a continuous flow retention vessel that allows oil droplets to rise and become separated from the main wastewater stream. Stokes' Law (see Equation 1) is the governing design equation used to predict the terminal rise velocity of spherical oil droplets through a fluid medium.

$$D_{droplet}\sqrt{\frac{18\,\mu_{water}\bullet v_t}{g\bullet(\rho_{water}-\rho_{oil})}} \qquad (1)$$

Where

v_t = terminal velocity of oil droplet

$D_{droplet}$ = diameter of oil droplet

ρ_{oil} = density of oil droplet

ρ_{water} = density of carrier fluid (water)

g = acceleration due to gravity

μ_{water} = viscosity of carrier fluid (water).

This equation, in combination with others, establishes a mathematical relationship to predict oil droplet sizes that can be separated completely as a function of average retention time. The relationship is governed by flow rate for a fixed hardware configuration. Table 1 shows that oil droplets smaller than 20 μm would take an unreasonable time to separate, even if an OWS tank was only 3 in. high, thus emphasizing the advantage of using horizontal parallel plates in a gravity-assist OWS design. OWS plate pack dimensions are approximately 1 1/2 ft to 4 ft high, 2 ft to 3 ft wide, and 3 ft to 5 ft long to meet throughput requirements with a manageable footprint. This results in an average plate pack retention time typically less than 8 minutes.

Table 1. Travel time for oil droplets to rise 3 in. in water (oil specific gravity = 0.85).

Oil Droplet Diameter (μm)	Approximate Rise Time (min)
10	155
20	38
30	17

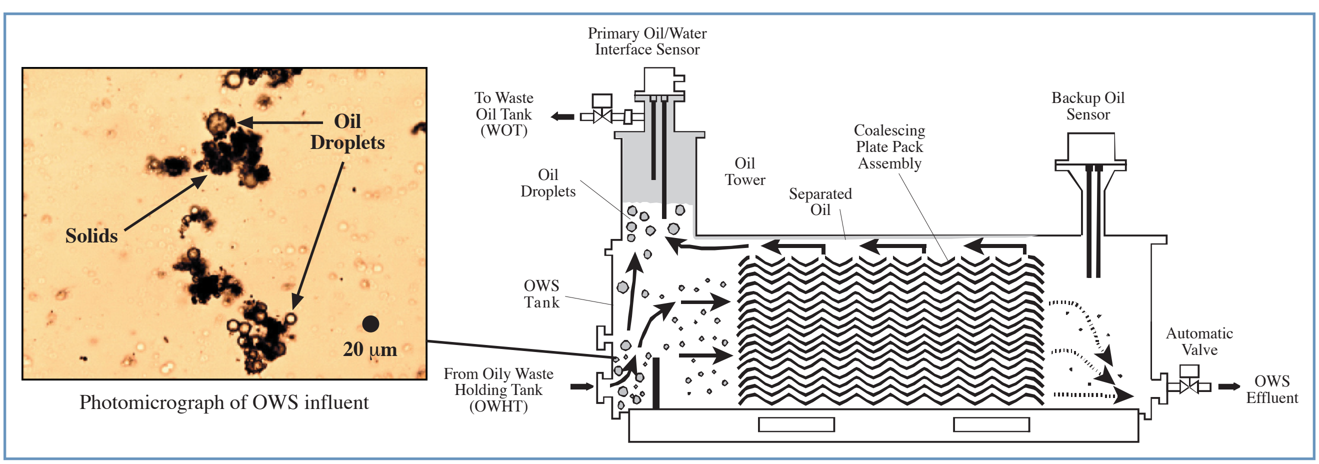

Figure 2. Navy Model 10NP parallel-plate oil/water separator. (Note: Weep holes are shown for the top plate only.)

Case Study

Problem

While there are many issues associated with shipboard integration of large- capacity OPA systems, this paper focuses on OCM backpressure requirements on ships that use wing tanks as the oily waste holding tanks. This subject exemplifies how the requirements of a critical piece of equipment (OCM) can drive the configuration of other components (e.g., OWS) and offset perceived OEM system improvements. It also demonstrates the need for the ISEA to be included early in the preliminary design and installation phases of shipboard equipment.

Background

A conventional Navy OPA system on a Navy surface combatant consists primarily of a single oil/water separator, one oil content monitor, an individual oily waste holding tank, and a dedicated waste oil tank. The OWHT and WOT are commonly located entirely below the level of the OWS. A single, positive-displacement, progressive-cavity screw pump is used to take suction from the OWHT and gently push the oily wastewater through the OWS at a nominal 10 gpm flow rate. This type of pump minimizes the energy and shear imparted to the oil droplets and thus, precludes further mechanical emulsification. (As predicated by Stokes' Law, smaller oil droplets are more difficult to separate from water.)

In contrast to those on smaller combatants, the OPA systems onboard larger ships are significantly different in design and scope, although the basic principle of a parallel-plate/coalescence with gravity-assist OWS remains intact. For example, the OPA systems onboard USS ENTERPRISE (CVN 65) and USS KITTY HAWK (CV 63) include two, dual flow rate OWSs (50 or 100 gpm nominal). Each one has two flexible impeller pumps located on top of the OWS and takes suction from downstream. As a result, these OWSs are "pull-through" versus "push-through" systems, the latter being typical of most OWSs in the Fleet. The ships use tall wing tanks for the four oily waste holding tanks and two waste oil tanks incorporated into the OPA system. These tanks are approximately 34 ft high, and extend above and below the OWS level. Oily waste is sometimes drawn through the system under vacuum (depending on the OWHT level) because of the oily waste holding tank and pump configurations on these ships. Figure 3 is a simplified schematic that shows one of the two OWS/OCM systems installed on these ships, one of four oily waste holding tanks, and one of two single waste oil tanks. The actual installation includes many more components and piping configurations with a great deal of cross connecting and interfacing that is not shown in Figure 3.

Stokes' Law dictates that the 50/100 gpm OWS on aircraft carriers be larger than the traditional 10 gpm separator to compensate for the retention time loss associated with increased throughput. The OEM made design changes that deviated significantly from the standard OWS design practices used for the Navy 10NP OWS system to provide an OWS large enough to process oily waste and still fit into available shipboard space. The changes included an effort to minimize the OWS footprint to accommodate space limitations, improve system performance, and incorporate additional flexibility. As discussed previously, the pumps were mounted on top of each OWS, instead of next to it, and on the discharge side of the OWS tank. Hence, the separator was converted to a "pull-through" system. The design change minimized the footprint of the system and reduced the potential for pump induced mechanical emulsification of oil in the OWS influent. In addition, the OWS operator gained the option to operate one or two pumps at a time and have one as a backup when the other requires maintenance. The significance of this one or two pump capability is that it provides the option of manually reducing throughput, which can improve effluent quality. For example, where oily waste generation rates are reduced below the 50 gpm level or if trouble was experienced reaching acceptable effluent quality at 100 gpm, the OWS throughput rate could be reduced to 50 gpm by securing one of the two pumps. It is important to note that the relationship between oil droplet size removal and flow rate is not linear, as indicated in Equation (2) and shown in Figure 4. For example, if all oil droplets 20 µm and above could be removed completely at 100 gpm throughput, then only oil droplets larger than 14

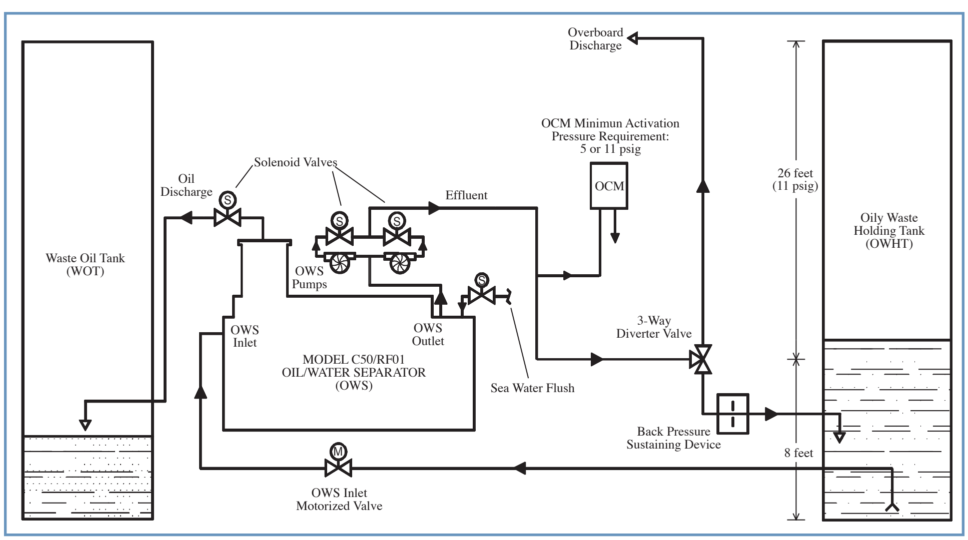

Figure 3. Large-capacity OPA system onboard aircraft carriers with tall wing tanks.

μm could be removed completely at 50 gpm, a 33% reduction in oil droplet removal size with a 50% reduction in throughput. While there is a definite benefit to processing at a reduced throughput, the actual oil removing capability is highly dependent on the oil droplet size distribution in the OWS influent stream.

$$D_{droplet} \propto \sqrt{Q} \quad or \quad D_{droplet} \propto \sqrt{\frac{1}{t}} \qquad (2)$$

Where

$D_{droplet}$ = the smallest oil droplet completely removed,

Q = the flow rate

t = the plate pack retention time.

Discussion

Performance expectations were not fully realized in the OEM design, but this was not recognized until the OPA system installation was nearly complete because the ISEA was not consulted in the shipyard design and planning phases of the initial installation onboard USS KITTY HAWK (CV 63). When the OWS was integrated with other shipboard equipment and systems, the ISEA identified issues in the system operation that would need to be investigated further. These issues were identified during the ISEA's inspections conducted as part of the newly implemented OPA System Certification Program.[2]

The OPA System Certification Inspection determined that the OEM design affected the operational pressure requirements of the OCM located downstream of the OWS. A minimum backpressure is required to activate the OCM automatically (generally 5 or 11 psig depending on the type of OCM used). The minimum backpressure is mandatory to ensure that the OCMs are receiving sufficient flow to adequately evacuate their respective sample chambers between readings. This condition optimizes the OCM's decision-making capability and is critical to ensure that effluent that exceeds the overboard discharge limit is not permitted to be pumped overboard. For traditional systems, an orifice plate is required in the recirculation line back to the oily waste holding tank because the entire tank is at a lower level than the separator. The traditional type of positive-displacement pump and tank configuration nearly guarantees that the backpressure remains constant at a pressure between the minimum activation and the maximum (safe) operating pressures that the OCM can be exposed to (25 psig). However, the operating conditions imposed by the OEM design changes (depicted in Figure 3) are dramatically different. Use of portable ultrasonic flow meters and pump performance curves determined that the impeller pumps chosen by the OEM are not true positive displacement pumps. The flow rates of the impeller pumps are highly dependent on many factors including the variable liquid levels in the source and receiving tanks (OWHTs), the operation of one or two of the OWS pumps since they share a common suction and discharge, and impeller wear. This situation precludes the use of a single universal orifice plate that would meet all system flow changes and maintain an acceptable backpressure range for the OCM.

During the Certification Inspection visit where the problem was first identified, the ISEA investigated the problem, contacted various manufacturers, presented alternative solutions, and recommended an optimal solution. Installation and successful tests of an automatic, hydraulically operated, pilot-controlled, modulating-type valve resolved the problem. This responsive pressure-sustaining device provides the lowest acceptable backpressures for the OCM under all possible operating and tank conditions, which is

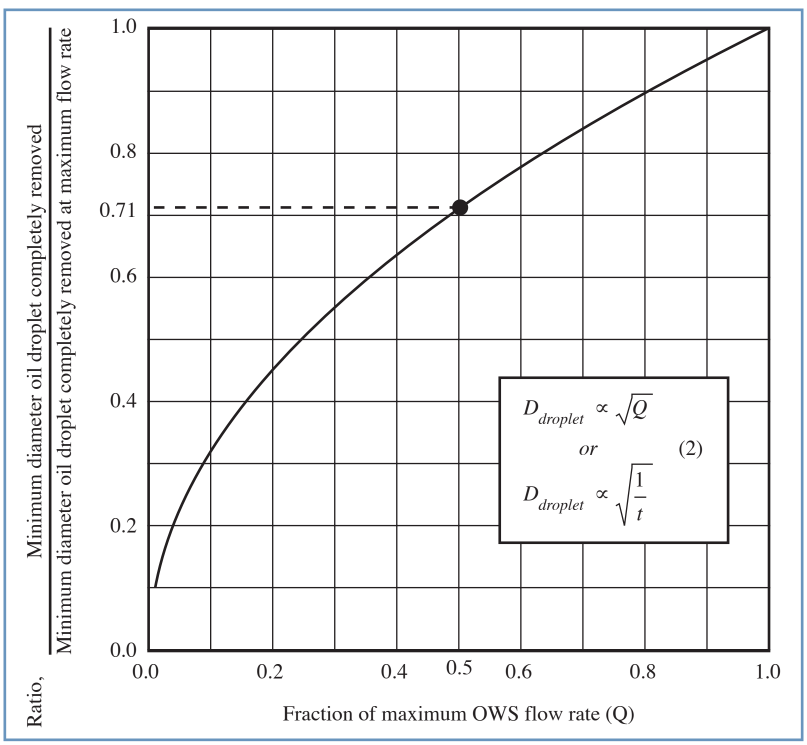

Figure 4. Smallest diameter oil droplet (in dimensionless form) that can be removed completely, correlated to the fraction of maximum OWS flow rate and retention time.

important because the OWS pump impeller life is shortened when exposed to relatively high pump discharge pressures approaching 25 psig.

The pressure-sustaining device compensates for all possible operating conditions ranging from drawing a suction from a nearly empty tank and discharging into a full tank, or drawing a suction from a full tank and discharging into a nearly empty tank. This translates into a pressure differential of approximately 14.5 psig for a constant flow rate. However, it has been demonstrated that the true flow rate of a single 50 gpm pump with new impellers can vary as much as 10 to 15 gpm. The importance of the pressure-sustaining device lies in the fact that the OCMs have a limited operating pressure range of either 5 to 25 psig or 11 to 25 psig, depending on the type of OCM used.

The installation and testing of four pressure-sustaining devices onboard two aircraft carriers allowed the OPA system to operate under most shipboard conditions. In fact, this solution is being recommended for other ships with similar configurations. It was found that the OEM's decision to use dual, flexible impeller pumps (vice truer positive-displacement pumps) combined with the OCM operating pressure constraints, and liquid static head pressures in the OWHT, introduced variability in the average throughput of these systems. Flow rates, 20 % lower than the advertised nominal, were observed at times when using new impellers. This occasional reduction in flow rate was deemed acceptable, especially in light of the fact that the OPA systems were otherwise fully functional.

Summary

Anticipated benefits associated with subsystem improvements and added flexibility were limited by the actual shipboard conditions and constraints imposed by the integration of other equipment. Occurrences such as those discussed here could have been avoided if the ISEA had been consulted early in the design and planning stages of the shipboard systems. One of the roles of the ISEA is to consider such integration issues. Only by evaluating the system as a whole will the actual impact/payoff of any improvement made to a particular subsystem or component be realized. ISEA involvement ensures proper system integration design to allow the systems to be fully functional over the entire range of operating scenarios.

Acknowledgments

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References

1. "Environmental Protection and Natural Resources Manual," OPNAVINST 5090.1B, Chapter 19, Change 2 (9 Sep 1999).

2. "Inspection and Certification Process for Oil Pollution Abatement (OPA) Systems in U.S. Navy Surface Ships and Craft," NAVSEA Inst 9593.21 (Oct 1996).

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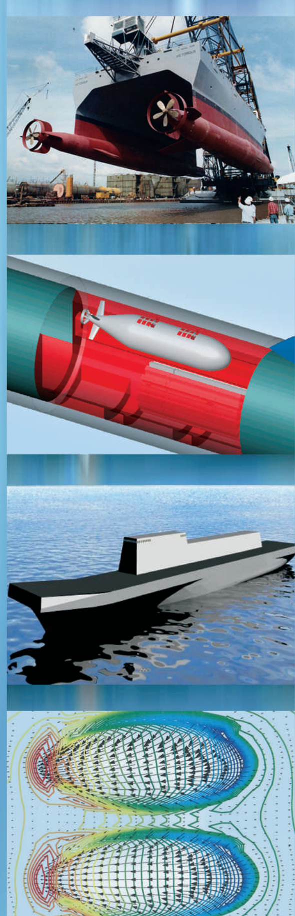

Integration Technologies

Design and Integration Technologies

Overview Article Follows

Design

TECHNICAL DIGEST

DESIGN & INTEGRATION TECHNOLOGIES

Design and integration technologies are focused on developing a capability to integrate multi-disciplinary technologies and systems into total ship designs and support analyses for surface ships, submarines, combatant craft, and Marine Corps vehicles. Included are the engineering processes that cut across the ship and craft designs including cost/warfighting effectiveness, total ship design concepts, shipbuilding and manufacturing technologies, logistic support systems, physics-based modeling and simulation, and information systems. It is a combination of specialized expertise, unique and complex computer codes, computer workstations, large screen computer visualization, Integrated Product Team spaces, facilities, and secure working environments. These building blocks provide a total system capability, technical depth and breadth, operational understanding, and a vision for producing effective and affordable naval and maritime ships and vehicles

Design and Integration Technologies: An Overview

Larry K. Wellman

This paper discusses some revolutionary improvements in functions, products, and services provided by the Design and Integration Technologies (D&IT) Directorate at NSWCCD. They include cost-estimating techniques, systems engineering, war-fighting effectiveness, shipbuilding and manufacturing technology, total ship open systems architecture, ship design and logistics concepts, condition-based maintenance, and NAVSEA and Program Executive Office support. The development and integration of new technologies is critical to increased affordability and war-fighting effectiveness of new surface and subsurface vehicle designs; however, this has always presented a challenge. A design that is functional, survivable, effective, affordable, and interoperable is a major priority for the Navy. This section of the Division's Technical Digest addresses some of the D&IT developments, including performance-based cost modeling, advanced prototyping of ships, open systems architecture, high-speed transport, and logistics over-the-shore.

Introduction

Developments in computer and information technologies over the last decade have dramatically improved Integrated Process and Product Development. NSWCCD's Design and Integration Technologies (D&IT) program area encompasses and supports all of the various technologies pursued by the Division, advances the state-of-the-art in product development, and contributes to significant reductions in cycle time (Figure 1) and total ownership cost (Figure 2). This, in turn, leads to more effective naval ships (Figure 3).

Today, the Division is in the forefront of the development of D&IT smart product models, virtual design and simulation tools, and integration processes to meet the challenges of providing the Navy with operationally superior and affordable ships throughout their life cycle. Two of NAVSEA's strategic goals relate to a disciplined engineering process, robust development, and transition of concepts and technology to the Fleet. D&IT tools, methodologies, and processes focus on these goals in the early stages of the ship development process and develop capabilities to assess and integrate multiple technologies throughout ship systems engineering. Proper execution of the D&IT function requires involvement in all the emerging technologies from the very beginning of development. The integration function also involves assessment of technologies

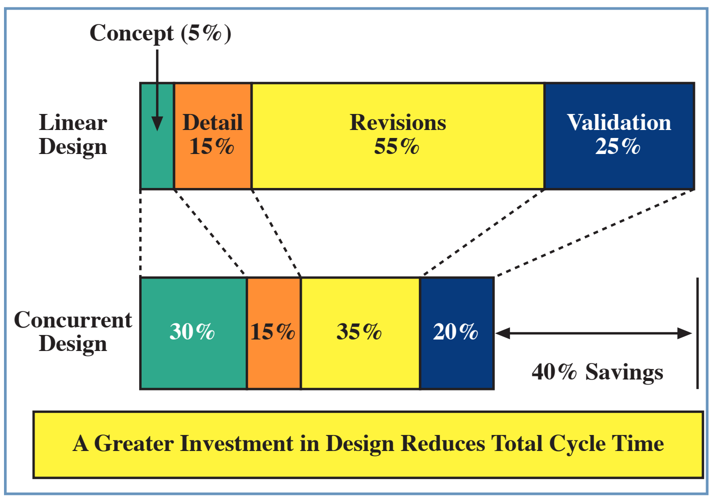

Figure 1. Design cycle time reduction, linear versus concurrent

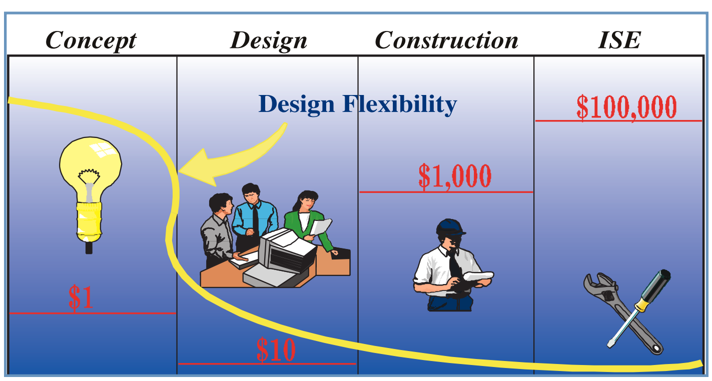

Figure 2. Change in total ownership cost

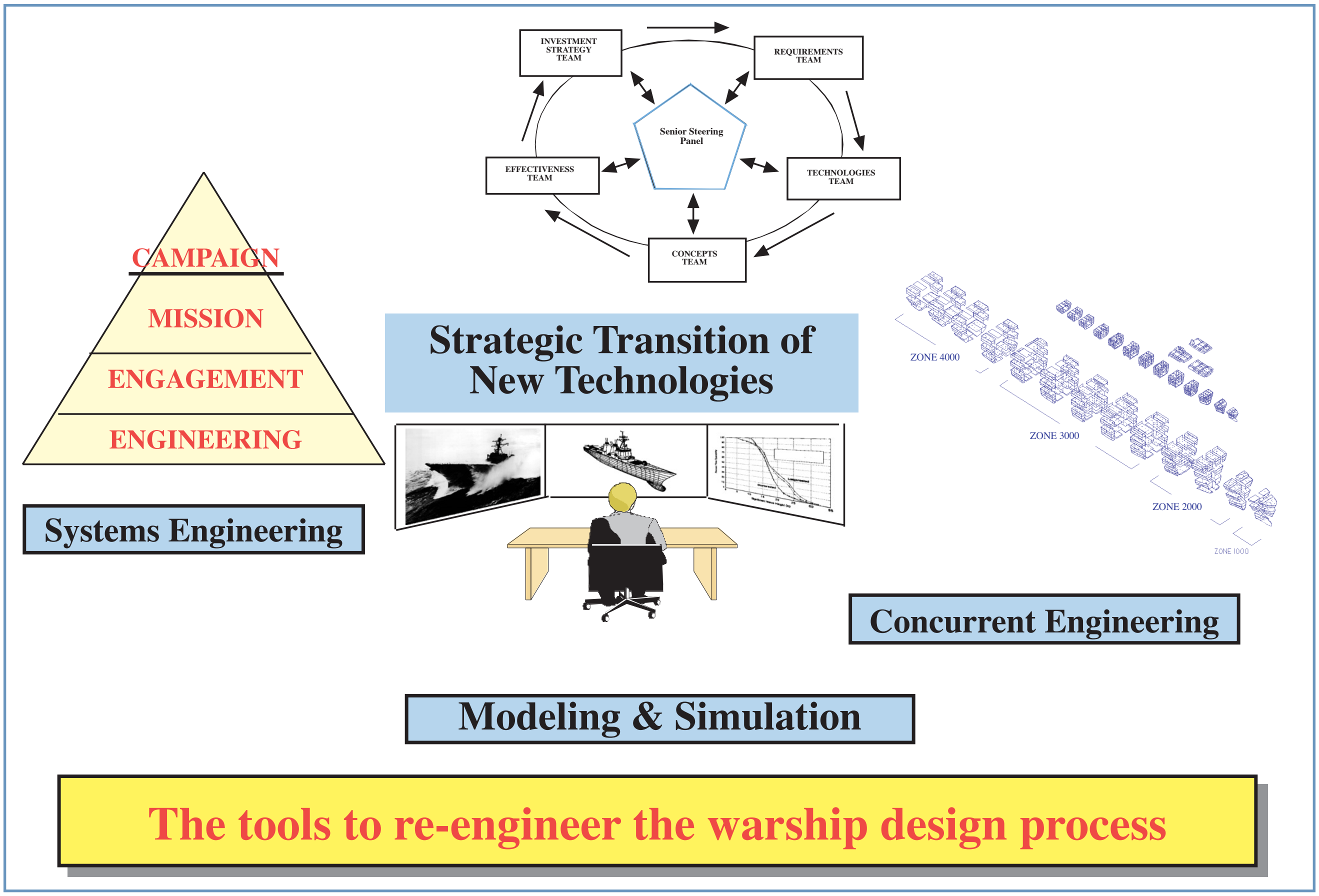

Figure 3. Developing the effective warship

from other Division program areas. Communication and the sharing of technical data are critical to integrating many technologies to operate as one total system. The systems engineering process is shown in Figure 4.

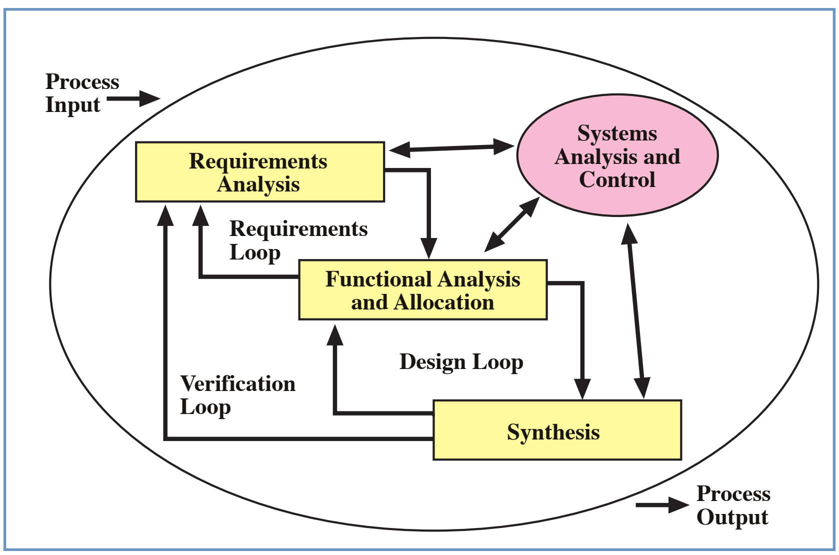

Figure 4. Systems engineering process.

The final product requires all the right elements to be integrated at the right time and in the right place. Reliability, maintainability, logistics support, human factors, and safety are just a few of the concerns that need to be addressed during the process to ensure the success of the final product. The engineer or scientist that works with D&IT has to be a master problem solver using an iterative "design, analyze, decide loop" and must continually be aware of the pitfalls of sub-optimization. The naval architect or engineer must understand how the requirements of the super-system impact the ship design and appreciate all the interdependencies across, among, and within the systems, subsystems, and components of the total product. D&IT covers the full life cycle from concept development based on operational requirements, all the way to introduction into the Fleet, including in-service operations and disposal. How some of these parts fit within the D&IT concept is discussed in the papers included in this Technical Digest. They include performance-based cost estimating, condition-based health and usage monitoring systems that use virtual sensors (maintenance), virtual prototyping of ship designs, high-speed transport ships, and logistics operation of offshore unloading of naval vehicles and supplies.

Overview

The Division leads the development of D&IT to meet the changing needs of the Navy. New initiatives of interest are the virtual prototyping of the total ship, the Center for Innovation in Ship Development, and the application of total ship systems engineering to warship development. All three initiatives will help to focus the Division's future efforts in D&IT in surface ship, submarine, combatant craft, Marine Corps craft and expeditionary logistics, deep submersibles, and autonomous unmanned vehicles.

Virtual Prototyping of Total Ship

This initiative encompasses:

- *Integrated Product Model Development* - Taking the lead to develop the Division's Leading-Edge Advanced Prototyping for Ships (LEAPS), which integrates recent advances in Smart Product Models and the Division's in-depth stand-alone performance prediction computer programs.
- *Integrated Data Environment Applications* - Supporting program offices in various integrated Information Technology activities and developing and fostering the use of international data exchange standards.
- *Design Tool Development* - Continuing development of the Navy's ship synthesis computer model (ASSET-Advanced Surface Ship Evaluation Tool) for a range of different ship types.

The Center for Innovation in Ship Development

Changes due to Acquisition Reform initiatives have had a dramatic effect on the roles of NAVSEA and the Warfare Centers with regard to the functions they perform in developing future advanced ship and Fleet concepts. Once Acquisition Milestone A has been reached, the role of NAVSEA and the Warfare Centers transforms from technology development and concept analysis functions to that of review. As a result, a new emphasis focuses on developing future ship and Fleet concepts prior to Milestone A, as well as tools, methodologies, and processes to improve the entire ship development cycle. Evidence of this new emphasis is apparent in the plethora of studies and initiatives whose focus is on the Navy after Next, or pre-Milestone A. The Innovation Center will be expected to respond to the changing roles of the Division in three primary areas.

1. Continue to perform advanced ship studies.
2. Expand the capabilities and facilities to perform pre-Milestone A concept studies.
3. Set up teaming arrangements with academia, industry and other government activities to exchange technology information and to collaborate in advanced concept studies to meet emerging Navy requirements. Create educational and outreach programs to develop innovative ship and Fleet concepts and implement smart product model and LEAPS environments.

Total Ship System Engineering

This effort focuses on development and application of design and manufacturing processes, methods, techniques and hardware/software solutions to improve the efficiency and economy of naval ship design and manufacture. It includes investigation of automating ship fabrication and repair technologies, advanced materials processing, cost and schedule risk assessment, and industrial base analysis. The objective is to seek increased throughput, shorter cycle times, and reduced total ownership costs. It should provide the capability to apply leading edge and emerging information technology to the acquisition, use, and management of Fleet-integrated product data. This would include interactive electronic technical manuals, implementation support to acquisition program managers, laboratory and field-testing of emerging commercial off-the-shelf products, information infrastructure enhancements, and shipboard integrated logistics concepts.

In addition, design computer synthesis programs like ASSET will help advance ship and submarine concepts, designs, and specifications. Other areas in total ship systems engineering are acquisition management support, intact and damage stability assessment, weight monitoring and reporting, ship general arrangements, systems safety program monitoring, reliability, maintainability and availability analysis, human systems integration (including manpower and workload analysis), human factors, and mixed gender (women-at-sea) initiatives. This area focuses on integration of hull, mechanical and electrical, combat systems, and mission area systems. It encompasses total surface ship and submarine design support/analysis capability. It is provided through using complex computer synthesis models and other computer-aided design tools. This capability for naval architecture at the total ship systems level is unique to the Carderock Division among all other NAVSEA field activities, and includes formulation of ship characteristics requirements, analysis of alternatives and assessment of technology investments, and total platform mission and cost assessment.

Design and Integration Technologies include a number of challenging functions, products, and services as shown in the early stage five-step systems engineering process shown in Figure 5.

D&IT functions in systems engineering include the following.

- Translate military requirements into concepts and specifications for naval and maritime ships and vehicles.
- Develop advanced ship design and analysis tools.
- Define critical ship design performance parameters at the total ship level.
- Provide life-cycle management, configuration management, acquisition support, and technical authority.
- Establish tools and processes to evaluate ship producibility alternatives.
- Foster processes to reduce overall design and manufacturing cycle time.

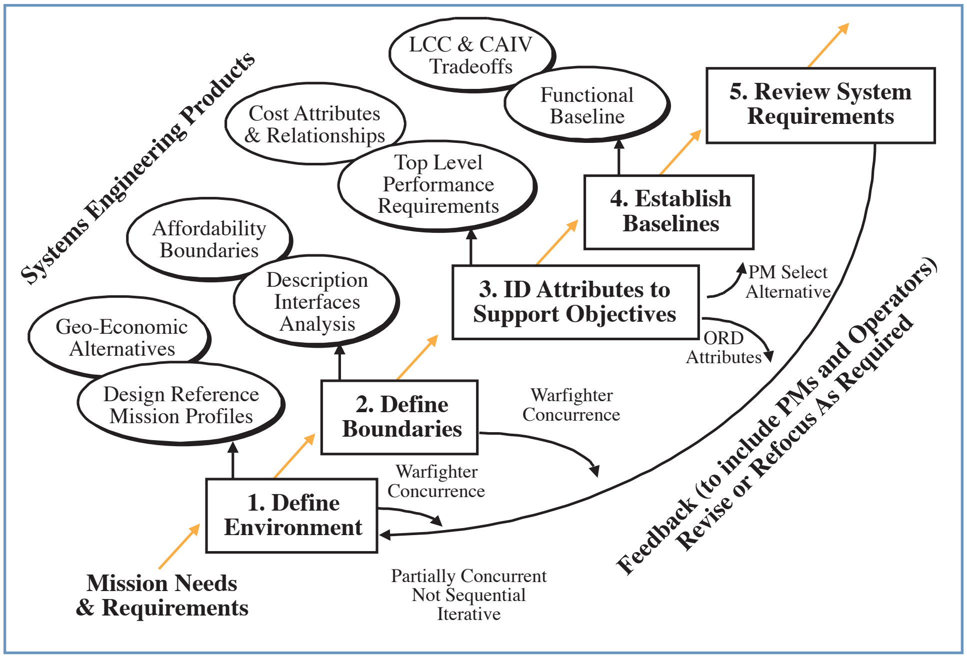

Figure 5. Five steps of the systems engineering process.

- Foster innovative technology for the overhaul, maintenance, repair, and new construction techniques for naval and maritime vehicles.
- Evaluate alternatives to quantify the cost and war-fighting effectiveness of ship concepts.
- Foster stewardship of an organic capability to assess the naval architectural designs provided by industry.
- Develop, evaluate, design, and assess Joint Logistics Over-the-Shore (JLOTS) concepts.
- Formulate physics-based models and simulations that link war-fighting effectiveness to hull, mechanical, and electrical system technologies including signatures, structures, materials, machinery, and ship hydrodynamics.
- Foster and maintain technical information systems to provide logistics support of Fleet and shore activities.
- Foster cooperative teaming with industry design teams.
- Support commercial standards committees.

Discussion Of Papers

The five papers which follow illustrate some of the Division's D&IT activities discussed above. In "Design Trends for High Speed Transports," a nondimensional Transport Factor (TF) parameter is used to analyze and make trade-off studies of various vehicle types to develop some general design and performance goals. TF analysis provides insight into the effects of major drivers for high-speed vehicles; i.e., weight, design speed, and installed power.

Generating some preliminary design parameters and applying "Performance-Based Cost Estimating Tools" provides an early estimate of the costs. When cost drivers and budget limits are known, iteration among the performance drivers can be made to identify a means to reduce costs and remain within budget constraints. Throughout the acquisition process, total ownership cost can be monitored using more sophisticated cost models.

LEAPS will support top-level requirements by fostering an expanded trade space of alternatives for the total ship, allowing more complete knowledge about each alternative, and providing rapid, thorough, and trusted evaluation of each alternative at an affordable price.

Once a ship or system becomes operational, there is a desire to improve the design process by using feedback from operational data. For example, virtual sensors, which incorporate neural networks, are discussed in "Case Study in Open Systems Architecture for Technology Insertion: The Joint Advanced Health and Usage Monitoring Systems." This concept can be expanded for the total ship and for vehicles that interface with the ship using open system architecture principles.

Ships and forces at sea and ashore must have the capacity to sustain their operational capability around the globe. In some cases, deep-water ports and offloading equipment are not available to support the forces ashore in areas where conflicts have developed; hence the need for an offshore unloading capability. Concepts developed under the JLOTS Technology Program proved to be valuable, especially when operational requirements now demand an offloading capability during Sea State 3 conditions. Information learned from JLOTS tests and other logistics operations will improve future designs and enhance existing ships by backfitting changes that will improve performance and reduce cost of ownership.

Summary

By carefully implementing tools and processes such as these, the D&IT community will pull together all various components, systems, and ship systems to develop the final product - a Total Force Solution (Figure 6) - that will be interoperable, effective, and affordable.

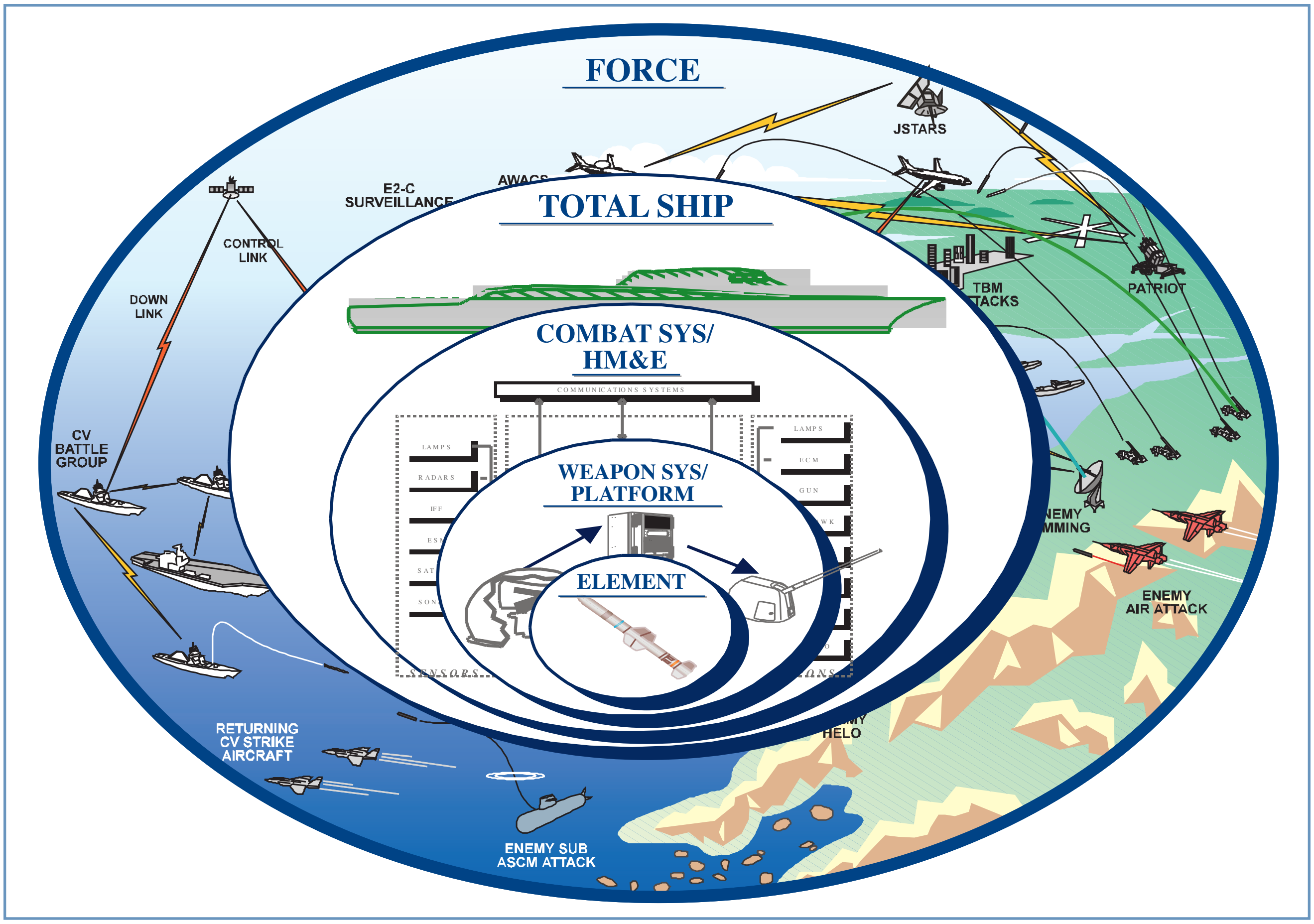

Figure 6. Total Force Solution, systems engineering at all levels.

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Design Trends in High Speed Transport

Colen G. Kennell

The maritime community is witnessing rapid technological change in some segments of the shipping industry. Fast-ferry evolution has been particularly energetic with a wide array of new hull forms being built and operated around the globe. Comparative evaluation of these hull forms is a complex problem. Wide variations in performance in areas such as seakeeping, maneuvering, noise, and powering are possible with the hull forms in vogue. Assessment of the implications of advances in major subsystems such as propulsion machinery and lightweight hull structures further cloud the issues due to their impact on the traditional performance areas and ascending arenas such as environmental-friendliness. The Transport Factor concept provides insights into the interaction of some of the fundamental parameters involved in these assessments. The parametric relationships developed link design values for ship weight, speed, range, cargo weight, installed power, and fuel efficiency to assess vehicle and subsystem alternatives. As a result, there is generally a unique Transport Factor value for each design. The focus of this work is on sealift-like ships capable of transporting large cargo over transoceanic distances at speeds of 40-100 knots that can have a significant military impact.

Introduction

The maritime community is witnessing rapid technological change in some segments of the shipping industry. Fast ferry evolution has been particularly energetic with a wide array of new hull forms being built and operated around the globe including wave-piercing catamarans, Surface Effect Ships (SES), foil-assisted catamarans and monohulls, semi-SWATHs, and Hydrofoil Small Waterplane Area Ships (HYSWAS). This evolution has been characterized by steady increases in ship size and progressively higher transit speeds. Ferries with displacements of several hundred to several thousand tons with speeds above 40 knots are now entering service. Rapid technological advances in subsystems have paralleled this frantic pace of vehicle development.

Serious efforts are underway to produce high-speed cargo ships that displace tens of thousands of tons with transoceanic range and speeds above 40 knots. Hull forms that differ significantly from conventional merchantmen have been proposed to meet these objectives including semi-planing monohulls, slender monohulls, and SESs. Such high-speed ships are attractive for military sealift missions. The quest for competitive advantage promises that this push for ever-increasing speeds and cargo capacity at an affordable price will continue as economies allow.

Comparative evaluation of this bewildering array of competing hull forms is a complex problem. Wide variations in performance in areas such as seakeeping, maneuvering, noise, and powering are possible with the hull forms in vogue. Assessment of the implications of advances in major subsystems such as propulsion machinery and lightweight hull structures further cloud the issues due to their impact on the traditional performance areas and ascending arenas such as environmental-friendliness.

The Transport Factor (TF) concept provides insights into the interaction of some of the fundamental parameters involved in these assessments. The parametric relationships developed link design values for ship weight, speed, range, cargo weight, installed power, and fuel efficiency to assess vehicle and subsystem alternatives. The concept is based on overall design attributes of ships (e.g., full load displacement, service speed, installed power) rather than performance characteristics that can vary with loading condition and speed. As a result, there is generally a unique Transport Factor value for each design.

While Transport Factor analysis seems applicable to all types of vehicles at all speeds, the focus of this work is on sealift-like ships capable of transporting large cargos over transoceanic distances at speeds of 40-100 knots. Data for other types of vehicles are included to provide perspective and enhance validity.

Transport Factor

Nomenclature

W	full load weight of ship (LT)
W_{cargo}	weight of cargo (LT)
W_{fuel}	weight of fuel (LT)
W_{ship}	$W\text{-}W_{cargo}\text{-}W_{fuel}$ (LT)
V_K	design speed (knots)
SHP_{TI}	total (propulsion + lift) installed power (hp)
R	range (nautical miles)
K_1	1.6878/550 (hp/lb-knot)
K_2	2240 (lb/LT)
K_S	ratio of endurance speed to design speed
K_{SHP}	ratio of endurance power to design power

The Transport Factor is the non-dimensional relationship between the weight, design speed, and installed power of a vehicle, given by equation (1). The TF has similarities to other parameters used to assess different types of vehicles.

$$TF = \frac{\dfrac{K_2 * W}{SHP_{TI}}}{K_1 * V_K} \tag{1}$$

The two most closely related are a parameter popularized by Gabrielli and von Kármán[1] generally known as Transport Efficiency (TE) and the ratio of Lift to Drag (L/D). Transport Efficiency is generally used to relate a vehicle's installed propulsion power to its weight and maximum speed. TF relates the sum of installed propulsion power and lift power (for powered lift vehicles) to design weight and design speed (i.e., sustained speed, service speed) while excluding power for hotel loads. Hotel load power is generally small compared to propulsion power for high-speed vehicles, but becomes more significant as speed decreases. There is a unique TF value for each design.

The ratio of lift-to-drag excludes the hydrodynamic and mechanical losses associated with the propulsor and power transmission system, which are included in TE and TF. Power for dynamic support and auxiliary power also are excluded. The L/D of a vehicle also varies with speed unlike TE and TF, which are unique for each vehicle.

The subtle differences between TF and the other two better-established parameters suggest that TF might be expressed as a special case of either TE or L/D. This has not been done to reduce confusion between the different terms.

Gabrielli and von Kármán used TE data for a large number of vehicles to establish minimum power requirements for each type of vehicle over a range of speeds. Transport Factor data could be analyzed similarly to produce a like result. However, more useful insight into design and technological issues associated with different vehicles can be obtained by separating TF into three components corresponding to different weight components of the vehicle.

The total weight of a ship can be considered as the sum of three principal parts corresponding to cargo weight, fuel weight, and ship weight. Separate Transport Factor components are related to these terms, as shown in equation (2).

$$TF = TF_{ship} + TF_{cargo} + TF_{fuel} \tag{2}$$

Equations (1) and (2) can be combined to obtain equation (3).

$$TF - TF_{fuel} = K_1 K_2 \left[\frac{W_{cargo}}{SHP_{TI}} \left(1 + \frac{W_{ship}}{W_{cargo}} \right) \right] V_K \tag{3}$$

Interesting features of the TF_{fuel} term become evident by relating fuel weight, installed power, speed, and range, as shown in equation (4). The average effective specific fuel consumption rate, SFC_{avg}, is defined by equation (4). It includes the cumulative effects of the energy conversion characteristics of the engines, the amount of power required to propel the ship for the design range, vehicle hotel loads, and numerous design practices.

$$W_{fuel} = SFC_{avg} * K_{SHP} * SHP_{TI} \frac{R}{K_S * V_K} \tag{4}$$

Fundamental to this term is the specific fuel consumption (SFC) rate of the power generation machinery, a measure of the efficiency of the process used to convert fuel into useful work. While there are SFC differences among the major prime mover types commonly used in ships (i.e., steam, diesel, and gas turbine), these differences generally have minor effect on SFC_{avg} for well-designed vehicles compared to the effects of the type of ship employed, the design of the machinery system as a whole, and other design-specific factors.

Differences in hotel loads, operating profile, and design practices peculiar to each vehicle are more significant. Wide variations in design parameters such as crew size, accommodation standard, environmental assumptions, dynamic lift requirements, design margins, fuel reserves, and ullage occur between different types of vehicles. While engine SFCs may be similar, these other differences result in significant changes in the relationship between SFC_{avg} and raw engine SFC. Differences in the SFC_{avg}/SFC relationship should be small within a class of similar well-designed vehicles where similar assumptions prevail. Equations (1) through (4) can be combined to form equations (5) and (6).

$$TF_{fuel} = \frac{K_1 * K_{SHP}}{K_S} SFC_{avg} * R \tag{5}$$

$$TF = K_1 K_2 \left(\frac{W_{ship} * V_K}{SHP_{TI}} + \frac{W_{cargo} * V_K}{SHP_{TI}} \right) + \frac{K_1 * K_{SHP}}{K_S} SFC_{avg} * R \tag{6}$$

Transport Factor Features

Equation (6) shows that the Transport Factor consists of some conversion constants (K_1, K_2), requirements-derived terms (W_{cargo}, V_K, K_S, R), and design terms (W_{ship}, SHP_{TI}, K_{SHP}, SFC_{avg}). While the requirements terms are specific to individual vehicles and vary widely, they are generally all well defined. The ratio of endurance speed to design speed, KS, can vary widely but is generally close to unity for commercial vehicles. Speed, range, and cargo are the primary variables affecting a vehicle's income generation potential.

Vehicle weight and installed power are the two design terms most sensitive to the manipulations of designers. Design life, structural design, material selection, subsystem choices, and vehicle type and form significantly affect these variables. K_{SHP} is generally close to unity for commercial transports.

Perhaps the most interesting observation to be made from this derivation is that the fuel part of the Transport Factor, defined by equation (5), is independent of vehicle size, cargo weight, and speed. TF_{fuel} is only weakly dependent on K_S and K_{SHP} because these terms almost always vary in phase (lower speed means lower power) and are generally close to unity for commercial vehicles. Furthermore, little variation in SFC_{avg} is expected for similar vehicles. Consequently, TF_{fuel} is primarily a function of range. The nature of TF_{fuel} is fundamental to the examination of the vehicle design trends that follow.

Gabrielli and von Kármán[1] suggest that a maximum achievable value of TE exists for each type of vehicle at each speed in its speed regime. These limit curves may change slightly for modern vehicles to reflect technological advances such as improved hull forms and more efficient propulsors. However, similar limits are assumed to exist for the modern counterparts of those historic vehicles, as well as for the non-conventional vehicles popularized since then. Existence of these assumed limits combined with TF_{fuel} characteristics allow construction of parametric relationships linking cargo weight, speed, installed power, and ship weight through equation (3).

Transport Factor Design Trends

High TF values are generally considered to be characteristic of good designs due to the implication of increased cargo-carrying capability, increased speed, or reduced power. Transport Factor values achieved vary significantly among vehicle types. TF also shows a strong speed dependence for the vehicles of interest in the speed range of interest, as shown in Figure 1. Most of the points in the figure represent ships and vehicles currently or formerly in service. Data are also included for a few mature designs (two monohulls and three Surface Effect Ships) that have not been built. While less desirable than data for actual ships, acceptance of these points was necessary to adequately define TF characteristics of the vehicles for the sizes and speeds of interest in the absence of actual ship data. A parametric curve for a notional submarine design has been included also.

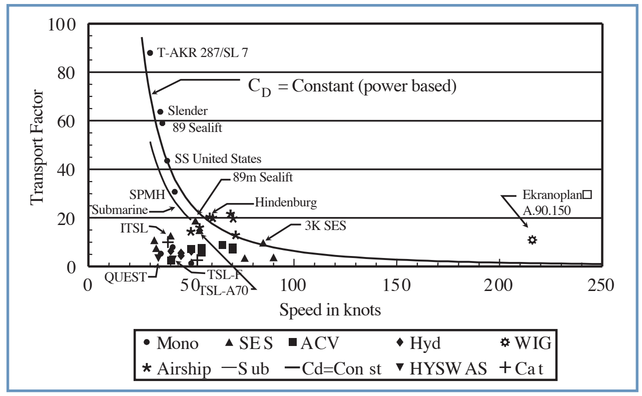


Figure 1. Transport Factor achieved.

Figure 1 shows that TF values are generally below 20 for all vehicles across the speed range shown. The primary exception to this generality occurs for buoyantly supported ships at speeds below 50 knots where extremely high TF values have been achieved. Design and operating economies associated with these high TF vehicles account for the dominance of displacement ships in this speed regime.

Few displacement vehicles have been produced with speeds above 50 knots. Most of the displacement vehicles in this speed range are airships (lighter than air vehicles) from an earlier era. Transport Factor values of 10 to 20 were achieved by these extinct giants, which allowed them to function in intercontinental commerce prior to development of long-range aircraft with much higher speeds.

Most airship TF values are somewhat overstated in the figure due to use of maximum speed rather than service speed in the calculations. This compromise was dictated by limitations in the available data[2]. Some data exists[3] on the performance of Hindenburg and Graf Zeppelin in service. The top speed of Hindenburg was 72 knots while Graf Zepplin made 69 knots. Table 1 shows that average speed made good in service was significantly lower than trial speed for these vehicles. However, these data are inadequate as a basis to characterize all airships. As a result, the Hindenburg point in Figure 1 is somewhat arbitrarily based on a 59- knot service speed, while all other airship points use trial speed.

Table 1. Speed in-service for airships.

Airship	Route	Average Speed (knots)
Hindenburg	Germany-Brazil	59.1
	Brazil-Germany	51.4
	Germany-US	49.9
Graf Zeppelin		
	Germany-Brazil	67.6

While there are no monohull displacement ships in the 50- to 70-knot range shown, some small surface craft have achieved these speeds. These small special purpose craft are characterized by TF values of 1 or 2. Limited range and cargo capabilities associated with such low TF values have precluded a meaningful transport role for these novelties.

The nature of the rapid TF decrease with increasing speed for displacement vehicles is largely explained by the curve labeled C_D = *constant* in Figure 1. This curve represents a hypothetical displacement monohull with drag coefficient and propulsive efficiency held constant at values characteristic of lower speeds. Subtle changes in drag and not so subtle changes in propulsor performance that accompany higher speeds are ignored for simplicity. The transport factor is proportional to V^{-2} for these assumptions. The simplified curve clearly reflects the trend of the monohull data in the figure. Validity of this simple model is reinforced by the similarity of the parametric submarine curve, which was developed with similar assumptions. A similar curve, shifted to the right, should result from application of this type of analysis to airships. The C_D = constant curve suggests that monohull designs might be possible with TF values from 10 to 20 over the lower part of this speed range. Since the assumptions behind the constant drag coefficient curve are considered optimistic, high-speed monohulls should fall below this curve. While necessarily coarse due to the simplifying assumptions, the overall trends illustrated by these curves are expected to be valid pending significant changes to the underlying physics associated with resistance and propulsion.

The variation of TF_{fuel} with range is shown in Figure 2. Vehicles with long range are highly desirable if not essential for transoceanic transport. Data in Figure 2 for displacement monohulls, aircraft, and airships show that these vehicles have been built with ranges above 5,000 miles. Lowering the range threshold to 2,000 miles adds Surface Effect Ships to the list of long-range vehicles. Other types of vehicles are generally built for short range.

The two lines drawn in Figure 2 represent upper and lower trend-lines for the data. While considerable variation is evident, data for low speed monohull displacement ships tend toward the upper trend-line; aircraft tend toward the lower trend-line. The ship line is about double the aircraft line. The limited SES data suggests that these vehicles may span the region between the aircraft and ship trend-lines.

Both aircraft and SESs are dynamically supported vehicles. These vehicles require less lift as fuel is burned resulting in less power needed to maintain a steady speed or an increase in speed at constant power. The effect is to decrease TF_{fuel} through either a decrease in K_{SHP} or an increase in K_S. The same is true for displacement monohulls if draft is not maintained by ballasting. However, a much smaller change results. The magnitude of this effect varies between vehicles due to variation in the size of the weight change. For example, about 45 percent of the departure weight of long-range aircraft is fuel weight while the comparable figure for displacement monohulls is about one-third as great. As a result, the effect of this fuel weight burn-off on TF_{fuel} is much lower on an uncompensated monohull and practically non-existent if the design draft is maintained.

The higher fuel weight fraction of long-range aircraft results in a larger reduction in TF_{fuel} by reducing lift-induced drag. This large drag component is theoretically proportional to the square of lift. If other drag terms are ignored, TF_{fuel} for a representative long-range aircraft with a fuel weight fraction of 0.45 would be about 70% that of a constant weight vehicle. While other drag terms would cause this factor to creep upward, fuel burn-off clearly has the potential to account for most of the difference between the ship and aircraft trend-lines in Figure 3. The remaining difference must be explained by differences in hotel load, design and operational margins, design philosophy, and ullage.

The design trends identified for TF and TF_{fuel} assume knowledge of the type of vehicle of interest, its range, and speed. These parameters are fundamental to setting requirements. Results from these trends can be used to derive relationships between cargo weight, ship weight, and installed power using equation (3). Although this expression is completely general, the derived results are more precise if certain assumptions are made about TF and TF_{fuel}. Specifically, (1) an achievable value for TF can be identified

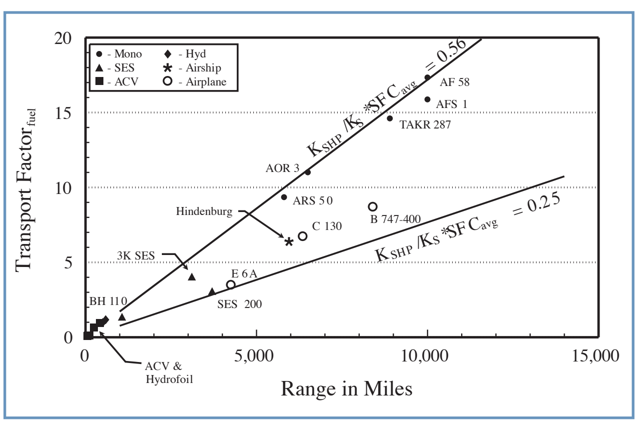


Figure 2. Fuel Transport Factor trends.

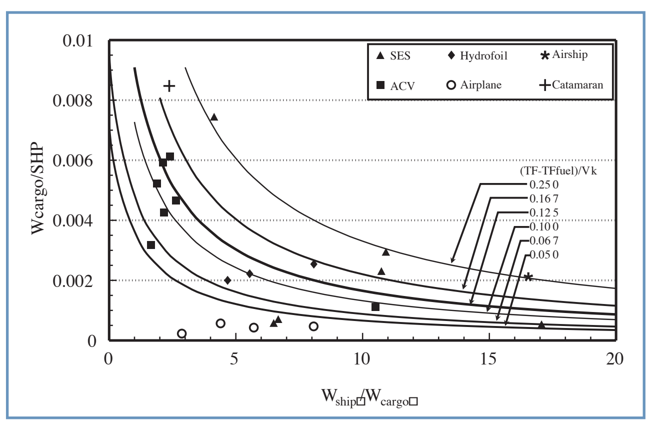


Figure 3. Weight and power parametric design trends.

based on vehicle type and design speed (Figure 1), and (2) TF_{fuel} can be determined based on vehicle type and range (Figure 2). Hence, equation (3) is of the form shown in equation (7), where the constant depends on particular values of TF, TF_{fuel}, and V_K.

$$\frac{W_{cargo}}{SHP_{TI}} = \frac{\textbf{Constant}}{\left(1 + \frac{W_{ship}}{W_{cargo}}\right)} \tag{7}$$

This parametric relationship is shown in Figure 3 for vehicles in the 40- to 80-knot speed range. Curves are shown for values of the ratio of ($TF-TF_{fuel}$) to V_K between 0.05 and 0.25, a representative range of values for high-speed vehicles. A number of interesting observations and assertions can be made about Figure 3.

- Definition of speed, range, hull form, and machinery constrains a design to a unique contour similar to those in Figure 3, which relates ship and cargo weight and installed power.
- Less installed power is required to transport a given cargo weight for designs with low ratios of ship-to-cargo weight.
- The power reduction associated with ship weight reduction is much larger for vehicles with a low ship-to-cargo weight ratio than for a high weight ratio.
- A change in the amount of TF available for ship and cargo weight (by changing TF or TF_{fuel}) can significantly affect installed power.

Summary

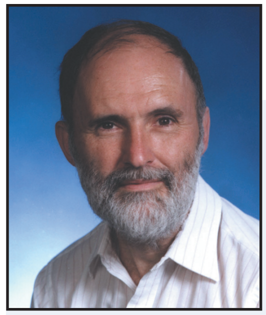
Transport Factor analysis provides a simple means to make comparative evaluations between different types of vehicles. The design trends derived from TF analysis provide useful insight into major design drivers of high-speed vehicles. Design choices such as alternative types of vehicles, improved hull forms, lighter weight designs, and more fuel-efficient machinery can be evaluated in terms of their effect on the TF variables - cargo weight, speed, range, ship weight, and installed power. Useful information can be derived for changes to a specific design or for trade-offs between competing designs.

References

1. Gabrielli, G., and T. von Kármán, *What price speed*. Mechanical Engineering, Vol. 72, No. 10 (Oct 1950).

2. Robinson, D.H., *Giants in the sky*, University of Washington Press (1973).

3. Dick, H.G., and Robinson, D.H., *The golden age of the great passenger airships Graf Zeppelin and Hindenburg*, Smithsonian Institute Press, Washington, DC (1985).



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Performance-Based Cost Models

Robert R. Jones, Michael F. Jeffers, Jr., and Marc W. Greenberg

Two Department of Defense acquisition program processes, Analysis of Alternatives (AoA) and Cost as an Independent Variable (CAIV), require new cost analysis tools. The Division has developed a new estimating process capable of providing these tools. These models, called Performance-Based Cost Models (PBCM), estimate the weight and cost of ships and submarines as a function of essential cost drivers - performance characteristics, technology factors, and market conditions. This paper briefly describes the background that led to the development of the first PBCM and the analytical underpinnings and typical uses of the model in support of AoA and CAIV studies.

Introduction

In the 1990s, two Department of Defense acquisition program processes, Analysis of Alternatives (AoA) and Cost as an Independent Variable (CAIV), presented new challenges for cost analysts. The need emerged for cost estimating tools and analysis techniques that could rapidly evaluate the effects of three kinds of essential cost drivers - performance characteristics, technology factors, and market conditions - on the cost of ship and submarine concept alternatives.

NSWCCD played a major role in developing a family of simple, yet robust, estimating models called Performance-Based Cost Models (PBCM) that responded to the need. PBCMs provide rough order of magnitude costs and basic weight estimates of ships and submarines as a function of the essential cost drivers. Appropriately formulated PBCMs provide a capability to address high-level cost-performance tradeoffs in the early stages of a program. Thus, PBCMs allow decision-makers to assess the individual or combined effects of cost drivers and to compare the costs of wide ranges of concepts with varying performance characteristics and technological content. Examples of useful graphic displays that PBCMs can generate to support such assessments are given in this paper.

Cost Models

Performance-Based Cost Models have been developed for attack submarines, ballistic-missile submarines, surface combatants, auxiliary ships, aircraft carriers, (United States Coast Guard) deepwater vessels, and a variety of unmanned underwater vehicles. All of these models are based on a single underlying mathematical theory that establishes a general logic and structure for performance-based cost modeling. A practical PBCM for a specific ship or system type consists of a set of specific equations derived from the general mathematical structure based on characteristics of the ship or system of interest. The equations are quantified by assigning specific numerical values to individual coefficients in the functional relationships. Quantification of the PBCM equations can be accomplished using regression analysis or other statistical procedures when sufficient appropriate data are available. Engineering analysis or other deterministic methods can be also used.

Essential Cost Drivers

It is assumed that the cost of ships (hereafter, "ships" refers to all naval vessels and vehicles) is determined by three factors.

1. *Performance Characteristics* (P) for ship systems and combat systems. There are two types of performance characteristics. First, a performance characteristic can be equivalent to the top-level requirements for a ship, including speed, quieting metrics, and endurance. Second, performance characteristics can be more particular in nature, such as combat system payload capacity, weapon systems loadout, shaft horsepower, and crew size.
2. *Technology Factors* (t) include the nature of materials and specific systems incorporated into the ship, the processes that are used in its construction, design standards and practices, and safety margins.
3. *Market Conditions* (m) relate the unit procurement cost to economic and production conditions during the period of the ship's development and construction. These include learning and production rate effects, numbers of production facilities, and inflation and escalation.

Basic Mathematical Theory

The simplest mathematical statement of the underlying theory inherent to PBCMs is:

$$C = F(P, t, m) \qquad (1)$$

Where

C = the unit procurement cost of a particular ship; it is a function of three variables or cost drivers.

P = a vector of performance characteristics.

t = a vector of technological characteristics.

m = a vector of market conditions.

Each of the variables is a vector in the sense that they are composed of multiple attributes. For example, the performance vector, P, might be composed of two attributes, speed and range; and the market conditions vector might be composed of the number of ships, the number of shipyards, and the build rate.

The influences of cost drivers can be analyzed in terms of the partial derivatives of F. For example, the change in cost that occurs in response to a unit increase in a single element, say speed, of the performance vector is $\delta F/\delta P_j$, where j is the element of P that contains speed. Similarly, $\delta F/\delta m_k$, where k is the element of the market factor vector containing the number of shipyards, is the change in cost that occurs when one additional shipyard is maintained in the industrial base.

Several important assumptions regarding Equation (1) are necessary to proceed with the PBCM development. The first two modeling assumptions are discussed below.

The Separability Assumption

The first important assumption is that the influence of market conditions is separable from the influences of performance characteristics and technology factors. This means that Equation (1) can be rewritten as

$$C = F(P, t, m) = g(m) \cdot h(P, t) \qquad (2)$$

The function g(m) captures the impact of market conditions and acts as a multiplier on a cost function, h, which is driven only by performance characteristics, P, and by technology factors, t.

The separability assumption is important for two reasons. First, the market conditions function, g(m), can be generated using information external to the database used to develop the performance and technology relationships. This benefits the analyst because additional data from different sources increases the possibility of generating meaningful statistical relationships for g(m).

Second, the effect of market conditions on unit procurement cost can be analyzed independently from the effect of performance and technology factors on unit procurement cost. The function h(P, t) can be constructed to produce a “standard” unit procurement cost under known, specific market conditions. The function g(m) can be used to modify the standard unit procurement cost to market conditions other than those for the standard unit procurement cost. For example, h(P, t) might represent a theoretical n^{th} unit procurement cost in a learning model. The function g(m) might be the learning curve function; it can be used to adjust the n^{th} unit procurement cost to that of any other unit.

The Technology Assumption

A second important modeling assumption concerns the influence of technology factors. Technology factors, represented mathematically by the vector t in Equation (2), are assumed to act as parameters that influence the values of the coefficients relating performance to cost. So, just as for the market conditions effect, the function h(P, t) can be constructed to produce a “standard” unit procurement cost for a ship with known, specific technological content. The vector t can be used to modify the unit procurement cost to technologies other than those for the standard. For example, the vector t could be used to adjust the unit procurement cost of a mild steel ship to that of a ship constructed of HY-100 steel.

The two important assumptions allow Equation (2) to be rewritten as

$$C' = C / g(m_o) = h(P, t) \qquad (3)$$

Where

m_o = a specific standard set of market conditions

t = a vector of technology factors.

The function h is defined on the individual elements of the performance vector; the semicolon notation indicates that the function h is parametric on the technology vector, t. In a parametric relationship such as Equation (3), the functional form of the relationship between cost and the performance variables is the same for all relevant technology combinations. However, the values of the coefficients of the relationship will vary with technology.

In Equation (3), C′ represents the unit procurement cost at some standard set of market conditions, $g(m_o)$. Analysis of market conditions, resulting in a new g(m), can transform the result, C′, to the new market conditions of interest.

$$C'_{New} = g(m)_{New} \cdot C / g(m_o) \qquad (4)$$

As a result of the two modeling assumptions, the following mathematical equation, without the prime (′) on the cost variable for notational simplicity, states the basic relationship for a PBCM.

$$C = h(P, t) = h(P_1, P_2, ..., P_N, t) \qquad (5)$$

PBCM Modeling Applied to U.S. Navy Ships

Through the use of the Navy's Ship Work Breakdown Structure (SWBS), the general PBCM formulation of Equation (5) is used to create a U.S. Navy ship PBCM. According to the SWBS cost accounting system, the unit procurement cost of a ship is

$$C_{ship} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 \qquad (6)$$

In Equation (6), the 1 stands for SWBS 100, hull structure; 2 for SWBS 200, propulsion plant; 3 for SWBS 300, electric plant; 4 for SWBS 400, command and control; 5 for SWBS 500, auxiliary systems; 6 for SWBS 600, outfitting and furnishing; 7 for SWBS 700, armament; 8 for integration/engineering services; and 9 for ship assembly and support services. Via a pro-rationing process, the SWBS 800 and 900 costs are included in SWBS 100 through 700. Therefore, Equation (6) can be rewritten as

$$C_{ship} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 \qquad (7)$$

The unit procurement cost of any of the seven SWBS groups can be defined as the product of the cost per ton times the weight in tons. So, for instance, the unit procurement cost of SWBS 100, hull structure, can be expressed as

$$C_1 = c_1 \bullet W_1 \qquad (8)$$

Where

c_1 = the cost per ton of SWBS 100

W_1 = the weight in tons of SWBS 100.

Equation (8) is an important definition and leads to a fundamental characteristic of PBCMs. When Equation (8) is combined with Equation (5), the result is that both the cost per ton, c_1, and the weight, W_1, are estimated as a function of performance characteristics and technology factors, or

$$C_1 = c_1 (P_1, P_2,..., P_N, t) \bullet W_1 (P_1, P_2,..., P_N, t) \qquad (9)$$

In Equation (9), the impact on the unit procurement cost comes through two routes. Increased performance may increase the cost per ton of the hull structure, the weight in tons of the hull structure, or both. The same is true for impacts due to technology factors.

The specific hull structure example of Equation (9) can now be extended to the other SWBS groups of Equation (7) resulting in the following equation.

$$\begin{aligned} C_{ship} &= \sum C_i \\ &= \sum c_i (P_1, P_2,..., P_N, t) \bullet W_i (P_1, P_2,..., P_N, t) \\ &\text{for } i = 1 \text{ to } 7 \end{aligned} \qquad (10)$$

Where

$$C_{platform\ systems} = C_1 + C_2 + C_3 + C_5 + C_6 \qquad (11)$$

$$C_{combat\ systems} = C_4 \qquad (12)$$

$$C_{weapon\ systems} = C_7 \qquad (13)$$

and

$$W_{ship} = W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 \qquad (14)$$

$$W_{platform\ systems} = W_1 + W_2 + W_3 + W_5 + W_6 \qquad (15)$$

$$W_{combat\ systems} = W_4 \qquad (16)$$

$$W_{weapon\ systems} = W_7 \qquad (17)$$

Equation (10) is the general unit procurement cost equation included in all PBCMs. Equations (11) through (13) subdivide Equation (10) into logical ship systems. Equations (14) through (17) are the associated weight relationships. While not discussed in this paper, similar logic is used to generate equations for estimating shaft horsepower, speed, and installed electrical power generation capability.

Generating the PBCM Equations

Least squares multiple regression analysis techniques are used to generate the seven cost-per-ton equations, c_i, and the seven weight equations, W_i, represented in Equation (10). Similar techniques also are used for the shaft horsepower, speed, and electrical power generation equations. Five principles guide the techniques used to generate the regression equations.

1. Cost, weight, performance, and technology data by SWBS group are required to generate the regression equations. Generally, such data are not in abundant supply. Therefore, the number of independent variables in each equation must be limited to the most obviously relevant ones to maintain sufficient degrees of freedom within each regression equation.

2. The constants and coefficients must be meaningful and easily interpretable. Adherence to this principle can assist with the understanding and acceptance of the PBCM equations.
3. Consistency must be maintained with physical phenomena and naval architectural principles. For instance, the speed and shaft horsepower equations should be of similar forms, be nonlinear, and should include a term to capture the resistance of the ship. In effect, adherence to this principle results in additional data to the analyst when generating the regression equations.
4. Apriori logic is used as a basis to develop relationships. For instance, one could expect the performance factor of speed or shaft horsepower to be an important, relevant parameter in the SWBS 200 propulsion plant unit procurement cost equation. In effect, the apriori logic principle can help to accelerate the regression equation development process.
5. Supplementary engineering or cost information is used where necessary to support the development of statistical relationships. This principle is the general statement of the premise that additional data from different sources increase the possibility of generating meaningful statistical relationships.

Appropriate functional forms for use in PBCM equations vary depending on the SWBS group and the underlying physical and cost phenomena being modeled. As an example, typical cost-per-ton and weight equations for SWBS group 100, hull structure, are shown below.

$$W_1 = K_1 \cdot (P_1)^{K_2} \cdot (\sum W_i - W_1) \cdot (1 + K_3 \cdot \text{time}) \quad \text{for } i = 1 \text{ to } 7 \qquad (18)$$

$$C_1 = K_4 \cdot e^{K_5 \cdot P_2} \qquad (19)$$

In the above equations, P_1 and P_2 are specific performance characteristics related to the platform systems; K_1 through K_4 represent the actual numerical values of coefficients determined via the least squares multiple regression analysis technique. Equation (18) models hull structure weight as proportional to the weight of the remainder of the SWBS groups; the proportion, represented by the coefficient K_1, varies depending on the value of the performance variable, P_1. The coefficient, K_2, is an exponent in a power law relationship of P_1 to weight; as such, it is an elasticity representing the percent change in weight resulting from a percent change in P_1. The time variable indicates there is an historical time-trend effect in the hull structure data. Equation (18) is an intrinsic equation in a system of equations because it depends on weights of other SWBS elements. This characteristic is typical of PBCM weight equations. Forming what is informally called a “ship synthesis loop,” PBCM models must be solved iteratively because PBCM weight equations interact with each other.

Equation (19) shows that C_1, the hull structure cost per ton, depends on performance variable, P_2. K4 is the cost per ton when P_2 is zero. In this exponential relationship, K_5 represents the percent increase in cost per ton per unit increase in P_2. These and several other relatively simple functional forms, which have straightforward interpretations that can be verified using a modest amount of calculus, have proved useful in the construction of PBCMs.

When PBCM equations are derived from historic data using statistical regression methods, specific statistics relating to the “goodness of fit” and statistical significance of the relationship are produced along with estimates of the coefficients. Further details will not be discussed here, however, these statistics provide an objective means to assess the overall quality of the relationships in the model and the general accuracy of predictions made using the model.

Implementation of Performance-Based Cost Models

The system of equations that quantify the model are typically implemented in Performance-Based Cost Models as shown in Figure 1.

Performance input variables initialize the equations used to estimate shaft horsepower (shp), speed, kilowatts, and system weights. The ship synthesis function is required

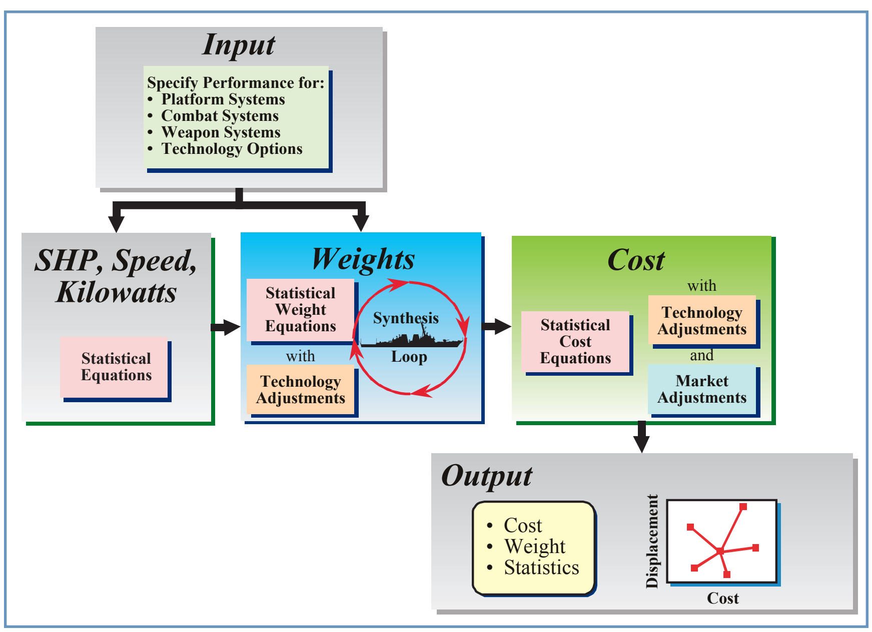


Figure 1. Performance-Based Cost Model implementation.

to solve the weight equations iteratively; it terminates when all of the algorithms converge to a balanced ship design. Figure 2 shows the typical design synthesis loop included in a PBCM. Two design synthesis loop options are included; one where shp is a given and speed is estimated, and one where the speed is given and shp is estimated.

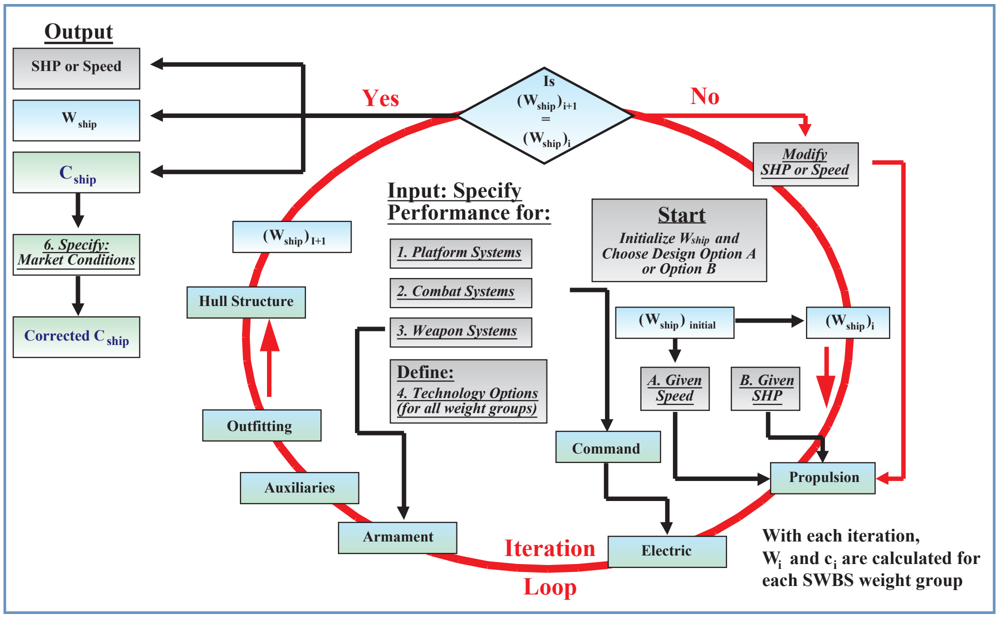


Figure 2. Typical Performance-Based Cost Model design synthesis loop.

Example Uses

Performance-Based Cost Models can generate a variety of outputs to support AoA or CAIV studies. Two of the more important output options are "spider plots" and "walkabout plots." A typical spider chart is shown in Figure 3. In a spider plot, C_{ship} and W_{ship} estimates are made for a ship concept baseline. Using the PBCM, each of the input performance variables is varied, one at a time, and a new estimate is made for C_{ship} and W_{ship}. In this way, the individual effects of performance variables can be assessed, and different ship concepts with different performance characteristics can be compared. The spider plot shown in Figure 3 demonstrates the added flexibility of a PBCM where C_{ship} is compared for three ship concepts as a function of speed rather than W_{ship}.

The second popular output of a PBCM is the walkabout plot shown in Figure 4. In a walkabout plot, C_{ship} and W_{ship} estimates are made for a ship concept baseline. One of the input performance variables is varied using the PBCM, and a new C_{ship} and W_{ship} line-segment is added to the ship concept starting position. Adding line segments continues, one at a time, for all of the input performance variables of interest. Walkabouts are particularly useful to demonstrate the individual and cumulative effects of increasing (or decreasing) performance requirements on C_{ship} and W_{ship}.

PBCMs were developed in response to the need to support the two Department of Defense acquisition program processes, Analysis of Alternatives and Cost as an Independent Variable. Designed to estimate total ship weight and cost as a function of performance, PBCMs have been used extensively for pre-Milestone 0 and Phase I estimating. PBCMs serve as a responsive means to gain useful information during the early stages of projects, are simple to use, capable of rapidly evaluating a wide variety of alternatives, and are consistent with historical costs, but sensitive to new technology options.

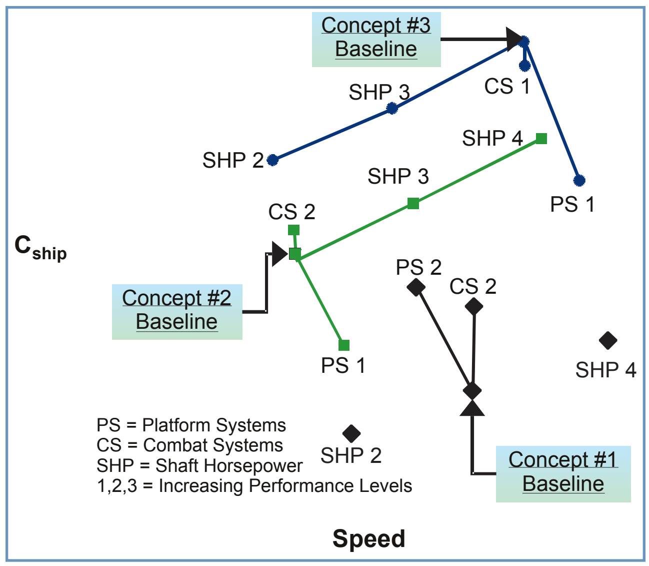


Figure 3. Typical spider plot from a Performance-Based Cost Model.

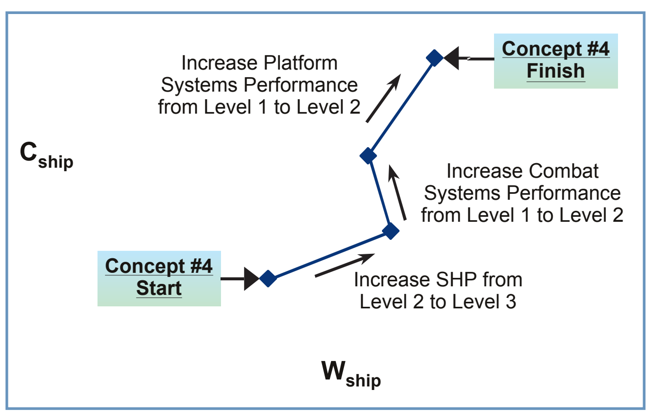
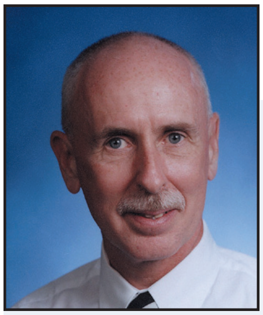


Figure 4. Typical walkabout plot from a Performance-Based Cost Model Summary.

Described as a system of equations, the PBCM has proved to be a powerful tool to assess how changes in a Navy platform's performance can influence cost. In a timely, straightforward manner, the PBCM can highlight those candidate design concepts that will help the future Navy meet mission requirements and future budget constraints.



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Leading-Edge Architecture for Prototyping Systems: An Integrated Product Design and Engineering Analysis Environment

Myles M. Hurwitz

The Leading Edge Architecture for Prototyping Systems (LEAPS) provides the ability to develop common, generic virtual representations of products such as ships, submarines, aircraft, tanks, missiles, and automobiles, and to link those representations to applications such as modeling and simulation software. With object-oriented methodologies providing complete geometric, physical, and functional relationships, subject matter experts are now able to gain superior insight into product design and behavior. Extraction of domain-specific information from a data repository organized under LEAPS is immediate through the aggregation of information into domain-specific views of data. In addition, application-specific translators, or wrappers, allow fast transformation of the extracted data to meet analysis software requirements. The result of these developments has been productivity gains of factors of 20 to 30 in the times to perform required, but nonproductive, data exchanges and re-formatting. These gains in product knowledge and productivity allow timely and trusted evaluations of design alternatives, thus significantly opening the trade space that can be explored for technology assessment, elicitation of technology requirements, acquisition program risk reduction, and increased weapons systems cost-effectiveness.

Introduction

For nearly 50 years, NSWCCD has used physics-based computational technologies to predict surface ship and submarine systems characteristics. From the prediction of fuel depletion in early nuclear submarines on a Univac LARC "supercomputer" for ADM Hyman G. Rickover, to today's routine predictions in disciplines such as hydrodynamics, structural mechanics, signatures, and survivability, computational science and modeling has been an important pillar complementing the Division's physical model and testing capabilities. In addition, with the unprecedented increase in computational capabilities over the past decade, not only can more detailed and precise analyses be performed, but also systems engineers can assess the interactions among systems prior to targeting specific physical testing requirements. However, the ability to analyze increasing amounts of more complex and detailed information has come at a price. The time required to access, extract, and transform information from multiple sources so that it is usable in a specific analysis tool has given back many of the gains provided by computational speed. These nonproductive data manipulations inhibit the achievement of the expected benefits of modeling and simulation (M&S), smart product model (SPM), and integrated digital environment (IDE) technologies.

Recognizing these problems, the Division assembled an Innovation Center Team to take a leap forward in M&S activities to integrate the flow of ship design information across the 3700-person organization. The NSWCCD LEAPS Innovation Center Team quickly realized that the focus of a successful effort required an approach that provided users with the following.

- A source of rich, context-based knowledge of products and processes.
- The means to extract that knowledge quickly from a repository and transform it to the data requirements of an individual application tool.
- The means to enrich that knowledge with results from the application.
- The ability to easily expand the scope of the products and the applications from those initially targeted.

That realization resulted in the following capabilities.

- Development of generic representations of products, or product meta-models.
- Development of product information relationships, including geometric, physical, and functional.

- Aggregation of product information into domain-specific views for fast extraction from a data repository.
- Fast transformation of extracted information for application requirements.
- Population of data repository with application results in multiple modes for downstream use.
- Flexibility for new products and processes.

Implementation Methodology

LEAPS has been under development for 5 years and has gained increased acceptance and use in acquisition and modernization programs. The overall implementation strategy has been targeted to achieve the integrated vision shown in Figure 1.

This vision slide, an example of an integrated digital environment that links a data repository to modeling and simulation applications, does not have starting and ending points (except for the establishment of initial requirements). The integration and the individual M&S activities are intended to endure throughout the product's complete life cycle, from concept to disposal, including product modernization. Note that the centralized (but physically distributed) information may include information for more than one product; i.e., for entities with which a product must interoperate. Note also that the processes are not sequential; the IDE must be able to accommodate many concurrent activities.

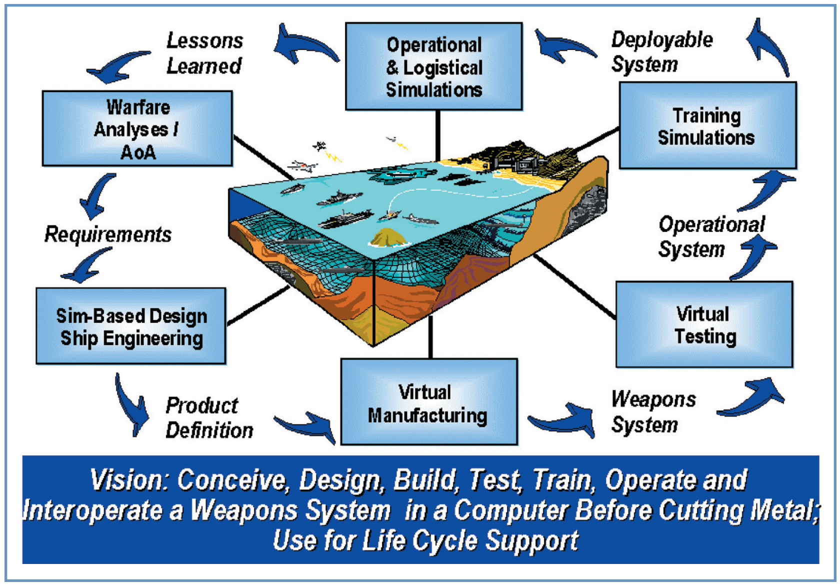

Figure 1. Weapon system virtual life cycle.

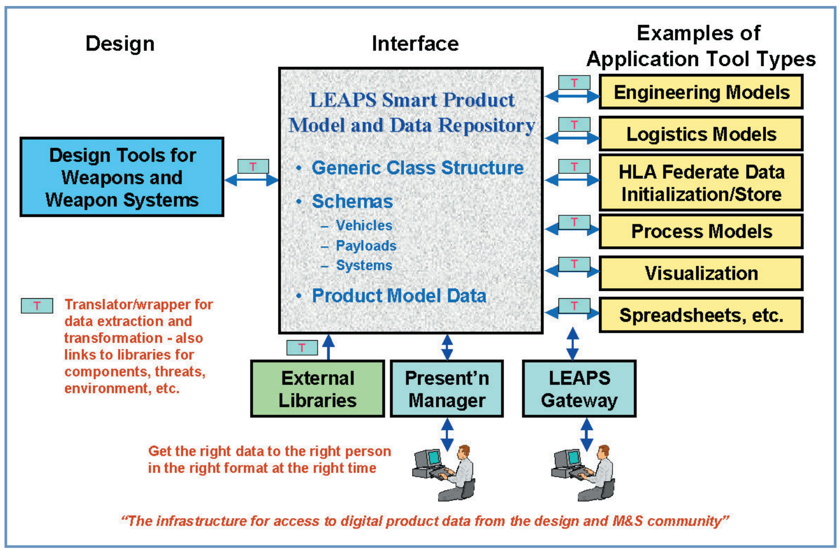

Figure 2. LEAPS-based SPM and IDE architecture.

The integrated software and data architecture being implemented to achieve this vision is shown in Figure 2. The center box of Figure 2 contains the product information, which is extracted and transformed by application-specific translators (the "T" boxes), for input to application software. The translators also populate the repository with application results. The product information is organized using "schemas," which provide generic representations of products and their attributes. The "Generic Class Structure" indicates that LEAPS can be used to develop schemas, or product meta-models, for any product. Finally, the term "smart product model" refers to the ability to provide enhanced product knowledge through robust information relationships.

Application Example

A Government/Industry Team led by NSWCCD has been developing and applying LEAPS in acquisition and modernization ship programs and is making plans to expand LEAPS applicability in a number of areas. One goal of most Acquisition Program Offices is to find the most cost-effective solution with minimal risk. Figure 3 shows a prototypical example of a portion of a ship design that must be evaluated in many functional disciplines (e.g., hull/structures; piping systems; cabling; heating ventilation, and air conditioning, etc).

Subject matter experts in each functional domain must locate and extract from a repository only that information

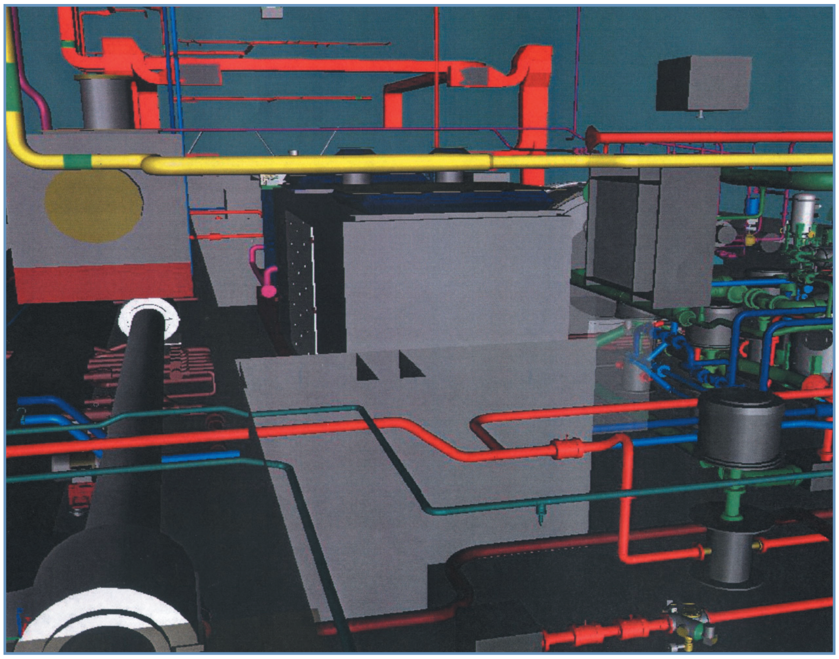

Figure 3. LEAPS Ship example.

they require for each of their specific domains. Then, they must transform that information to the requirements of their different software applications. The LEAPS Team has found, in still-early metrics determinations, productivity gain factors of 20-30 in these information transfers and transformations, saving many days and weeks of labor time. Savings such as these allow for many more design evaluations in a fixed time and cost than might otherwise be possible. That expansion of the trade space (evaluation of options) reduces program risk and increases the chances of finding more cost-effective solutions than might otherwise be the case.

The up-front investment that enables these savings is modest. Only 3 days were required to populate the LEAPS database with full ship data, a portion of which is shown in Figure 3, despite the fact that the design data came from three different commercial CAD systems. (A note of caution: There are many methods used to develop CAD models and associated information, many of which may cause the LEAPS database population effort to increase substantially.) The time investment is being reduced as the LEAPS Team develops more advanced population tools. Once the investment is made, the savings become available to every functional discipline, assuming that a LEAPS translator has been developed for each required software application.

Future Development

Future LEAPS development will be focused in a number of areas. (1) expansion of the current surface ship product meta-model as new functional domains are addressed; (2) additional product meta-models; (3) translators for additional applications; and (4) porting of LEAPS objects to a commercial Product Data Management system to take advantage of services such as configuration management, automated change notification, and work flow management.

Figure 4 shows the LEAPS Team's vision for a broader architecture associated with the suite of products addressed by the Navy acquisition community.

In this vision, the LEAPS Class Structure and Application Programmers Interface (API) (i.e., the architecture framework) is used to develop LEAPS product meta-models that are associated with Deputy Assistant Secretary of the Navy and Program Executive Office communities. An integrated modeling and simulation architecture is developed for each meta-model to assess alternative designs for that product area. For operational effectiveness and integration, it is assumed that either individual simulations or high level architecture (HLA) federations will be used. In either case, data from individual product model data repositories will be used, and for HLA federations, the LEAPS API will be used to develop the HLA federation object model (FOM). The LEAPS API can dynamically create new objects to enable easier FOM development than might be possible otherwise.

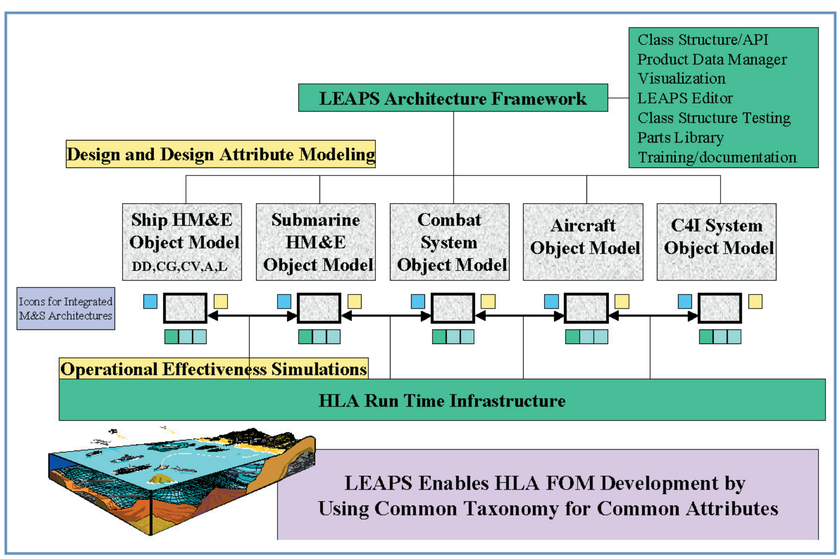

Figure 4. Notional LEAPS vision for Navy acquisition.

Summary

NSWCCD has been developing and applying LEAPS for 5 years, and we know of no other product that is supplying the capability and the breadth and depth of implementation that the LEAPS effort provides. Excellent productivity gains have been shown that provide trade space expansion, resulting in risk reduction and improved product cost-effectiveness. However, LEAPS is still in its infancy, with a great deal of work still to be done, and with some of the most difficult work being in complex translator development. The benefits of the underlying LEAPS methodology, represented by the LEAPS Class Structure and API, are proven, and a patent application for a portion of the Class Structure has been filed. However, the overall implementation remains to be completed. With more Navy programs understanding the benefits that the LEAPS capability can provide, and with new DoD policy requiring programs to implement integrated digital environments (DoD 5000.2-R of June 2001), the LEAPS Team is confident that the job will get done.

Acknowledgments

The author would like to express appreciation to the LHA 5 Modernization Program, the LHA Life Cycle Management office, and to other ship acquisition and modernization programs that are using LEAPS as their IDE architecture.

References

1. Ames, R., and R. Van Eseltine, “A Framework for Modeling Complex Structures,” 5th International Conference on Numerical Grid Generation in CFD and Related Fields, Mississippi State University (1-5 Apr 1996).

2. Hurwitz, M., “LEAPS: An Integrating Architecture for Ship Assessment Software,” The Second Modeling, Simulation, and Virtual Prototyping Conference, American Society of Naval Engineers, Arlington, Virginia 24-25 Nov 1997).

3. Ames, R., and R. Van Eseltine, “A Framework for Modeling Complex Structures,” 1st Symposium on Marine Applications of Computational Fluid Dynamics, McLean, Virginia (19-21 May 1998).

4. Hurwitz, M., “ LEAPS: An Integrated Ship Design and Engineering Analysis Environment,” Undersea Weapon Simulation Based Design Workshop, Newport, Rhode Island (7-9 June 2000).

5. Hurwitz, M., “Information Integration via Navy LEAPS,” Enabling the 21st Century Acquisition Enterprise: 3rd Simulation Based Acquisition Conference, National Defense Industry Association, Springfield, Virginia (15-17 May 2001).

6. Ames, R., and R. Van Eseltine, “Architecture for Multidiscipline Integration of Analyses in a Common Product Model Environment for LHA(R) Topside,” Electromagnetic Code Consortium 2001 Annual Meeting, Kauai, Hawaii (28 May - 1 June 2001).

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Case Study in Open Systems Architecture: The Joint Advanced Health and Usage Monitoring System

David J. Haas and Phong H. Nguyen

The Joint Advanced Health and Usage Monitoring System (JAHUMS) Advanced Concept Technology Demonstration (ACTD) Program is a joint Navy/Army Program that supports a dynamic change in the maintenance philosophy of military helicopters. HUMS technology will help the Navy transition from a time-phased maintenance approach where all aircraft are treated alike to a condition-based maintenance approach. The objective of the JAHUMS ACTD is to demonstrate advanced HUMS technology and to validate an open systems approach for technology insertion. A virtual sensor system developed at the Carderock Division using artificial neural networks is presented as one example of technology insertion. Based on the lessons learned to date, a generic approach for open systems implementation is also proposed.

Introduction

Within the U.S. military, condition-based maintenance practices and policies are being adopted that require embedded diagnostics in weapons systems and weapon system platforms. These new policies, coupled with many industrial applications of advanced diagnostic technologies are a fundamental driving force in the rapid development of new sensor concepts and diagnostic and prognostic techniques. Diagnostics technology is being developed and applied to all types of commercial and military systems. These include land, air, and sea (surface and subsurface) vehicles, as well as commercial and industrial applications.

In parallel with the increased emphasis on embedded diagnostics, the benefits of designing systems with modular open architectures are becoming widely recognized. Open systems architectures are being pursued at the platform level (e.g., DD (X)),[1] as well as the system level (e.g., health and usage monitoring systems).[2] An open systems approach offers many benefits. In the short term, it reduces acquisition cycle time by taking advantage of commercial off-the-shelf technology. In the long term, an open systems approach lowers total ownership costs by providing multiple sources for system components, upgrades, and technology insertion. The long-term benefits of open systems are significant considering that for many military platforms the majority of the life-cycle costs occur after initial acquisition.

An open architecture approach implies a modular architecture involving individual functional components that are integrated using standardized "open" interfaces. An open interface is an interface that is completely defined, available to the public, and consensus-based. Department of Defense (DOD) acquisition policy mandates the use of open systems processes in the acquisition of military systems. To support this policy, the Office of the Secretary of Defense established the Open Systems Joint Task Force to further develop and institutionalize the open systems process.

An Open Systems Approach involves a modular architecture with individual components integrated using publicly available, standardized interfaces

Artificial Neural Network Technology

A key focus of the JAHUMS ACTD is the application of artificial neural network (ANN) technology to enhance the functionality of health and usage monitoring systems (HUMS). An artificial neural network is a method of computing that is inspired by the structure and function of the brain and nervous system. They are highly parallel in structure and are formed from many simple processing units (neurons) connected by weighted connections analogous to neuronal synapses. The output of a typical processing element is computed as the weighted sum of the inputs modified by a linear or nonlinear transfer function, typically a sigmoidal squashing function or a Gaussian distribution (Figure 1). The collective arrangement of processing elements, the specific learning algorithm used, and the partitioning of the hidden layers defines the topology of the ANN system.

A feed-forward neural network is a popular ANN topology and consists of an input layer, an output layer, and one or more hidden layers (Figure 2). The input layer accepts input data to the neural network where it is processed by the hidden layer(s) and passed to the output layer. Through a supervised or unsupervised learning process, the neural network is trained to learn the correct input/output mapping that best matches the training exemplars taken from a larger "universe" of data. Once a neural network has been trained successfully and its internal connection weights fixed, it can process and generalize correct input/output mappings on data never seen by the neural network during the training process. This ability to generalize correct solutions from unique and often noisy data is one of the distinct strengths of artificial neural networks.

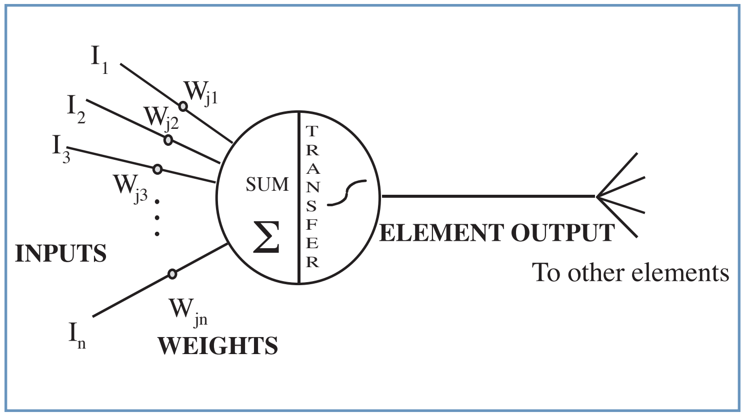

Figure 1. Typical artificial neural network processing element

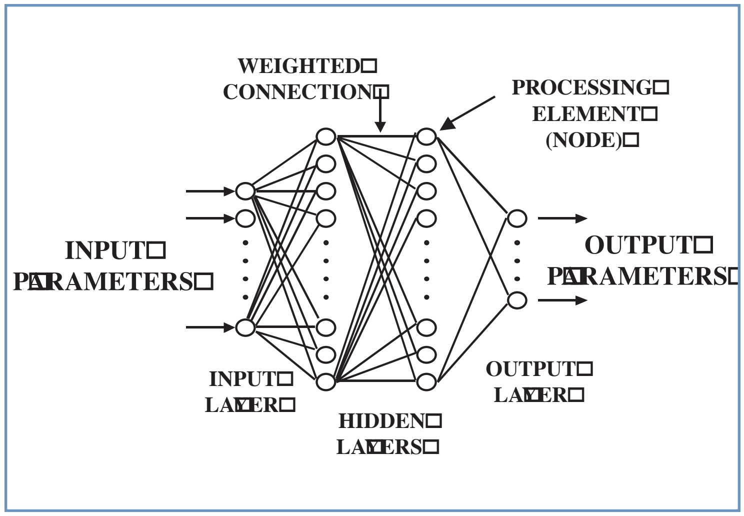

Figure 2. Typical feed-forward neural network

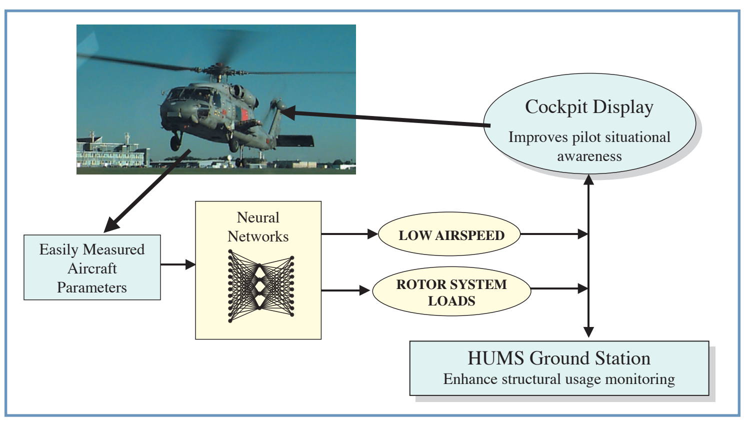

Figure 3. Virtual sensor system

JAHUMS Virtual Sensor System

The Virtual Sensor System (VSS) is a neural network-based sensor system developed at NSWC-CD that will be demonstrated on the Navy SH-60 in the JAHUMS ACTD. The VSS uses existing parameters recorded by the HUMS to synthesize loads in critical life-limited rotor system components and to predict aircraft airspeed and wind azimuth during low airspeed flight (less than 40 knots), where the physical airspeed sensor becomes unreliable (Figure 3). A primary advantage of the VSS is its ability to predict dynamic component loads and low airspeed information without the need for physical strain gauges or complex and costly mechanical low airspeed systems.

Outputs from the VSS enhance the HUMS structural monitoring algorithms and also make low airspeed and component loads data available to the pilot in real time. Low airspeed and wind azimuth information is important for pilots to maintain control margins and situational awareness in low airspeed flight, such as frequently occurs when operating around ships. Component load information can also provide maneuver severity cues to aid the pilot in carefree maneuvering flight while preventing excessive damage to the rotor system.

In addition to loads and airspeed information, the feasibility of automatically estimating aircraft gross weight is being evaluated as part of the Virtual Sensor System. An accurate assessment of gross weight is critical for structural usage monitoring of life-limited components and is important to determine aircraft performance characteristics such as the ability to hover out of ground effect (i.e., away from the surface of the ground). In some missions such as vertical replenishment of naval ships and transport of equipment and troops from ship to shore, the gross weight can change significantly within a flight. Accurate accounting of gross weight during these missions can be quite burdensome to the crew, especially in hostile environments.

For the virtual strain gauges, a modular neural network architecture is used. The neural network inputs consist of pilot control positions, aircraft attitudes and rates, normal load factor, engine torque and rate of climb/descent. A key aspect in developing a neural network is the proper selection of a training data set. The training data set must include data that are representative of the problem domain. To accomplish this, a self-organizing feature map (SOFM) was used as a tool for training data selection. The SOFM transforms the high-dimensional input space into a two-dimensional grid. A uniform distribution of points over the two-dimensional grid is used to train the neural network. This approach yields a training data set that closely resembles the data population and includes sparse data regions.

Data from a flight loads survey of an SH-60B were used to develop the neural network algorithms. These data consisted of approximately nine flight hours sampled at 8 Hz corresponding to over 250,000 data points that represent all of the various maneuvers in the SH-60B flight envelope. After training the neural network, it was validated on a second separate flight test aircraft also instrumented with strain gauges.[3] Figure 4 shows sample results for the pushrod and damper loads during a severe pullout maneuver and highlights the extent to which the neural network predictions follow the trends of the strain gauge measurements during flight test validation.

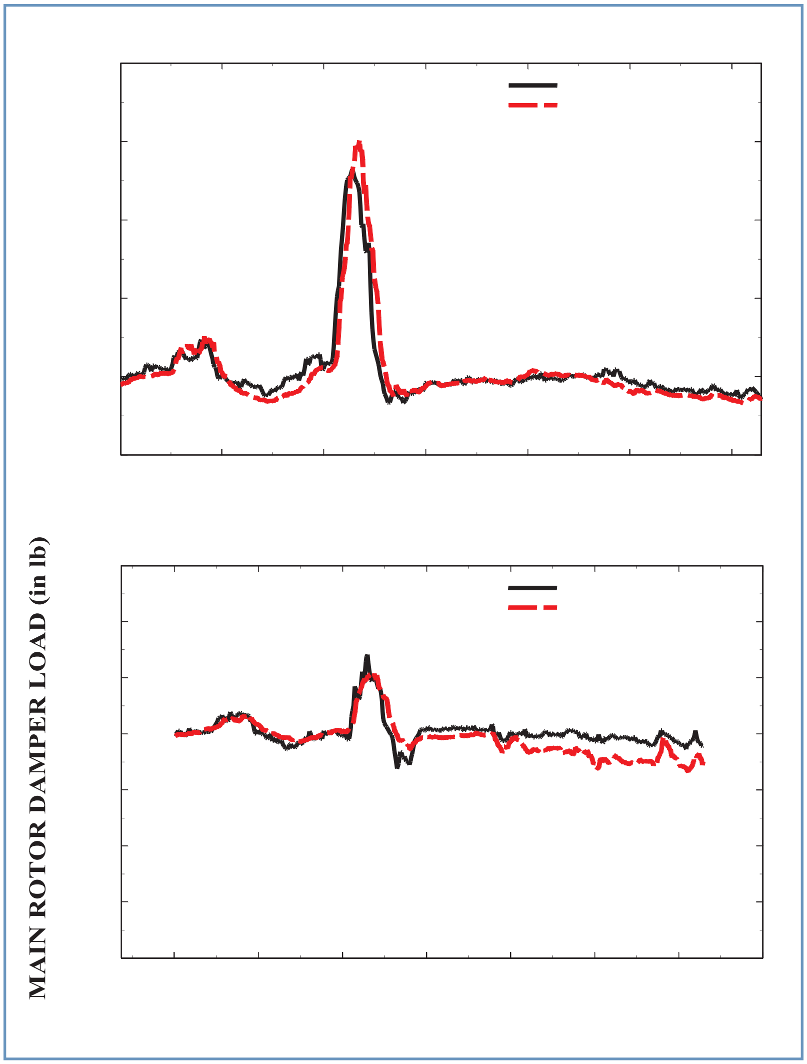

Figure 4. Virtual strain gauge results for a severe pullout maneuver

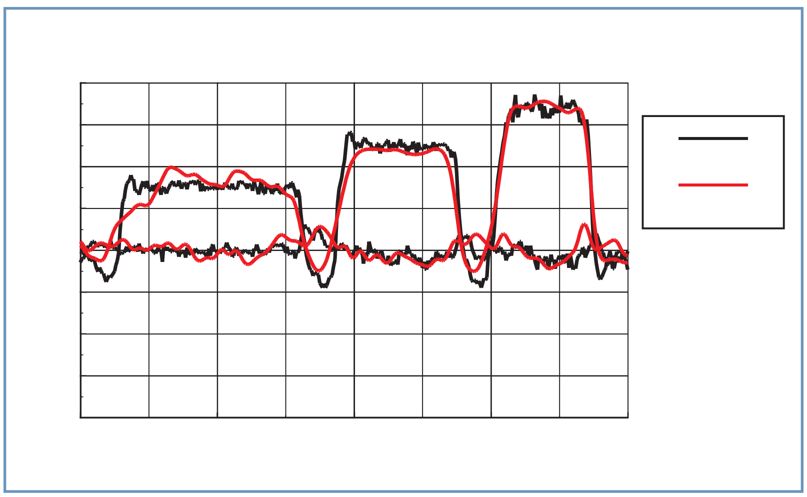

Figure 5. Virtual low airspeed sensor results

The virtual low airspeed sensor was developed and validated using approximately 4 1/2 hrs of flight data that were carefully collected when ambient winds were less than 5 knots. Data were collected for both the in-ground effect and out-of-ground effect flight conditions. A Radial Basis Function network paradigm with 400 nodes was determined to be optimal for the virtual low airspeed sensor application. An Infinite Impulse Response single-pole filter with a cut-off frequency of 0.18 Hz was applied uniformly to all of the input parameters because most of the input parameters have frequency content significantly above that found in the airspeed information.

Sample results for the low airspeed virtual sensor are shown in Figure 5. The network predictions for the lateral and longitudinal components of airspeed and the reference airspeed measurements are shown for comparison. The time trace in Figure 5 corresponds to a helicopter in right sideward flight. The longitudinal velocity is zero during the entire time trace, whereas the lateral velocity (i.e., right sideward flight) increases from zero (hover) to 15 knots and then back to zero as the pilot returns to a hover. The pilot repeats the right sideward flight maneuver for speeds of 25 and 35 knots. A comparison of predicted airspeed with the reference airspeed illustrates that good accuracy can be obtained with a virtual sensor. Additional details on the development of the Virtual Sensor System are available in references 3-5.

JAHUMS Demonstration Approach

The JAHUMS ACTD uses an open architecture HUMS developed by Goodrich Aerospace as the baseline system for technology insertion and demonstration. The baseline system is being acquired by the U.S. Navy under the Integrated Mechanical Diagnostics (IMD) Program for both the H-53 and H-60 platforms.[6] An open architecture for HUMS is particularly important because it provides the means to take advantage of rapid changes in diagnostic and sensor technology and avoids premature obsolescence as new technologies become available. The U.S. military is expected to benefit from the application of an open systems approach to HUMS because it operates a fleet of several thousand helicopters of different configurations, sizes, and age. Each class of helicopter is used differently and has different requirements for HUMS technology.

The HUMS consists of an onboard avionics box with processor cards and external interfaces to aircraft sensors and data busses, additional HUMS sensors (e.g., accelerometers for vibration monitoring), a ground station computer where the HUMS diagnostic database resides, and a data transfer unit to download recorded flight data from the aircraft to the ground station (Figure 6). The system functionality includes onboard rotor track and balance monitoring, regime recognition for structural usage monitoring of critical life-limited components, drive train vibration monitoring, and engine performance trending.

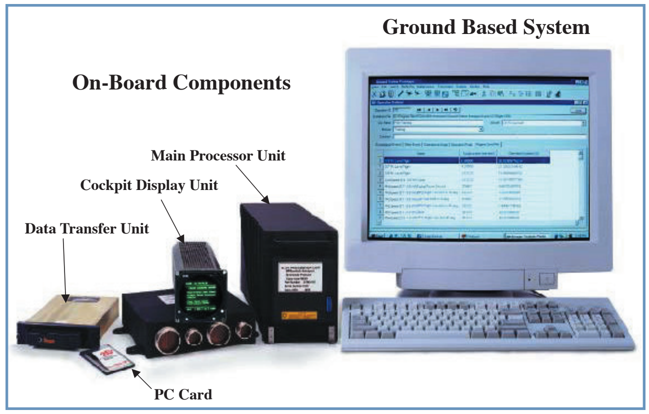

Figure 6. Components of the health and usage monitoring system

The JAHUMS technology modules are developed by independent third parties to extend and enhance the basic HUMS functionality. The technology modules include the following.

The *Integrated Support System* technology module (developed by Sikorsky Aircraft, GE and Qualtech Systems, Inc.) uses a knowledge-based diagnostic model of the T700 engine to optimize diagnostic troubleshooting and repair by using existing HUMS sensor data and an expert system to monitor system health in real time. The system consists of software components embedded in the onboard HUMS processor, and software in the ground station and an interface to the interactive electronic technical manual and the maintainer's portable electronic display.

The *Neural Network Drive Train Diagnostics* module (developed by AMTEC, Inc.) relies on self-organizing neural networks, advanced feature extraction, and severity assessment techniques to provide time-to-failure metrics to the maintainer for drive system components. The system consists of a combination of hardware and software elements designed to take advantage of the Goodrich open interfaces. The combination of self-organizing feature maps and adaptive resonance theory neural networks allows the system to discriminate between faulty and normal components, independent of both aircraft tail number and flight condition.

The *Smart Monitor System* (developed by System Excelerator, Inc.) provides the means to remotely transmit HUMS data directly from the aircraft to the ground station. This capability eliminates the logistics challenge of getting data from the HUMS on the aircraft to a remote ground station for military helicopters that are detached from their home base. The Smart Monitor System also provides the means to transfer maintenance data prior to landing so that maintenance assets and replacement parts can be pre-positioned to facilitate rapid aircraft turnaround. The Smart Monitor System also can support a number of wireless networked remote sensor nodes.

The *Crash Survivable Memory Unit* (provided by Smith Industries) is an application of a commercial flight data and cockpit voice recorder. The crash survivable flight data recorder stores data transmitted to it in a bank of crash-protected memory that, in the event of an accident, can be recovered to assist in accident investigations.

The final technology module is the Virtual Sensor System described previously. The JAHUMS technology modules will be demonstrated in an operational environment on several H-60 "technology demonstrator" aircraft. Additional information on the JAHUMS technology modules can be found in reference 7.

Open Systems Implementation

In JAHUMS, the technology module provider is responsible for the development and performance of their specific technology module. The goal of the open systems process is to develop and integrate each technology module without the need to exchange proprietary data. The technology modules use each of the open system interfaces (hardware and software). The primary means of data exchange is through an Open Systems Specification and a Technology Integration Questionnaire filled out by technology module providers describing their specific interface and resource requirements. The Charles Stark Draper Laboratory is being utilized to assess and facilitate the open systems implementation process. Draper Laboratory has executed nondisclosure agreements with both the technology module providers and the HUMS system integrator to assist both parties without posing a competitive risk. Each technology provider works with technical support from Draper Laboratory and independently from each other.

The technical and business aspects of HUMS involve many of the same complexities and issues found in other acquisition programs. Since the JAHUMS ACTD is inserting technologies in parallel with initial fielding of the HUMS, lessons learned occur at an accelerated pace. For this reason, the Open Systems Joint Task Force is using the HUMS case study as a pilot program for open systems implementation. As such, the lessons learned and challenges for DOD and industry are being captured for the acquisition community at large. A goal of the JAHUMS ACTD is to help formulate a generic process for open systems implementation.

Results and Lessons Learned

Several lessons have become apparent from the HUMS case study. First, in the design and development stage of a new system, the open systems architecture should be treated as part of the formal systems engineering process. Open systems goals, objectives, progress, and acceptance criteria should be evaluated at system design reviews. Second, it is important to realize that the implementation of open systems involves technical and business aspects, and that business issues, not technical issues, may well be the limiting factor in an open systems approach.

The application of open systems to the acquisition of military systems is still developing. Although each program will have its own objectives and goals for open systems, a common open systems implementation process is needed. The concept of "openness" is similar to the concept of "quality" in that both require a definition of objectives and goals to be meaningful. Thus, a structured process similar to that embodied in ISO 9000 for quality may also be beneficial for the implementation of open systems. Based on the experiences and lessons learned to date, a generic open systems implementation process has been proposed.

- **Step 1 -** Define what you want to accomplish and determine if open systems applies.
- **Step 2 -** Perform trade studies to define open systems objectives and the degree of openness desired.
- **Step 3A -** Develop an open systems *technical architecture* that describes the technical system interfaces.
- **Step 3B -** Develop an open systems *business architecture* that describes the business approach that will promote competition.
- **Step 4 -** Conduct an independent assessment of the documentation from Steps 3A and 3B.
- **Step 5 -** Demonstrate and validate the open system interfaces (hardware and software).
- **Step 6 -** Certification of open systems.
- **Step 7 -** Provide continuous improvement and life-cycle support of open systems architecture and periodic recertification as the system changes.

Summary and Conclusions

The open systems implementation process has been iterative and will continue to evolve as JAHUMS technologies proceed from design to testing to fielding, and ultimately to production. Artificial neural networks are one example of emerging technologies that have the potential to significantly increase the capabilities and benefits of health and usage monitoring systems. The application of HUMS technologies to military helicopters will evolve over a period of years of operation as systems are fielded in greater numbers. An open architecture approach to HUMS provides the means to make revolutionary changes in how DOD maintains and operates its helicopter fleet and the cost of doing so.

Acknowledgments

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References

1. Vasilakos, J., et al, "Total Ship Open Systems Architecture," presented at ASNE Day 2000, published in the *Naval Engineers Journal*, Vol. 112, No. 4 (July 2000).

2. Muldoon, R., et al, "Integrated Mechanical Diagnostic (IMD) Health and Usage Monitoring System (HUMS); An Open System Implementation Case Study," Proceedings of the 18th DASC Conference, St. Louis, MO (Oct 1999).

3. McCool, K.M., et al, "Development and Flight Test Evaluation of a Rotor System Load Monitoring Technology," *Journal of the American Helicopter Society*, pp. 19-27 (Jan 2000).

4. McCool, K.M., et al, "Neural Network Based Low Airspeed Sensor," Proceedings of the American Helicopter Society Annual Forum, Virginia Beach, VA (2-4 May 2000).

5. Morales, M., and D.J. Haas, "Feasibility of Aircraft Gross Weight Estimation Using Artificial Neural Networks," Proceedings of the American Helicopter Society Annual Forum, Washington DC (9-11 May 2001).

6. Hayden, R.E., and R. Muldoon, "US Navy/USMC/BF Goodrich IMD-COSSI Program: Status," Proceedings of the American Helicopter Society 55th Annual Forum, Montreal, Quebec, Canada (25-27 May 1999).

7. Haas, D.J., et al, "Joint Advanced Health and Usage Monitoring System (JAHUMS) Advanced Concept Technology Demonstration (ACTD)," Proceedings of the American Helicopter Society 56th Annual Forum, Virginia Beach, VA (2-4 May 2000).

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Logistics Over-The-Shore Technology

Arthur B. Rausch and Francis A. Leban

Logistics Over-the-Shore (LOTS) operations involve the unloading of ships without the benefit of fixed-port facilities. Container ships and roll-on/roll-off ships are the most common dry cargo merchant vessels to transport military cargo. A major problem is that the current LOTS system is inoperative above Sea-State 2 due to the dangerous relative motions of the ships, transfer platforms, and lighters that carry cargo to the shore. The war-fighting Commanders in Chief (CINCs) have identified a critical need to develop a Sea-State 3 LOTS capability by 2005, because existing environmental limitations halt military operations, cutting off the flow of critical supplies. This paper describes some of the R&D projects and new technologies being developed by NSWCCD to provide this capability.

Introduction

Logistics Over-the-Shore (LOTS) operations are defined as ".... the loading and unloading of ships without the benefit of fixed-port facilities in friendly or unfriendly territory, and in time of war during phases of theater development. LOTS operations are conducted over unimproved shorelines, through fixed ports not accessible to deep-draft shipping, and through fixed ports that are not adequate without the use of LOTS capabilities." When LOTS operations are performed jointly with the Army, they are called Joint Logistics Over-The-Shore (JLOTS) operations.

Thousands of vehicles and containers and the millions of gallons of fuel required for a major military operation are brought to the operating area by ships. The ships involved include large containerships, roll-on/roll-off (RO/RO) ships, heavy-lift barge carriers, semi-submersible ships, and deep-draft tankers. Most are commercial cargo carriers designed to offload in large deep-draft ports. In certain areas, however, such ports are not available or are too small to take more than one or two ships at a time. The Navy and Army must be able to offload cargo from ships anchored offshore at rates fast enough to quickly build up and sustain fighting forces ashore. NSWCCD has extensive LOTS and JLOTS expertise and is a leader in RDT&E of systems to perform this task efficiently. In the 1970s, the services, with Division technical support, began to develop and test a number of unloading and transfer systems capable of moving containerized cargo, military vehicles, and fuel from commercial ships anchored offshore to the beach. Collectively, this equipment can perform functions normally performed at fixed-port facilities (Figure 1).

Navy auxiliary crane ships provide lift-on/lift-off capability to transfer cargo containers loaded with military supplies and other equipment to lighters (barge ferries and landing craft) capable of carrying the equipment to unimproved shorelines or into small ports. The calm-water roll-on/roll-off discharge facility (RRDF) was developed by the Division in the 1980's as an interface between a RO/RO ship at anchor and lighterage used to carry the vehicles to shore. RRDFs allow tanks, trucks, and other military vehicles to drive off ships anchored miles from shore for transit to unimproved shorelines (Figure 2). A variety of Navy and Army lighterage ferry supplies and equipment to where they can be discharged at the beach by cranes on the Navy's elevated causeway (portable pier), to the Army's floating causeway, or directly to the beach if the beach gradient allows. Navy Offshore Petroleum Discharge Systems also provide bulk fuel at unimproved shore locations.

Figure 1. A collage of a complete JLOTS operation. (Not to scale)

Figure 2. RO/RO ship discharging to lighters via discharge facility.

Operational Issues

Current LOTS and JLOTS operations are limited to operating in relatively calm seas with significant wave heights (average of the one-third highest waves) no higher than 3 ft, and where long-period ground swells do not affect the ships. Based on their mission analysis, the unified commanders have stated a requirement to operate in Sea-State 3 (SS3). Therefore, all LOTS systems must be able to operate and be interoperable in 5-ft significant wave heights and where long period ground swells affect ship motions. The Division recently completed a JLOTS Environmental Requirements Study that provided a compilation of environmental characteristics needed to develop valid system requirements for LOTS and JLOTS operations in the littoral area. The study addressed 52 specific potential amphibious logistics sites from nine broad regions. The data were gathered from many sources and include the following for each site: wind, waves, current, tides, distance to 50-ft water depth, beach gradient (calculated), bottom condition and hazards, and distance to road network and general geographic characteristics of the area. Wave data revealed that Sea-State 3 occurs more than 50% of the time in some littoral operating areas. This study has been distributed to all CINCs and JLOTS connected units.

Approach

The Services, under the auspice of a Joint Staff chartered JLOTS board, have initiated several R&D programs to satisfy the unified commanders SS3 operating requirements. These programs are being coordinated through a JLOTS Joint Integrated Process Team (JIPT) in a system-of-systems approach to develop a SS3 operational capability. The Division is an active member of the JIPT. As part of this joint effort, the Navy has initiated several R&D programs which are on the critical path to provide a SS3 capability by 2005. These are encompassed in the following broad areas.

Surf Entry and Barge Offload System (SEABOSS)

The SEABOSS, formerly the Joint Modular Lighterage System (JMLS), Advanced Concept Technology Demonstration (ACTD) is an acquisition program to design, demonstrate, and procure a service-interoperable causeway lighterage system that can be safely assembled and operated in SS3. This system includes warping tugs, roll-on/roll-off discharge facilities (shown in Figure 2) with an integrated platform to load Navy Landing Craft Air Cushion (LCAC), causeway ferries, and floating causeway piers to be used in a LOTS/JLOTS operation. The Division supported the NAVFAC ACTD as members of both the structures and test and demonstration integrated product teams; and performed the initial ship interface analysis. The Division's involvement in the acquisition program includes the design of a composite version of the SEABOSS modules and support of the warping tug propulsion and winch systems designs. The new lighter system, along with existing Army Logistic Support Vehicles (LSVs) and Landing Craft, Utility (LCU) 2000s, and Navy LCACs, will be able to operate in SS3 conditions. However, other critical ship and shore interfaces must be improved to achieve a total JLOTS SS3 capability.

Ship Operations/Interfaces

Ship operations/interfaces include all JLOTS ship-to-ship, ship-to-lighter, and ship to RRDF interface systems such as mooring and fendering, personnel transfer, ship ramp/platform motion compensation, ship heading control, and the transport of LCACs on SEABEE (Figure 3) and Lighter Aboard Ship (LASH) barge ships. It is difficult and dangerous to moor a small vessel alongside a ship in Sea State 3 using the existing floating fenders. NSWCCD has contracted with MAR, Inc., to adapt a submarine fendering concept for this application. The new system is called the Deep Draft Composite Fender (DDCF) and will remain stable in Sea State 3 and provide a constant fendering surface despite the small craft's vertical motion. The fender will be fabricated of composite materials to reduce weight and increase corrosion resistance. The difficulties imposed by the requirement to provide interfaces between the various vessels and systems has been the impetus to investigate new technologies previously unknown in the maritime environment. For example, magnetorheological (MR) fluids are materials with a viscosity that can be controlled via an applied magnetic field. Depending upon the strength of the field, MRs behave like a smooth-flowing liquid on a continuum up to a state similar to peanut butter. The ability to adjust the viscosity may be exploited to develop "tunable" ship fenders and controllable motion damping systems. These are new applications for this technology that previously were used in the field of seismic engineering to protect structures through foundation isolation and structural mode dampers. Personnel transfer problems from small craft to or from ships were addressed by a Division study of maritime and offshore oil industry and Navy practices. The study recommends a combination of approaches including the use of commercial off-the-shelf equipment and Coast Guard and Pilots Association procedures to rig personnel ladders.

Figure 3. Landing craft air cushions on a SEABEE ship.

Ship Cargo Movement Systems

Ship cargo movement systems include all ship cargo handling systems such as the ship-mounted cranes on the Auxiliary Crane ships (T-ACS) (Figure 4), the Marine Corps' Maritime Prepositioned Force ships, and the Army's Large Medium-Speed RO/RO ships. Shipboard cranes lift cargo containers or vehicles from within their holds or from ships moored alongside in the case of the T-ACS, and place them in smaller craft or on barge ferries for transport to the beach or to small ports. The cranes on these ships are extremely susceptible to movement of the ship, which causes the load to swing and move vertically. Ship movement is caused by long-period waves (swells) that coincide with the natural roll period of the ship. Most military crane operators do not have the experience to compensate for the pendulation and vertical movement of the loads caused by roll of the ship and are forced to stop discharge operations in the interest of safety.

The Advanced Shipboard Crane Motion Control System, a Navy Advanced Technology Demonstration (ATD), is in progress with Office of Naval Research funding under Division leadership to develop a system to control dangerous load pendulation (Figure 5). Inspired by recent advances in the understanding of nonlinear dynamical systems, the Division formed a team, which included contracts with the Sandia National Laboratory to develop control algorithms (swing-free controller (SFC)) and MacGregor USA, Inc./MacGregor Cranes to upgrade the controls of the cranes on the T-ACS test ship.

The crane motion control system, also referred to as the Pendulation Control System (PCS), is designed to compensate for the three significant sources of cargo pendulation - sub-optimal operator commands, seaway-induced ship motions, and external disturbances.

First, the operator commands are sub-optimal in the sense that only the most skilled operators can move a load without inducing pendulation by their own inputs. To account for this, the PCS employs an adaptive filter to "shape" the operator's commands and minimize the excitation of pendulation from the onset of a movement. Second, once the load is in motion, changes in the attitude of the ship hull to which the crane is attached induces additional pendulation. In fact, it has been observed in practice (and verified in scale-model tests) that the ship motion can approach the resonant conditions for the suspended load in normal operations, resulting in extremely dangerous pendulation that stops operations. To overcome this, the PCS continually adjusts the crane jib position radially and tangentially to isolate the load from the attitude changes of the ship. The third source of load pendulation is external disturbances such as wind, out-of-balance loads, or forces applied through taglines or impacts. This part of the PCS system is implemented as a feedback loop based on displacement measurements of the load or the hoist cables supporting the load. The feedback loop effectively adds damping to the system to suppress pendulation. An additional benefit of the control system responding to the out-

Figure 4. Auxiliary Crane Ship operations.

Figure 5. Pendulating 20-ft container.

put (pendulation) of the crane is that minor inaccuracies in the modeling of the system dynamics or changes in the dynamics that may result from aging of the system components and that would normally result in larger-than-planned residual pendulations will be minimized.

Performance monitoring of the PCS system in real time is being investigated for online diagnostics. The PCS development has contributed to the general field of control systems and human-machine interaction. Past approaches to operator input shaping have been implemented in the joint-space or coordinate system most natural to the crane dynamics. The PCS filter operates on the commanded path in Cartesian space with a significant improvement in the reduction of induced pendulation (Figure 6).

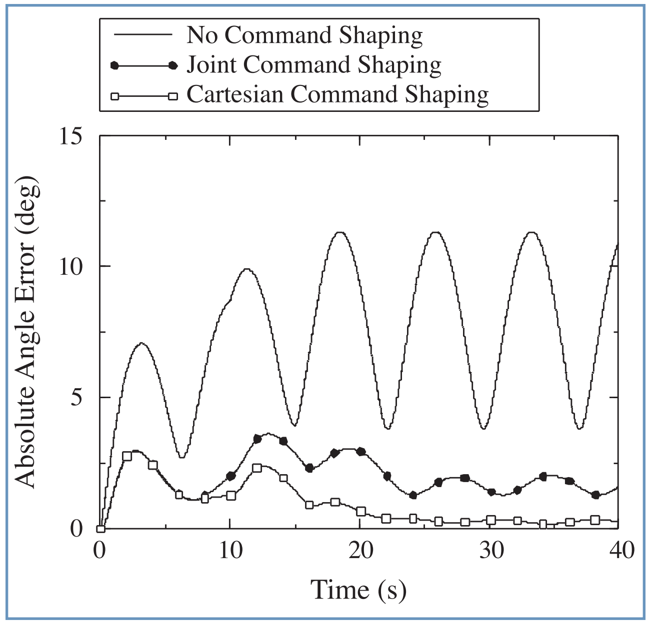

Figure 6. Input shaping performance (unfiltered, joint space, and Cartesian filtering).

From its inception, a goal of the ATD was to implement the control system with minimal impact on the crane. Fortunately, as a result of an independent effort by the crane manufacturer, MacGregor Cranes, a digital control system for the crane machinery has become available. The ATD system builds on this digital system, adding a "black box" which communicates over a serial communications line to the controls of existing shipboard pedestal cranes such as those on the T-ACS. These new controls and sensors will automatically control the movements of the crane to compensate for, or eliminate, pendulation and vertical motion without affecting the operator's ability to move the load and place it on the lighter. Implementing the PCS as a stand-alone box also enables the system to be tested in a hardware-in-the-loop environment using a computer simulation of the crane.

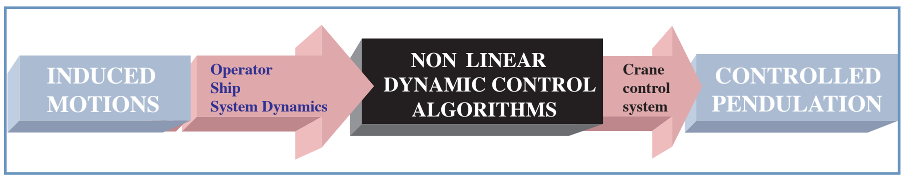

Figure 7. Crane advanced technology demonstration approach.

The overall approach of the Advanced Shipboard Crane Motion Control System ATD is shown in Figure 7. The control algorithms use the input from the operator and ship and load motion sensors to command the crane motions that will accomplish the operators' directions while preventing pendulation. Figure 7 depicts the relationship between the non-linear control algorithms, the sources of pendulation, and the crane's response. The control algorithm accepts all the inputs to the system including the operator commands.

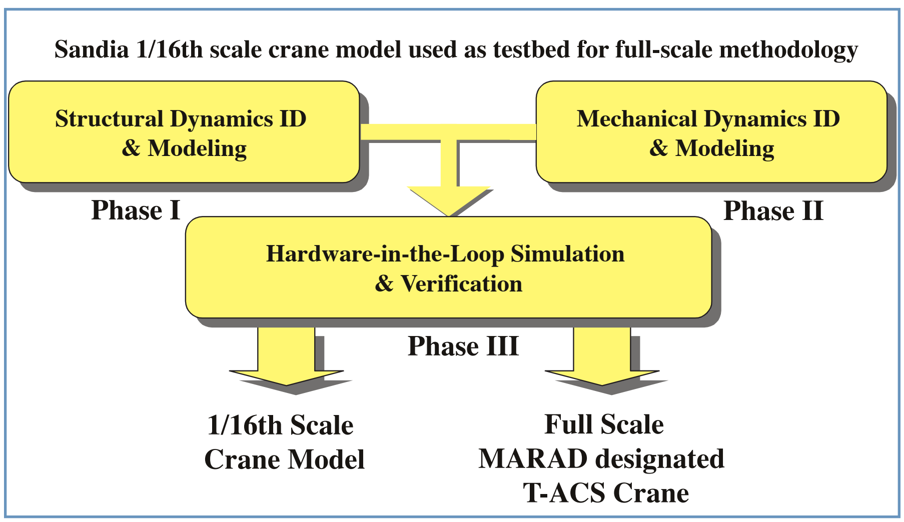

Figure 8. Swing-Free controller algorithm development/implementation strategy.

These algorithms have been developed using the scheme represented in Figure 8. Model tests of the control algorithms were conducted initially using Sandia's 1/16th scale crane on a six degree of freedom motion base. Full-scale machinery and structural performance measurements were then made on USNS FLICKERTAIL STATE (T-ACS 5). The data were incorporated into the algorithms and tested in simulation.

Simultaneously, CSC Advanced Marine, Inc., was contracted to develop an operator-in-the-loop crane simulator to test the new control system and train military operators for the demonstration program. The independently developed simulator software has been run with the characteristics of the Sandia 1/16th model, and the results closely match and validate the Sandia algorithm performance (Figures 9 and 10). The simulator will continue to be used to check out the interface of the new MacGregor crane controls (CC 2000) with the Sandia swing-free controller.

As depicted in Figure 11, the crane simulator will be installed in the Training Facility located at the Naval Cargo Handling and Port Group, Cheatham Annex, Virginia, the home of the Navy's operational and training capability for shipboard cargo handling. All crane operators used in the ATD will become thoroughly familiar with the PCS before operations are attempted on board the ship. Another feature that should increase the operator's confidence in the system is the ability to predict (based on ship motion) the expected maximum pendulation during an operation.

The presentation shown in Figure 12 was developed in the course of conducting a work space analysis to determine the limits of PCS effectiveness in terms of slewing angle and jib outreach. Looking down at a plan view of the portion of the ship that the crane can reach, the arc of colored blocks shows the predicted pendulation by colors. The color scale represents the magnitude of pendulation expected within a space accessible by the crane for a given ship motion. We expect to be able to display this information in real time so

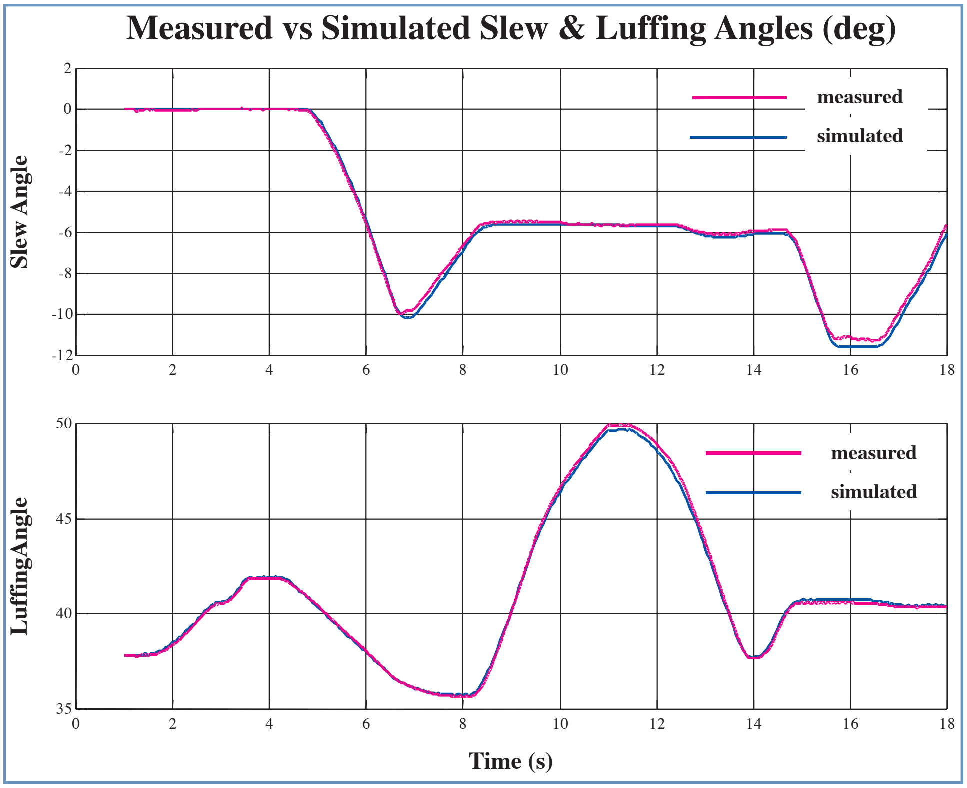

Figure 9. Sample model validation results for a combined slewing and luffing maneuver of crane dynamics.

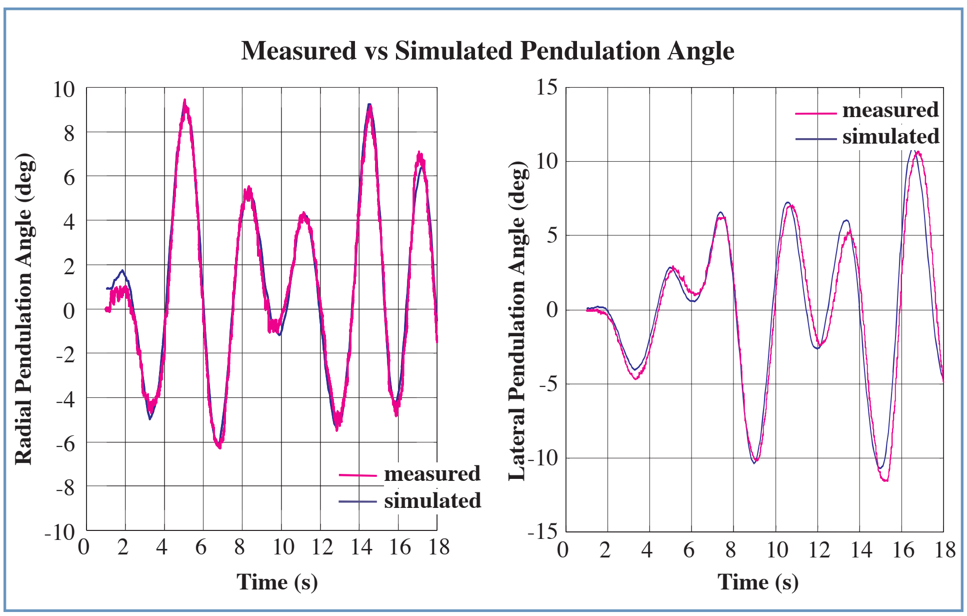

Figure 10. Sample model validation results for a combined slewing and luffing maneuver for pendulation dynamics.

the operator can see a time-varying spatial display of the expected PCS performance before load movement is initiated. The combination of control upgrade, control algorithms, sensors, and operator display comprise the Pendulation Control System that will be installed on one crane of USNS FLICKERTAIL STATE (T-ACS 5) in 2002.

Tests and demonstration of the PCS equipped shipboard crane will be performed by stimulating ship roll either alongside the pier, or at anchor. The Ship Roll Stimulation System (SRSS) is a pumped water system developed by NSWCDD Coastal Systems Station and their contractor, Craft Engineering. It is a modular system of two groups of water tanks, which fit into the existing container cells of the T-ACS (Figure 13). A commercial bow thruster unit located in the duct connecting the two tanks pushes the water from one side of the ship to the other causing 3 degrees, or more, of roll. The SRSS will allow crew training and tests of the PCS to be conducted under controlled and repeatable conditions. The alternative to the SRSS was to take the ship into the ocean and wait for the right combination of waves to cause the ship to roll, a choice that would be unaffordable and risky for personnel and equipment. The final demonstrations of the PCS will take place in late FY02 with a follow-on involvement in a Navy/Army JLOTS exercise planned for FY03.

Other crane enhancements to facilitate crane operations are being developed under Division direction. These include a stereovision system to allow the crane operator to see all areas of load movement, and other shipboard cargo handling innovations, such as the Spreader-Bar Tagline System, to pull containers onto the lighters without having personnel close to the load.

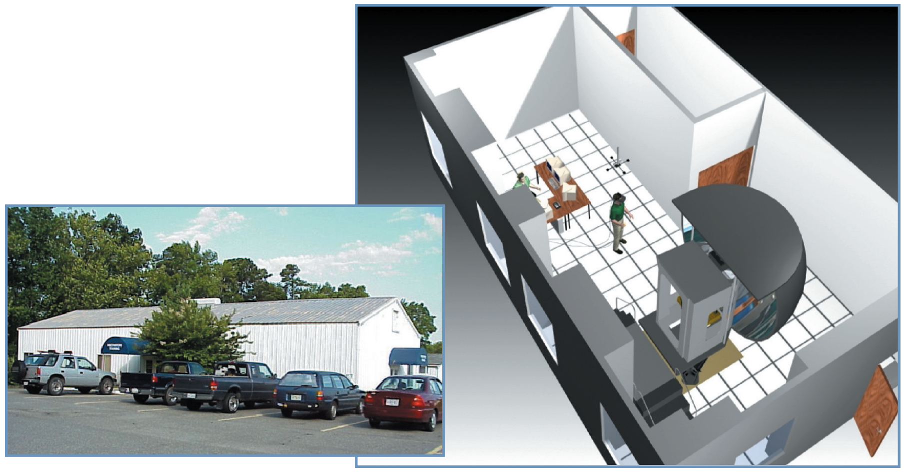

Figure 11. Artist's rendering of the training facility where the crane similator will be installed.

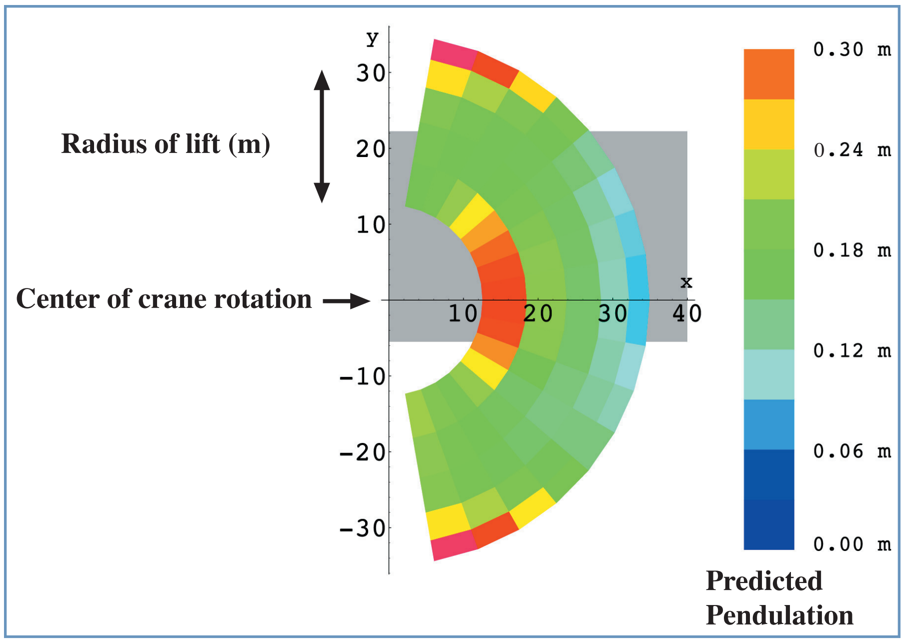

Figure 12. Sample workspace analysis results.

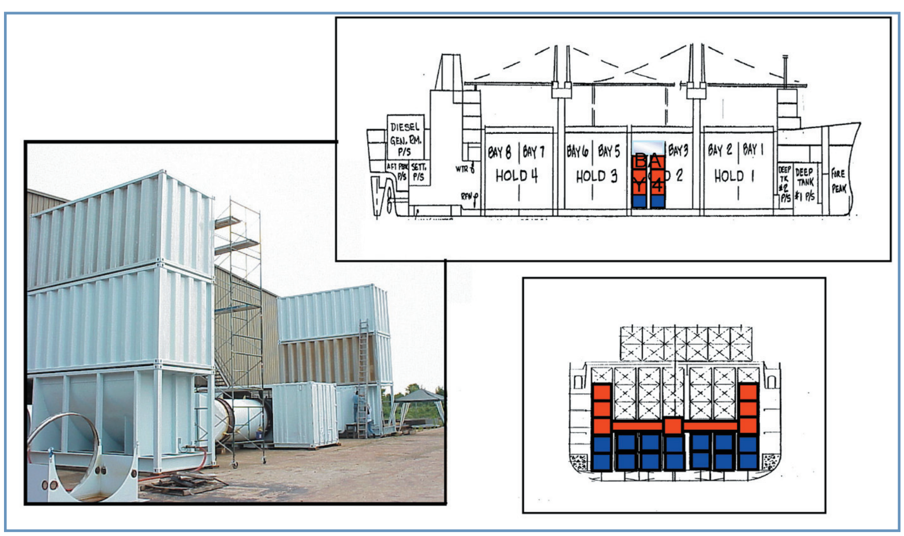

Figure 13. Ship Roll Stimulation System land test and arrangement on ship.

Training, Command and Control, and Doctrine

This critical area addresses command and control and training simulators. NSWCCD is working with the Expeditionary Warfare Training Group Pacific to develop a CD-ROM packaged training course and planning tool to enable CINC staff and military units to learn about JLOTS systems and plan JLOTS operations. JLOTS test results revealed a need for coxswains and crews to have greater experience operating their craft, especially in rough conditions. To address this need, the Division was tasked to develop an Advanced Lighter Simulator for Navy causeway systems. The simulator (Figure 14) was developed to investigate advanced simulator technologies, to be used as a team trainer for coxswains and pilots, and as an R&D tool to aid in the evaluation of new lighterage. The Division's contractor, CSC Advanced Marine, Inc., fabricated and installed the simulator at Amphibious Construction Battalion TWO (Little Creek, VA) for use in operator training and as an R&D platform.

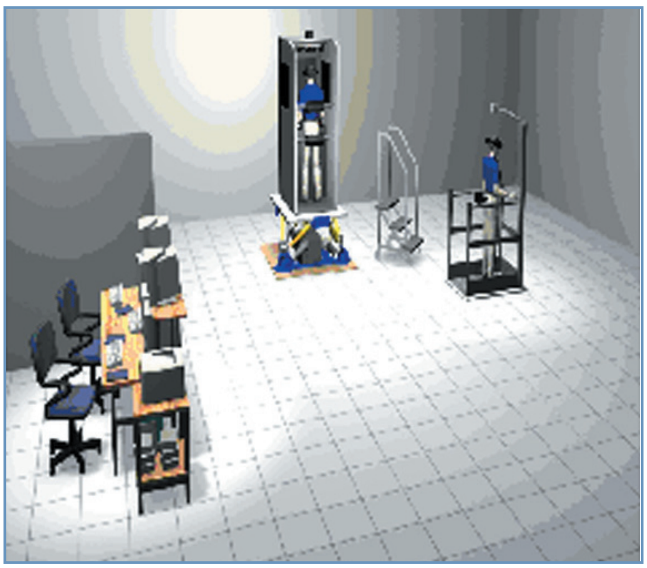

Figure 14. Advanced Lighter Simulator.

Summary

The Division continues to support ONR, OPNAV (N42) and its agents, NAVSEA (PMS 325), and NAVFAC in all facets of strategic sealift R&D planning and execution. The principal thrust is to develop and apply new concepts and technologies for existing and future sealift and merchant ships, as well as lighters and cargo handling and interface systems. The overall objective is to provide a capability to perform Logistics Over-the-Shore operations safely in Sea-State 3.

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