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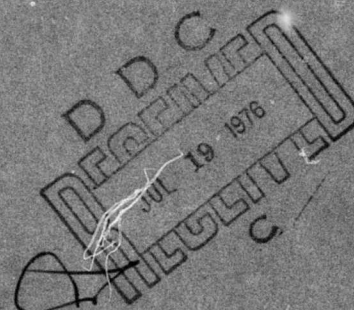DISTRIBUTION UNLIMITED.

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THE SWATH CONCEPT: DESIGNING SUPERIOR OPERABILITY

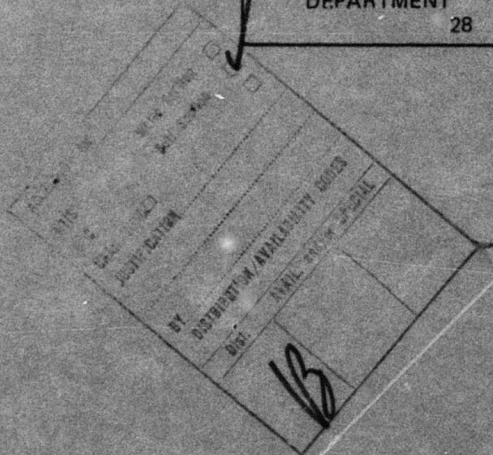## INTO A SURFACE DISPLACEMENT SHIP

by

G. Robert Lamb

D D C
JUL 19 1976

SYSTEMS DEVELOPMENT DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

December 1975

Report 4570

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Small Waterplane Area Twin-Hull Ship
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

SWATH ships are characterized by twin submarinelike lower hulls, thin struts (one or two per side) at the air/sea interface, and a wide expansive bridging structure to tie the two sides together. With most of the buoyant volume under the water surface and most of the arrangement volume considerably above it, only a small part of the ship interacts

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with waves on the surface. Consequently, a SWATH ship is much
steadier and easier riding than a conventional monohull of
equal size. As a result, SWATH offers increased speed in a
seaway, and has less need to change course than do monohull
equivalents. These benefits, moreover, can be realized with
displacement ship-level technology. The principal dis-
advantages of SWATH, compared to monohulls, are: (1) generally
higher fuel consumption rates at low and moderate speeds; and
(2) less ability to accommodate weight growth beyond design
margins over their operating lifetimes. This report summarizes 5)

The findings summarized here cover five years of
coordinated analyses and testing which have raised the level
of knowledge of SWATH ship technology and design to the stage
where the concept is judged to be a relatively low risk
candidate for advanced development by the Navy.

FOREWORD

A review of all published material on small waterplane-area twin-hull (SWATH) ships reveals a gap between broad-brush articles which advocate the SWATH concept and its advantages, and in-depth technical reports which have a narrow focus. The need has been evident for a document which synthesizes accumulated knowledge at an intermediate level of detail and technical depth.

This report was written to fill the gap by summarizing and attempting to put in proper perspective the results of completed investigations in what are considered the key areas of SWATH technology. An effort has been made to strike a balance between advocacy and sterile objectivity in the manner of presentation. Recognizing that disparate aspects of the subject matter will be of interest to specific segments of the expected readership, the report is broken down into two self-contained parts.

Part I, somewhat different in tone from the rest of the report, serves the function of orientation. It sets forth briefly for the reader's consideration a framework within which a picture of the naval potential of SWATH ships is rapidly coming into focus. Additionally, the historical background and approach of the Navy SWATH ship Exploratory Development Program are described.

Part II describes and interprets findings thus far in five key technical areas that interact to determine the feasibility and potential of specific SWATH ship sizes. These key technologies are grouped under three broad categories: (1) hydrodynamics, (2) hull structure, and (3) feasibility design. Lastly, general conclusions are given in the form of an updated assessment of the probable naval potential of SWATH ships.

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NOTATION

A_{wp}	Total waterplane area of all struts at the design draft
A_{33}	Total added (hydrodynamic) mass due to heave motion
A_{55}	Total added inertia due to pitch motion
B_c	Critical heave damping
B_{33}	Heave damping coefficient
B_{55}	Pitch damping coefficient
C_f	Frictional resistance coefficient
$C_{L\alpha}$	Slope of lift curve for the control surfaces
C_R	Residuary resistance coefficient
C_{wp}	Waterplane area coefficient for a strut at design draft
C_{33}	Heave restoring force coefficient
C_{55}	Pitch restoring moment coefficient
c	Chord length of one of a pair of control surfaces
$\mathcal{C}_L$	Longitudinal centerline of a SWATH ship
D	Maximum diameter of a SWATH lower hull
d	Distance from the cross-structure neutral axis to middraft
E	Total energy of a seaway wave spectrum
ehp	Effective horsepower
e_h	Propulsive hull efficiency
e_p	Open water propeller efficiency
e_{rr}	Relative rotative propulsive efficiency
F_n	Froude number
F_0	Peak amplitude of the sinusoidal wave exciting force

GM_L	Longitudinal metacentric height
GM_T	Transverse metacentric height
g	Acceleration of gravity
h	Wave height
$h_{1/3}$	Significant wave height
IED	In-house exploratory development
I_5	Ship mass moment of longitudinal inertia about the y axis
KB	Vertical center of buoyancy above the keel
KG	Vertical center of gravity above the keel
L	
LOA	Length of a SWATH lower hull
L_h	
L_s	Length of a strut at the design waterline
L/D	Lower hull length-to-diameter ratio
$|\ell|$	The distance from the ship's longitudinal center of gravity to the quarter-chord point of a horizontal fin
M	The ship's mass
$M_{1/3}$	Significant motion amplitude
M'_w	Coefficient of pitch moment due to heave velocity
P.C.	Propulsive coefficient (efficiency)
pcf	Pounds per cubic foot
psf	Pounds per square foot
psi	Pounds per square inch
RAO	
	Response amplitude operator
$R(w)$	

RBM	Relative bow motion with respect to the wave surface
R/C	Radio controlled
S	Total wetted surface area
S	Transverse spacing between longitudinal strut centerlines
S(w)	Spectral density of a seaway
shp	Total shaft horsepower
s	Span of a horizontal control surface fin
T	Draft to keel at design waterline
T_H $\Big\}$ T_z	Heave natural period
T_p	Pitch zero speed natural period
T_r	Roll natural period
T_w	Wave period
T/D	Draft-to-diameter ratio
U	Ship speed, feet per second
U_0	Speed for onset of pitch instability, feet per second
V	Ship speed, in knots
$V/\sqrt{L}$	Speed-length ratio, knots per foot$^{1/2}$
V/STOL	Vertical/short takeoff and landing
V_w	Wave celerity
W	Maximum width of a strut
W/D	Ratio of strut width to the lower hull diameter
x-struct.	Cross structure (upper hull box) of a SWATH ship

$Z(t)$	Heave motion over a period of time, with respect to equilibrium	
z_0	Peak heave amplitude	
$\dot{z}$	Heave velocity	
$\ddot{z}$	Heave acceleration	
β	Phase angle of wave motion about the ship longitudinal center of gravity	
Δ	Ship full-load displacement	
ΔC_F	Frictional resistance correlation allowance	
ζ_{h0}	Heave damping ratio for uncoupled motion	
ζ_{p0}	Pitch damping ratio for uncoupled motion	
θ	Pitch angle	
Λ	Tuning factor for motion response	
λ	Wave length	
ρ	Density of water	
ϕ	Phase angle of peak upward heave motion with respect to a wave crest above the ship longitudinal center of buoyancy	
ω	Wave frequency	
ω_e	Wave encounter frequency	
ω_n	One of the natural motion frequencies of a ship	
ω_{OH}	Undamped natural heave frequency	
ω_z	Zero speed heave natural frequency	
ω_θ	Zero speed pitch natural frequency	
ω_ϕ	Zero speed roll natural frequency	

ADMINISTRATIVE INFORMATION

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PART I

NAVAL POTENTIAL OF SWATH SHIPS AND OVERVIEW OF
THE TECHNOLOGY DEVELOPMENT EFFORT

Figure 1 -- Artist's Concept of a 4000-Ton SWATH Combatant

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"It really isn't clear to me why a hull
that has a major task of operating air-
craft, (helicopters are aircraft) even
though it is named a destroyer, should
look like a ship designed in the 1900's
before the helicopter was invented....
I would assert that the innovative in-
vention, and the ideas that are required
to make the right compromises between
something that carries a sonar in the
bottom and a helicopter in the top--as well
as other weapons systems--really have not
been applied."

<div align="right">
Hon. Robert A. Frosch
ASNE Banquet Address--May, 1970
</div>

INTRODUCTION

This is a technology-oriented status report on efforts since 1969
to apply one such bold, innovative ship concept to precisely the issue
addressed in May 1970 by the then Assistant Secretary of the Navy for
Research and Development. The concept, a small-waterplane-area twin-
hull (SWATH) ship, will have the general configuration shown in Figure 1
when designed as a destroyer.

The acronym SWATH was selected by the Navy in 1972 to reduce con-
fusion between this concept and another type of twin-hull ship--the con-
ventional catamaran, which is different in many important respects.
Physically, the most apparent differences between the two concepts are
below waterline. Whereas conventional catamarans have more or less
standard displacement ship hulls, SWATH demihulls consist of a submerged
cylindrical body connected to one or two slender surface-piercing struts.
For both concepts the structure connecting the two hulls is a considerable
distance above the calm-water surface. Taking the form of a large
rectangular box, this structure furnishes most of the arrangement volume
as well.

What needs to be pointed out is that far from being superficial, the difference in configuration is a manifestation of the fundamental idea behind the SWATH ship concept. Put concisely, it is a case of form following function. Hydrodynamicists knew as long ago as 1880 that placing the major part of a ship buoyant volume below the air/sea interface enabled a drastic reduction in hull planform (waterplane) area at the interface, thereby decreasing wave-exciting forces with consequent reduction in ship motion response.

Ship motions are forced periodic oscillations excited by the waves it encounters. Motions vary with the geometry of the ship, particularly the distribution as well as amount of waterplane (horizontal cross section) area and inertia in relation to ship mass and draft. Generally, the less waterplane area for a given displacement, the less the wave excitation force and the longer the ship natural periods. Indeed, with proper design, heave and pitch wave excitation forces can be reduced essentially to zero over a narrow range of encounter frequencies.[1]

This is the principle used in designing the mobile offshore oil-drilling platforms that have proliferated in recent years. The amount of waterplane area is minimized by employing widely spaced vertical columns to connect its deeply submerged underwater volume to a boxlike structure high above the water surface. One result is that these platforms have natural periods of roll, pitch, and heave of the order of 20 seconds, much longer than conventional ships of equal displacment. More important, the wave excitation force on these platforms is negligible in the sea conditions that occur most commonly. Their motions are correspondingly small.

The configuration of a SWATH ship is fundamentally an adaptation of the column-stabilized platform, streamlined for lower drag at moderately high speed (i.e., > 25 knots). But most naval SWATH ships will be considerably smaller than existing mobile drilling platforms. A second difference is that the beam of a SWATH combatant will generally

_____

[1]Motora, S. and T. Koyama, "Wave Excitationless Ship Forms," Sixth Naval Hydrodynamics Symposium, Wasington, D.C. (Oct 1966). A complete listing of references is given on page 141.

be constrained (to Panama Canal width, for example) so the planform of
its weather deck will be rectangular rather than square. Their chief
similarity is that because the amount of waterplane area is so reduced,
this area must be distributed in two widely spaced hulls to provide
sufficient transverse inertia to ensure damage roll stability and limit
heel in high winds.

On balance, the analogy between SWATH ships and stable ocean plat-
forms should not be carried too far. The smaller size and relatively
greater waterplane area of SWATH ships cause them to be less "detuned"
from typical ocean waves. Compared to conventional ships, however,
SWATH ships extend considerably the range of wave conditions in which
excellent seakeeping qualities can be maintained and in addition they
have much less need to change heading or speed. It is also possible to
tailor somewhat the motion characteristics of particular SWATH designs
to expected operating environments and predominant mission speeds. This
more sophisticated approach should result in a ship of enhanced operability,
i.e., increased probability that the ship and all essential equipment
can function properly to carry out the intended mission even in adverse
conditions. At the same time, this approach necessitates new, or at
least different, criteria for making design tradeoffs.

Consideration of seakeeping performance primarily entails concern
with three qualities--operability, habitability, and survivability. In
practice, the first two of these are not given enough attention by
designers. According to Hadler and Sarchin, most seakeeping design
criteria that have evolved for combatants are directed to ensuring
survivability.[2] These criteria are necessarily based on those very
severe storms that will be experienced only rarely in the lifetime of a
ship. Criteria have not been established for allowable degradation of
performance in the lesser wave conditions that occur more frequently.

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[2]Hadler, J.B. and T.H. Sarchin, "Seakeeping Criteria and Specifications,"
SNAME Seakeeping Symposium, Webb Institute of Naval Architecture, Glen
Cove, N.Y. (Oct 1973).

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If higher design priority is assigned to improving the seakeeping of traditional workhorse combatants at speeds from 20 to > 30 knots, the existing state of affairs suggests a different solution than the conventional displacement hull form. Once the causes of unacceptable motions and accelerations are understood, appropriate design steps can then be taken to alleviate these characteristics; roll is the only characteristic of a typical monohull that can be decreased appreciably by adding active fins.

WHY SWATH SHIPS?

Faced with the need to replace large numbers of WWII-era ships, the Navy can afford to pursue only genuine and economic solutions to real problems. A ship is built to provide a specific military capability (weight, area, volume, and manpower) for transit to any desired location as rapidly and surely as possible under diverse environmental conditions. Mobility is crucial to the difficult task of maintaining a credible sea control force, but it is not sufficient. Platform/ weapons compatibility and military carrying capacity are also important.

Serious problems affecting military effectiveness arise from the inadequate seakeeping ability of conventional destroyer escorts with displacements of 5000 tons or less. Indeed, the ability of destroyers to perform their role effectively is limited to State 4 or lesser wave conditions occurring in the North Atlantic about two-thirds of the time year round. Their sonar performance in not uncommon wave conditions is degraded by an accompanying periodic emergence and quenching of the bow sonar dome. If ship heading is changed to take the waves off the bow, then helicopter operations become hazardous because of the rolling deck. Even their mobility varies with seaway conditions. Operators of the 4100-ton DE 1052 class, for example, are unwilling to sustain 20 knots in head seas characterized by a significant wave height of 15 ft (State 6) because of excessive deck wetness caused by pitching.[3]

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[3]Kehoe, J.W., "Destroyer Seakeeping, U.S. and U.S.S.R.," Naval Engineer's Journal, Vol. 83, No. 6 (Dec 1973).

Traditionally, it has been thought possible to improve destroyer seakeeping only incrementally; e.g., increasing the size and length provides a steadier platform for helicopters and sonar at the penalty of increased costs for acquisition and operation. New naval combatants tend to be substantially larger than their predecessors for other reasons as well. Large amounts of precious topside space are needed for modern weapons and associated antennas. Ship-based helicopters require additional topside space and increased manning, while habitability standards have been improved substantially. ...l combine to make the hull size of modern conventional destroyers volume- and area-limited.[4] One unfortunate result is that the cost of providing these qualitative improvements is judged to be too high for the substantially larger new combatants to be built in quantity.

The marked numerical shrinkage in the size of the U.S. Fleet has been widely publicized and is common knowledge. Because of inflation and limitations on the Navy budget for ship acquisition, even if the ships now being built were as austere as their WWII counterparts, the latter could not be replaced on a one-to-one basis. The effectiveness of the Fleet with fewer ships can be maintained only by ensuring that each ship is more capable, commensurate with its cost. This imperative makes each conventional surface combatant still more expensive and means an even smaller Fleet.

WHAT MAKES SWATH SHIPS A PROMISING ALTERNATIVE?

To begin with, a relatively small SWATH ship can provide more topside deck area and enclosed volume to accommodate modern military payloads than a monohull of comparable size. The principal limiting factor will be the need for buoyancy to support the associated weight. Over a range of sizes, SWATH ships could provide relatively steady, 30- to 40-knot surface platforms capable of operating in a broader range of wave height/heading/speed combinations than conventional

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[4]Oakley, O.H., "Size Determinants in Destroyer Design," Marine Technology (Oct 1968).

displacement ships. The small roll and pitch response, large weather deck area, and efficiency of arrangement available with the SWATH configuration make it a natural candidate to support helicopter or V/STOL aircraft operations. In addition, their deeply submerged hulls and near-level ride in moderate seas suggest that SWATH ships will be excellent surface sonar platforms. It follows that they have great potential for improved antisubmarine warfare (ASW) capabilities. More generally, the characteristics of this hull form make it practical to build SWATH combatants for some naval missions for which they can offer greater capabilities than conventional ships of equal displacement.

SWATH ships should be thought of as filling a cost/performance gap in advanced ship alternatives. As the least radical departure from conventional surface ships, they will be the most compatible with existing naval practices and support equipment. Further, instead of sacrificing other factors to gain increased speed, SWATH ships provide a well-balanced set of capabilities and few drawbacks. Overall, the concept is judged to be applicable to a wide variety of naval combatant and support missions. The maximum speed for SWATH ships (with practical machinery arrangements) tends to decrease with increasing size, from almost 40 knots for one of 2000 tons to about 30 knots for 20,000-ton or larger sizes.

A SWATH ship may cost somewhat more than a monohull equivalent but the improved capabilities it offers can be far greater. Differences between monohulls and SWATH ships in hull structure and propulsion machinery represent a small fraction of the total cost. The majority of other components and subsystems, requiring a large fraction of the investment, will be similar for the two types of ships. On the other hand, compared to monohulls, SWATH ships potentially offer:

- Increased operational flexibility (less affected by sea conditions).
- Substantially increased helicopter/VSTOL operating capabilities.
- Seaway speeds compatible with much larger naval and merchant ships.
- Significant improvement in sonar performance.

At the same time, SWATH ships require considerably less development cost than other advanced platform concepts.

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SWATH ships appear to have two important disadvantages:

- They cannot easily accommodate weight "growth" during their operating lifetime beyond the margin allowed for in the design (because the slender struts provide relatively little reserve buoyancy and draft increases reduce cross-structure clearance, which degrades seakeeping ability).

- Thus fuel consumption rates in calm water are somewhat higher than for comparable monohulls over most of the operating speed range.

STATE OF DEVELOPMENT

For years FY73-75 the SWATH ship was an exploratory development effort sponsored by NAVMAT under their DLF Program. The funding level was $1.25 million in FY73, increased to $1.5 million in FY74, and fell to $1 million in FY75. A shift to NAVSEA sponsorship occurred in FY76. Technical management of the SWATH Ship DLF Program has been by the Systems Development Department of the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). DTNSRDC technical departments have carried out most of the technology development to date, with assistance from the Naval Underseas Center (NUC) as well as industrial and academic institutions. The Naval Ship Engineering Center (NAVSEC) has been responsible for SWATH ship concept design studies; NUC has had the lead in the areas of mission analysis and mission equipment.

Additionally, a 190-ton SWATH craft named SSP KAIMALINO was constructed by the Coast Guard Shipyard at Curtis Bay for use by NUC as a workboat. The design characteristics are listed below.

Overall length	88.3 ft
Beam	49.7 ft
Maximum draft	15.3 ft
Installed power	4000 (two 2000-hp gas turbines)
Maximum seaway speed	Approx. 22 knots in State 4 sea

This craft carried out SWATH program-related technical trials off the coast of Hawaii during the summer of 1975. Figure 2 is a photograph of KAIMALINO underway in Chesapeake Bay prior to delivery to Hawaii.

Excluding the construction cost of the SSP, about $7.5 million were expended over 6 years for coordinated analysis and testing. This raised the level of knowledge of SWATH ship technology and design to a point where the concept is judged to be a relatively low-risk candidate for advanced development. Specifically, to verify expected performance advantages of the SWATH configurations while simultaneously searching for potentially crucial problem areas, essential SWATH know-how has been developed in the areas of hydrodynamics, structures, and configuration selection and arrangements, to permit rational designs to be developed and enable comparisons with other alternatives. A broad foundation had to be laid and interdependencies noted before SWATH ship designs could be developed that truly represent capabilities for particular applications and missions.

It is recognized that reaching the goal of a balanced ship design should not mean that equal attention is given to all considerations. Rather, it requires that each receive an appropriate level of attention. Hydrodynamics took precedence in evaluating SWATH design requirements because it sets limits on the degree of mobility as well as on platform compatibility with helicopter and sonar operations. Measures resulting in less structural weight were considered important from the standpoint of increasing payload capability.

Technical characteristics unique to SWATH ships present designers with a more complex synthesis problem than conventional monohulls. Consequently, development of tradeoff data and prediction techniques is required. Broadly speaking, the objective of the on-going program is to reassess and document the feasibility, advantages, and state of technology of the SWATH concept for naval applications. Points of concern include the general level of confidence in predicting each SWATH characteristic and its effect on total ship performance and cost. It is also necessary to assess the seriousness of errors in predicting characteristics which might invalidate estimates of total ship performance affecting concept viability.
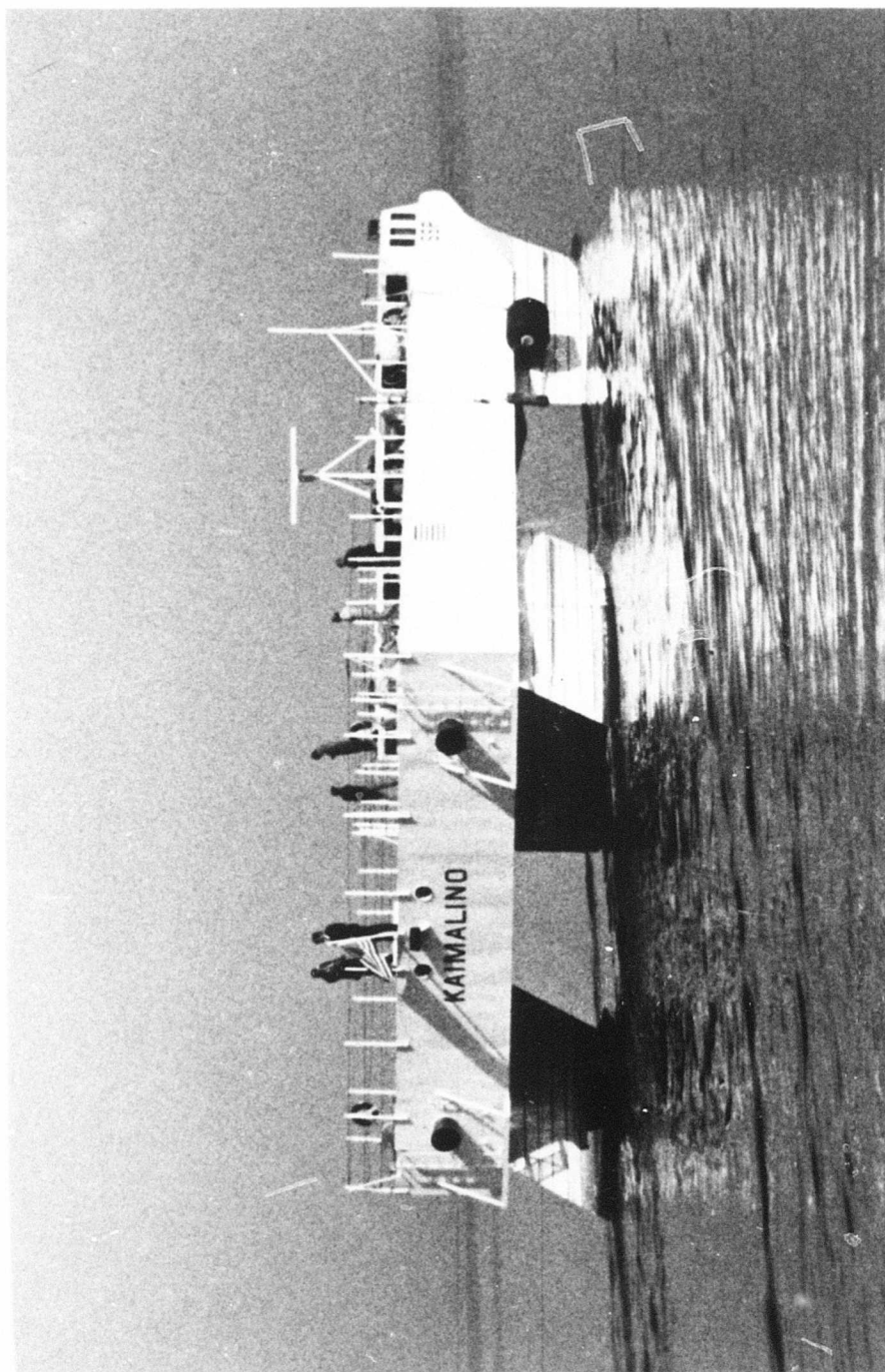
Figure 2 -- The SSP KAIMALINO at Low Speed in the Chesapeake Bay, April 1974

At the present stage of development, both a relatively large manned SWATH ship and further technology development are needed for the following reasons:

• Prior to construction of the first tactical SWATH ship, an adequate technology base and realistic design criteria must be available together with a cost estimate and credible assessment of mission utility.

• The potential of SWATH ships for improved sonar performance and increased helicopter operating capability must be validated with the actual hardware in a realistic environment.

• Scale effects and other limitations inherent in model testing make it certain that a full-size ship will behave in the real world environment somewhat differently than predicted. Consequently, full-scale verification is essential to determine SWATH seaway motion response both in typical and in extreme conditions.

• Because of dependence on seakindliness characteristics and on numerous complex wave/control surface/propeller interactions, speed degradation at various headings in a seaway must be verified on full scale.

• The paths by which seaway-induced loads are absorbed by the structure of a SWATH ship are necessarily assumed during design (with an ample safety factor) because of the difficulty and expense of determining them through testing. These should be verified by strain measurements of the actual structure to permit development of more efficient, lighter scantlings.

• The accuracy of model predictions of actual full-scale wave impact pressures on the cross structure and struts of a SWATH ship is presently in question. This issue can be resolved only by full-scale measurements.

• Although not needing drastic departures from conventional ship practice, no high performance SWATH ship for a naval application has ever been designed. Thus no relevant experience base is available.

Reasonably adequate experience can be obtained in the areas of packaging, distribution, and operation of SWATH subsystems in the course of developing a layout for the developmental ship. Similarly, building experience can be obtained only by constructing a SWATH ship, preferably to naval specifications.

• Proven debugging and successful operation of essential subsystem hardware, such as the power train, is extremely desirable before making decisions in these areas for a class of tactical ships.

On the premise that tactical SWATH ships will be built only if they do, in fact, provide better motion characteristics and more efficient arrangements, the SWATH developmental prototype must be sufficiently large to verify this facet of their predicted performance. The working goal has been to produce tactical SWATH ships capable of sustained operation at speeds of 25 knots or more at various headings in mid-State 6 seas. Because this requires at least 18 ft of cross-structure clearance, the minimum tactical ship displacement is about 2500 tons.

SCOPE OF DESIGN STUDIES

Results and tentative conclusions drawn from the principal NAVSEC design effort to date have already been documented.[5] This covers extensive computer and feasibility-level studies in which a total of 145 conceptual SWATH combatant designs were produced. Most of these consisted of predominantly ASW ships of two classes: (1) 2000-2500 tons and (2) 4500-5500 tons. The effects of structural material and the proportions of configuration elements (lower hulls, struts, and cross structure) were assessed in terms of their influence on displacement and speed/range performance as well as on numerous other design considerations. In addition, a preliminary study was completed to compare representative SWATH conceptual designs with monohull designs configured to have about the same payload, volume, and installed power.

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[5] Sarchin, T. et al., "Technical Report: Small-Waterplane-Area Twin-Hull (SWATH) Combatant Ships Feasibility Design Studies," NAVSEC Report 6114-74-8 (Jan 1974).

A quasi-conceptual level design of a 2900-ton developmental SWATH was completed by NAVSEC during FY75. This would be built of steel and require a minimum of subsystem hardware development to avoid introducing extraneous issues in subsequent evaluations of the concept.

It appears that evaluations of SWATH ships relative to conventional monohulls will always consist of deciding between alternatives that are unequal in performance as well as cost. One reason is that SWATH ships and monohulls sized for equal payload and arrangement area could have displacements which differ by as much as 20 percent. In addition, matching of their speed-power, seakeeping, and sonar performance is simply not possible. Nor will the alternatives have the same reliability, vulnerability to environmental or weapons damage, and detectability. Differences in any of these factors will affect the relative viability of the ship as an integrated weapons system, and thus complicate an evaluation of true worth.

The purpose of Part I of this report has been to present the "nature of the beast" and to demonstrate that this innovative hull form merits further attention. Part II is an attempt to describe the current status and understanding of SWATH ship technology within a coherent framework. Its purpose is to enable technologists and technical managers to become acquainted with fundamental aspects of key SWATH ship technology both within and outside of their specialities. A generalized interpretation of findings in three broad areas (hydrodynamics, structures, and feasibility design) is presented. An evaluation of the comparative worth of SWATH ships for specific applications was considered to be beyond the scope of this report, except that some relevant issues for any such evaluation are discussed briefly.

The findings of a NUC investigation of SWATH potential for improved surface ship hull-mounted sonar performance[6] have been omitted to avoid the need for classification. Sarchin et al.[5] should be

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[6]"SWATH Ship Sonar System Description (U)," Naval Undersea Center Document 356-00100-73 (Jun 1973) SECRET.

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consulted for specific preliminary SWATH combatant ship exploratory design efforts. These studies were carried out by NAVSEC during FY72 and FY73. NUC has also investigated the potential of various sizes of SWATH ships for a particular ASW mission.[7]

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[7]Avery, J.T., "ASW Mission Performance of Alternative SWATH Configurations and Competitive Platforms, Vol. 1: Background Development (U)," NUC Report TN 1341 (Apr 1974) SECRET.

PART II
AN INTERPRETATION OF SWATH SHIP TECHNOLOGY AND DESIGN

DESIGN CONSIDERATIONS

Every ship design is the product of compromise between conflicting objectives and considerations. It is emphasized at the outset that a SWATH ship is more difficult to design for a given application than is a conventional monohull. Not only is there little design experience to draw on but also a more sophisticated (and more complicated) approach is entailed to achieve the general SWATH design goal of increased operability in adverse sea conditions.

A prime objective of feasibility design is to determine what size ship is required. In the context of hydrodynamics, ship size is a matter of displacement as well as waterline length and beam and, to a lesser extent, draft. To the extent that emphasis can be placed on any single category of technology needed to design SWATH ships, hydrodynamics in all of its facets should be given precedence when selecting principal dimensions and hull shape. Simplicity of hull structure and propulsion machinery are subordinate considerations for high performance naval combatants.

As is the case with conventional ships, the design process for SWATH combatants is iterative. At either the feasibility or conceptual stage, the designer starts with a "reasonable" hull form and general arrangement as the basis for estimating weights, displacement, resistance and powering, range, stability, and so forth. These initial, first-cut numbers then serve as a point of departure for increasing refinement through successively more detailed analyses until a consistent and satisfactory design is obtained.

DIMENSIONS

Hydrostatics dictates that all SWATH hull forms considered must provide sufficient buoyancy and intact stability, both longitudinal and transverse. Accurate weight prediction is crucial to SWATH design because any changes in weight can be compensated for only by relatively large changes in draft or by altering strut and lower hull dimensions.

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Conventional ship designs are frequently characterized as being either weight limited or volume limited; the greater configuration flexibility of SWATH designs may be constrained by both considerations simultaneously. The submerged lower hulls are always weight limited and the upper box size can be volume limited.

Ironically, a third reason why it is more difficult to design a SWATH ship is the greater freedom allowed the designer in his choice of hull dimensions. The freedom is manifested in two principal ways. All surface displacement ships must have sufficient transverse waterplane inertia to ensure damage roll stability; the beam of conventional ship designs is usually constrained by this consideration. But the amount of transverse inertia for a SWATH is proportional to the product of waterplane area times the square of the distance between the centerlines of the two hulls. Two factors are thus involved. Consequently, if the designer finds that a more slender strut results in lower resistance, he will often be able to choose the better strut because the transverse inertia thereby lost can be compensated for by a small increase in hull spacing. The principal arrangement limitations on lower hull and strut slenderness include propulsion machinery and reduction gear size and intake ducting requirements.

Once the amount of waterplane area is decided, another design decision involves selecting the longitudinal distribution of this area. The choice between a single long strut or two stubbier struts in tandem (for each hull) can have a substantial effect on resistance as well as on longitudinal stability (and thus motion) characteristics.

The great variation in possible SWATH ship configurations suggests that their characteristics can be tailored to specific mission require-ments. Viewed in the light of our limited understanding of the inter-relationship between some of these parameters, the multitude of design factors and innumerable combinations thereof constitute a difficult synthesis problem. Because they are interdependent, the various aspects of SWATH technology can be discussed meaningfully only in the context

of the ship as a whole rather than in the isolation of a particular discipline. By the same token, any conclusions drawn from studies completed thus far must be qualified carefully, especially with respect to ship size (displacement, volume, and length), hull structural material, and design speed. In other words, few general or categorical statements will be valid for all SWATH ships.

Nevertheless, it can be stated that compared to a monohull of equal tonnage, SWATH ships will differ in the following respects:

- Greater beam overall.
- Shorter length.
- Deeper design draft.
- Greater freeboard to weather decks.
- Increased seakindliness/much lower vertical accelerations.
- Higher sustained speed (as a result of reduced motions) and less need to change course in adverse wave conditions.
- Boxlike upper hull potentially offers higher degree of survivability in damaged conditions.
- Weight-limited in nature (once hull dimensions are fixed) because their slender struts provide little reserve buoyancy and, therefore, weight growth beyond design margins cannot easily be accommodated.
- Fixed or moveable antipitch stern fins expected to be required for operating at certain headings and speeds in some wave conditions.
- Greater trim sensitivity underway (only 15 to 20 percent as much waterplane area as a conventional ship of equal tonnage) so that ballast shifting or fin angle adjustments needed to maintain even keel.

The lack of a design data base for SWATH ships emphasizes the need for numerous tradeoffs and fundamental sensitivity studies before deciding on principal ship dimensions. With limited manpower and financial resources, only a computerized design snythesis mathematical

model would enable timely exploration of many SWATH configurations. Such a design computer program[8] was developed by NAVSEC during FY72 and has been refined further since.

In keeping with the overall objectives, technology development efforts to date have focused on understanding the character of SWATH ships. What are the most important design factors? How sensitive are they to changes in other factors? How can the technologies and subsystems best be amalgamated into a balanced design?

Technology was therefore viewed in terms of design requirements rather than from the narrower standpoints of hydrodynamics, structures, etc. This meant, simply, that if some aspect of these disciplines was found to have little impact on total ship performance, it was not pursued any further, however interesting in itself. A brief discussion of the above-mentioned technologies from the viewpoint of the designer is now presented.

DRAG AND PROPULSION

A drawback of the SWATH configuration is that it has almost twice the wetted area of a monohull of equal tonnage, which means the SWATH ship has nearly double the skin friction drag. This is not completely compensated for by lower wavemaking drag. Accordingly, considerable care must be taken to minimize the speed-power disadvantage of SWATH designs in calm water. This task is made more difficult by the absence of an historical data base (except for the few models listed in Table 1) of SWATH designs with known powering characteristics. Fortunately, the cylindrical body and thin struts of SWATH ships are well suited for using potential theory to provide an accurate analytical prediction of wavemaking drag. Three separate computer programs have been developed

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[8]Setterstrom, D. and P. Cojeen, "SWATH Design Snythesis Model Documentation and User's Manual," NAVSEC Report 6114-74-3 (Nov 1973).

TABLE 1 -- SWATH MODELS FOR WHICH DRAG CHARACTERISTICS
HAVE BEEN MEASURED

(The type of test is identified as resistance (R)
and powering (P))

Designation	Model Number	Design Displ. Tons	Number of Hulls Tested	Type
SWATH I	NSRDC 5226	25,000	Pair	R and P
SWATH II	NSRDC 5266	101,000	Pair	R and P
SWATH III A-E	NSRDC 5276	3,760	Single and Pair	R and P
SWATH IV	NSRDC 5287	4,000	Pair	R and P
SWATH V A, B	NSRDC 5301	4,320	Single	R
SSP*	NSRDC 5267	190	Pair	R and P
RC-2*	NUC	3,000	Pair	R

*Tandem strut configuration.

for this purpose.[9-11] Predictions for all three correlate well with model drag measurements. These analytic tools are used to achieve relatively low wavemaking drag by appropriately sizing and locating the strut(s) so that their wave train "cancels" that generated by the submerged lower hull. The drag of well-designed SWATH ships thus can be made competitive with monohulls over the upper third of their operating speed range.

A factor tending to partially offset the calm-water drag penalty of SWATH ships is their generally superior propulsive efficiency compared with that of monohulls, particularly the twin-screw monohulls typical of high-speed applications.

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[9] Chapman, R. and R. Wernli, "Operating Instructions for 'Drag' Computer Program," NUC Report TN 1385 (Jul 1974).

[10] Chen, R., "The Pien Wavemaking Resistance Computer Program, Part II: User's Manual," NSRDC Report 4371 (Apr 1975).

[11] Lin, W.C. and W. Day, "The Still-Water Resistance and Propulsion Characteristics of Small-Waterplane-Area Twin-Hull (SWATH) Ships," AIAA/ AME Advanced Marine Vehicles Conference, Paper 74-325, San Diego, California (Feb 1974).

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SPEED DEGRADATION IN WAVES

The trend for designing ships to be capable of sustaining higher speeds and remaining operational in adverse seas is apparent in much of the advanced ship development work now underway in the Navy. The problem with monohull combatants has not been that they are power-limited in the face of added wave drag, but rather that large motions and accelerations force "voluntary" acts of slowing down or changing course to ameliorate the situation. The latter factors are absent from SWATH ships in the same sea conditions so that they experience relatively little speed loss. Because of better seakeeping in moderately adverse wave conditions, SWATH operating speed capability, for a given installed power, will usually be faster than that of a comparable monohull.

MOTIONS AND CONTROL

Typically, SWATH designs have a heave natural period nearly double that of a comparable monohull and a pitch period that may be three times as great. This is important in light of the relatively rare occurrence of ocean storm waves with long periods. The long natural periods are a result of the small waterplane area, which also decreases substantially the wave force for motion excitation at most ship headings and speeds in the majority of seaway conditions. Consequently, large forced motions of a SWATH ship occur (in a manner analogous to mechanical vibrations) only when the ship/wave encounter frequency is close to one of the natural frequencies of the ship. Moreover, curves of heave and pitch response as a function of wave length are narrow and steep because the unappended SWATH form provides little damping. For this reason, stern fins are needed to dampen heave and pitch motions and thus minimize cross-structure impacts when wave conditions near resonance are encountered. Since the additional fin damping dominates response, SWATH motions in head and beam seas can be predicted quite accurately. Work is progressing on theories for stern headings.

It is essential to keep in mind that the high-speed seakeeping ability of a SWATH ship in severe wave conditions will always be

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contingent on the existence of sufficient cross-structure clearance above the mean water surface. Model tests indicate that about 18 ft is probably the minimum clearance for avoidance of unacceptable wave impact pressures or impact frequency on ships with displacements of 2000 to 4000 tons. This height is based on the design criterion that SWATH must be able to sustain high-speed capability in mid-State 6 seas.

Equally as important as peak motion excursions to the seaworthiness of a ship are the accompanying accelerations. In the case of heave (the dominant SWATH motion), even if SWATH and monohull responses are about equal for a given wave condition, the peak heave acceleration experienced by the SWATH ship will be only one-fourth of that for a monohull of the same displacement.

So far, tests to quantify SWATH seakeeping characteristics have focused on displacements of 2000 to 4000 tons because this size range promises the greatest improvement over monohull combatant performance while also posing the most taxing seaworthiness problem. Recent model tests* have demonstrated that a 3000-ton SWATH ship will be capable of maintaining speeds of over 25 knots in State 6 head seas (15-ft significant wave height) and of withstanding State 7 seas at about 20 knots without incurring damage. With larger SWATH ships, resonant wave conditions will be encountered less often, peak responses will be reduced, and it will be easier to incorporate sufficient cross-structure clearance to minimize the frequency and severity of wave impacts at high speeds.

STRUCTURAL LOADS AND DESIGN

The problem of seaway-induced loads on SWATH ships was studied by a combination of experimental and theoretical methods. Several self-propelled models, fitted with load and pressure sensing devices, were tested in various controlled seaway conditions at various speeds and headings.[12] Analyses of the resulting data not only provided insight

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*DTNSRDC report on the SWATH VI model is in preparation.

[12]Jones, H. and D. Gerzina, "Motion and Wave Induced Bridging-Structure Load Characteristics for a Large Modified Catamaran CVA in Waves," NSRDC Report 3819 (Jun 1973).

into the dominant types of loads but also served as a quantitative check on theoretical predictions.[13] (In both respects, SWATH investigations utilized the limited base of conventional catamaran technology.)

The predominant type of seaway load which affects SWATH primary structure design is the zero-speed/beam-sea transverse vertical bending moment that acts on the box structure and tends to push the hulls together or apart. Analytic predictions of the magnitude of transverse bending agree well with model measurements. There is also agreement that the peak bending moment does not occur at roll resonance, for reasons which are explained in Lee et al.[13] It is worth noting that the magnitude of wave-induced primary loads does not govern the scantlings* of SWATH ships with displacements of less than 4000 to 5000 tons if they have a two-level bridging structure.[14] Instead, scantlings of small SWATH ships are determined by local design load considerations for decks and shell. The most important secondary (local) hydrodynamic loads are those caused by wave impacts on the frontal area and undersides of the box structure. Unfortunately, no current design tool is capable of predicting SWATH impact pressures. Limited model test data are available.

When the time comes to finalize hull dimensions, it is highly advantageous to be able to predict the structural weight accurately. The penalty for uncertainty takes the form of larger weight growth margins, and the resulting greater dimensions with increased wetted area degrade powering performance. As it is, twin-hull ships designed for a particular mission usually have greater enclosed volumes and deck area than an equivalent monohull; consequently, a greater percentage of their displacement tends to be taken up by structural weight. To further

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[13] Lee, C.M. et al., "Prediction of Motions and Hydrodynamic Loads of Catamarans," Marine Technology, Vol. 10, No. 4 (Oct 1973).

[14] Aronne, E.L. et al., "Structural Weight Determination for SWATH Ships," AIAA/SNAME Advanced Marine Vehicles Conference, Paper 74-326, San Diego, California (Feb 1974).

* Scantlings are the dimensions and specifications for structural plates and stiffeners.

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complicate matters, the structure of a SWATH ship differs in so many respects from that of monohulls that previous structural design experience does not provide much of a guide.

If the same material is used throughout, about one-half the structural weight of a SWATH ship will be that of the cross structure and the remainder will be divided fairly evenly between the struts and hulls. It follows that the greatest payoff in terms of weight reduction will result from careful design of the cross structure.

Careful structural design requires an investigation of many alternatives, a process that is simply not possible by using the traditional drawing board approach with limited manpower and financial resources. Accordingly, a structural design computer program was developed[15] to provide timely hull weight predictions for the numerous SWATH configurations that would be investigated in the course of exploratory design. This was a modified version of a program that had already been developed at DTNSRDC for designing the midship section of destroyers. Agreement was excellent for scantlings and weights predicted by the SWATH structural program and those obtained for the same ship design by the laborious drawing board approach. These predictions are now considered more than adequate for exploratory design tradeoffs. Selected findings from completed weight sensitivity studies are presented in Nappi.[15]

ASSESSMENT

Computerized design snythesis studies provide a means of grossly sizing SWATH ships for given payloads and estimating such aspects of their performance as speed-power in calm water. But computer-generated designs do not resolve the question of whether ship functions can realistically be accommodated in acceptable arrangements and with structurally realistic configurations, nor is seakeeping performance investigated.

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[15] Nappi, N.S., "Structural Design of a 4000-Ton Steel Small-Waterplane-Area Twin-Hull (SWATH) Ship," NSRDC Report 3886 (Nov 1972).

True conceptual design requires drawing board arrangement and structural scantling layouts, damage stability/subdivision calculations, control-surface sizing studies, and more detailed weight estimates as well as the determination of propulsion and subsystem machinery availability, suitability, and interfaces. Only when all this has been accomplished will computer-produced SWATH ship designs be validated sufficiently to qualify them for serious evaluations as alternatives.

DESIGN/TECHNOLOGY ISSUES

Generally the design technology for SWATH combatants has progressed to the point where there is a fairly sound understanding of the trade-offs necessary to achieve balanced ship designs, with reasonable pay-loads and operational characteristics. For example, comparative studies of both single and tandem strut-per-hull configurations for a specific application were continued during FY75, focusing on their relative performance in a seaway. Barring some startling new discovery, it is not possible to state categorically that single-strut configurations are superior to tandem strut or vice versa. This question must be resolved anew for each application being investigated.

The initial decision to focus investigative efforts on technology relevant to specific conceptual designs proved to be correct. Analyses of several key technical areas in considerable depth for each SWATH design soon revealed greater coupling between certain areas than was initially realized. Technical factors governing SWATH ship design can be interpreted most meaningfully in the context of the ship as a whole rather than in the isolation of a particular discipline. Beyond this, any conclusions drawn from the studies completed thus far must be qualified carefully, especially with respect to ship size (displacement/volume and length), construction material, and design speed.

There is no longer any doubt that the SWATH concept is feasible; what needs to be addressed is the broad area of comparative naval utility. Will SWATH be the best configuration for the intended

mission? If so, which particular SWATH configuration should be selected?
How well a conceptual SWATH ship measures up against other alternatives
depends, of course, on whether a "good" configuration is chosen for the
evaluation. Perhaps the key to a fair assessment of SWATH potential is
the need for balanced candidate designs. No single performance attribute
should be optimized at the expense of severe degradation of some other
desired capability.

Important tradeoff areas needed both for SWATH design and mission
evaluation will be discussed in a general way in the remainder of this
report.

CALM-WATER PERFORMANCE
Mission Requirements
In general, the advantages of increased speed are more difficult to
justify at the tactical level of naval planning than at the strategic or
operational planning levels:

"At the strategic planning level, major considerations tend to be
response times and forward deployment or basing strategies needed
to provide specific military capabilities at geographic points
within desirable time constraints. This implies that ship speed
is probably the single most important factor; i.e., the higher
the speed, the shorter the response times or the longer the transits
for the same response time and therefore the greater the flexi-
bility in strategic planning. Seakeeping effects on speed are
often overlooked but are equally important to speed in strategic
planning and should be incorporated in the response time estimate.
Factors of range and payload are also important but tend to be
secondary, within limits, to speed."[16]

To illustrate, 7 1/2 days are needed for a ship to transit 3600
n.m. at the nominal Navy cruising speed of 20 knots. The effect of
higher sustained speed may be seen in Figure 3. Response time can be

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[16]Holmboe, E.L. and A.D. Evans, "A Guide to Assess the Operational
Implications of New Ship Design Concepts, Part II," Operations Research Inc.
(Mar 1973).

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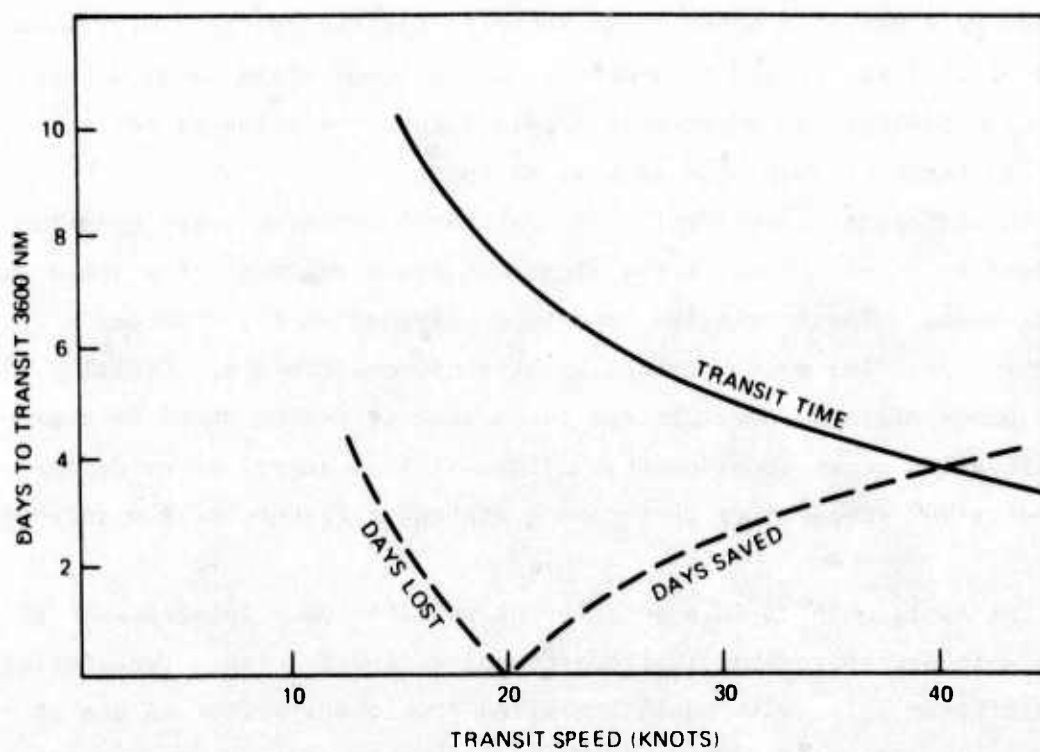
Figure 3 -- Number of Days Required to Transit 3600 Nautical
Miles as a Function of Average Ship Speed

REPRESENTATIVE SWATH SPEED-POWER CAPABILITIES
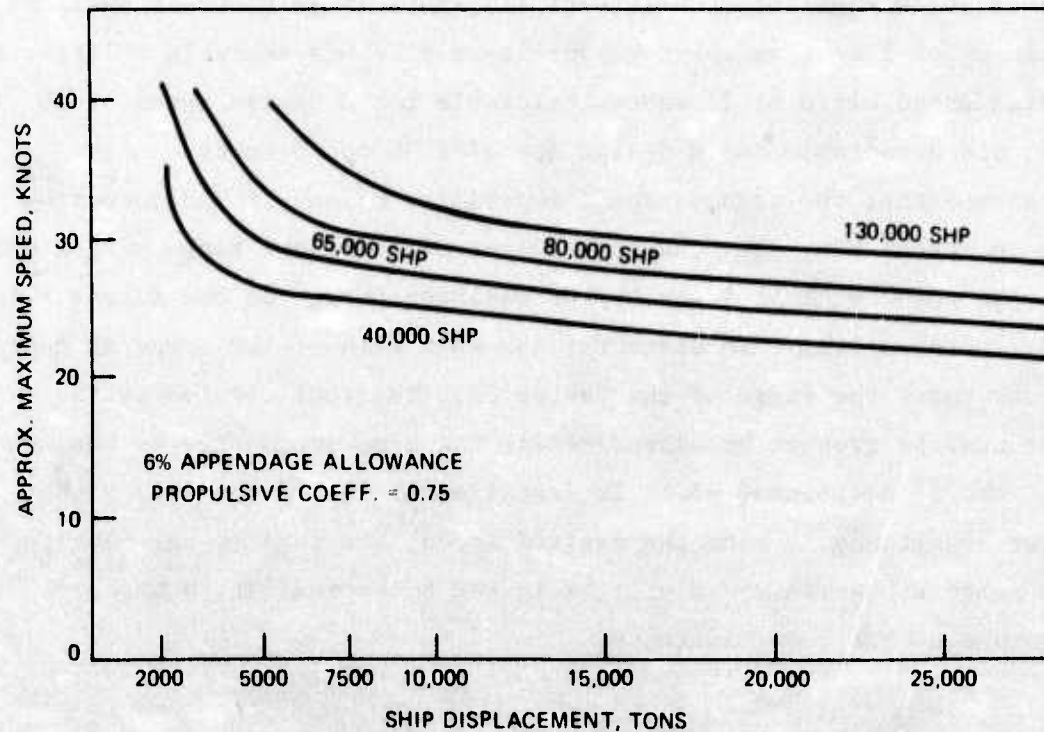
Figure 4 -- Predicted Maximum SWATH Speeds with Various Installed
Powers as a Function of Full-Load Displacement

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reduced by 1 day if a speed of 23 knots is maintained, by 2 days with a speed of 27.3 knots, and by 3 days if the average speed is 33.3 knots. Such time savings are worthwhile provided that the price is not too great in terms of ship size as well as cost.

An additional complication is that naval combatants are normally required to be efficient in two disparate speed regimes: top speed and cruise speed. Their relative importance depends on the expected ship operating profile, as determined by mission requirements. Cruising performance affects range whereas resistance at design speed determines the installed power requirements. Thus, it is meaningless to define "competitive" speed-power performance without reference to the intended mission.

For small changes in speed, the propulsion power requirements of a given ship are approximately proportional to speed cubed. Considering two different ships with equal installed power, the effect on one of having, say, 10 or 20 percent greater resistance depends on the design speed. For 20 percent greater resistance, ship speed is lowered by about 6.2 percent, which translates into a short fall of 1.2 knots if the goal is 20 knots or a deficit of 1.8 knots if 30 knots is desired. A deficiency of 1 knot in speed capability may be unacceptable relative to a design speed of 20 or 25 knots, tolerable for a design speed of 30 knots, and acceptable for a design speed of 35 to 40 knots.

Assume that the reduced speed capability of one of two competing ships is acceptable. For the same amount of fuel, the range of the ship at design power will be lower by the same percentage as the decrease in speed. Alternatively, in order for the ship with slower speed at design power to match the range of the faster one, the fuel carried by the former must be greater by approximately the same percentage as the speed loss. Or, if additional power is installed to enable the ship with greater resistance to make the desired speed, its fuel requirement for a given range at design speed will be larger by approximately the same percentage as the power increase.

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Speed or Range?

In general, for both monohull and SWATH ships, the increase in displacement required to accommodate more fuel to extend the range at cruising speed (or to provide the same range at higher speeds) is significant. Nevertheless, the price paid in terms of reduced maximum speed is not too substantial, and it becomes less so as the baseline displacement increases. This fact is brought out in Figure 4 which is a comparison of predicted maximum speeds as a function of full-load displacement for single-strut SWATH designs with varying amounts of installed power.

Completed feasibility studies of a 2150-ton aluminum SWATH combatant design (see Sarchin et al.[5]) arrived at a predicted maximum trial speed of 39 knots with 65,000 hp installed. A 40 percent increase in displacement to 3000 tons (accommodated by redesigned lower hulls and struts) could result in a SWATH ship with substantially greater fuel or payload capability and a top speed of about 34 knots, a decrease of 5 knots for equal installed power. But, relative to a baseline displacement of 4000 tons, a 40 percent increase to 5600 tons, if properly done, would decrease the top speed of the larger SWATH ship by only 2.5 knots (29 versus 31.5) for the same 65,000 hp installed.

The comparatively small speed loss which accompanies increased displacement also bears on the penalty paid by SWATH ships for their generally greater calm-water drag at cruising speeds relative to a functionally equivalent monohull. Typically, fuel comprises, at most, 20 percent of the displacement of a conventional naval combatant. If an equivalent SWATH design has a 20 percent higher powering requirement at cruise speed than the monohull, the amount of fuel must be increased by a little more than 20 percent to attain the same range capability. Even taking into account the need for additional structure, the net result in this example will be to increase the total SWATH displacement by about 5 percent. Obviously, the impact of such a small increase in displacement on maximum speed capability of the SWATH will be minor. Furthermore, the acceptance of a powering penalty in return for enhancement of another facet of mission capability, e.g., seakeeping, is not without

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precedent. For example, the addition of a large bow sonar dome to the DE-1052 class of monohull combatants resulted in a substantial increase in total powering requirements at 20 knots.*

Speed-Power versus Ship Size and Proportions

Even though the SWATH configuration is most attractive as a means of improving ship seakeeping capabilities, reasonably good speed-power performance is nevertheless essential if SWATH ships are to be a viable alternative for most naval missions. They are at a considerable disadvantage in this regard because they have from 1.8 to 2.0 times the wetted surface area of a monohull of the same displacement. In fact this understates the problem because, typically, if both are predicated on the same structural material, a SWATH design will have greater displacement than a monohull designed for the same mission.

SWATH speed-power capabilities in calm water will be most competitive for those combinations of size and speed where monohulls are at a disadvantage because of high wavemaking resistance. Except for unusual instances, such as the presence of a large bow sonar dome, this situation obtains only for monohulls forced to operate at Froude numbers of about 0.39** or greater. By the same token, a SWATH design that is optimum from the standpoint of powering requirements at top speed will usually be less competitive with monohulls at lower speeds. In designing a SWATH ship there is greater need to compromise between the best configuration for powering at cruise speeds and that for powering at high speeds.

The amount of power required to drive a ship is proportional to the product of its speed and total resistance. Ship resistance, in turn, is computed from an equation such as

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*Model test results reported informally in TMB Test Report C-011-H-01.

**Equivalent to a value of 1.30 for the speed-length ratio.

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$$\text{Resistance} = \frac{1}{2} \rho \ S \ U^2 \ (C_f + \Delta C_f + C_R)$$

where ρ = density of seawater

   S = total wetted surface area at design waterline

   U = ship speed

   C_f = flat plate nondimensional friction resistance coefficient

   ΔC_f = correlation allowance constant for roughness and fouling

   C_R = nondimensional residuary resistance coefficient

In terms of ship properties, the value of the frictional resistance coefficient depends only on speed and length (Reynolds number). Residuary resistance is comprised mainly of wavemaking resistance which varies with ship shape and slenderness as well as Froude number.

Figure 5 shows the effect of speed (or more precisely, Froude number) on the relative contributions of frictional and residuary drag to the total resistance of a 2000-ton monohull combatant.[17] Frictional resistance is dominant at low speeds because only small waves are created. A crossover occurs around 20 knots, above which wavemaking drag increases rapidly until at 30 knots residuary resistance accounts for two-thirds of the total. Figure 6 is a similar comparison of the two drag components for high-performance single strut and twin struts-per-hull SWATH designs, both displacing about 2000 tons with the same length and waterplane area.[18]

In general, residuary resistance comprises a larger proportion of the total powering requirement of the twin struts-per-hull SWATH design than that of the single strut design. But, unlike the monohulls, wavemaking resistance predominates only at relatively low speeds (16-17 knots). Indeed, wavemaking resistance of both SWATH designs continues to decrease in importance at speeds above 27 knots.

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[17]Carpenter, J.C., "USS Dealey (DE-1006) - Analysis of Standardization Trials and Comparison with Model Test Results," NSRDC Report C-911 (Feb 1958) CONFIDENTIAL.

[18]Hawkins, S. and T. Sarchin, "The Small-Waterplane-Area Twin-Hull (SWATH) Program - A Status Report," Paper 74-324, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, California (Feb 1974).
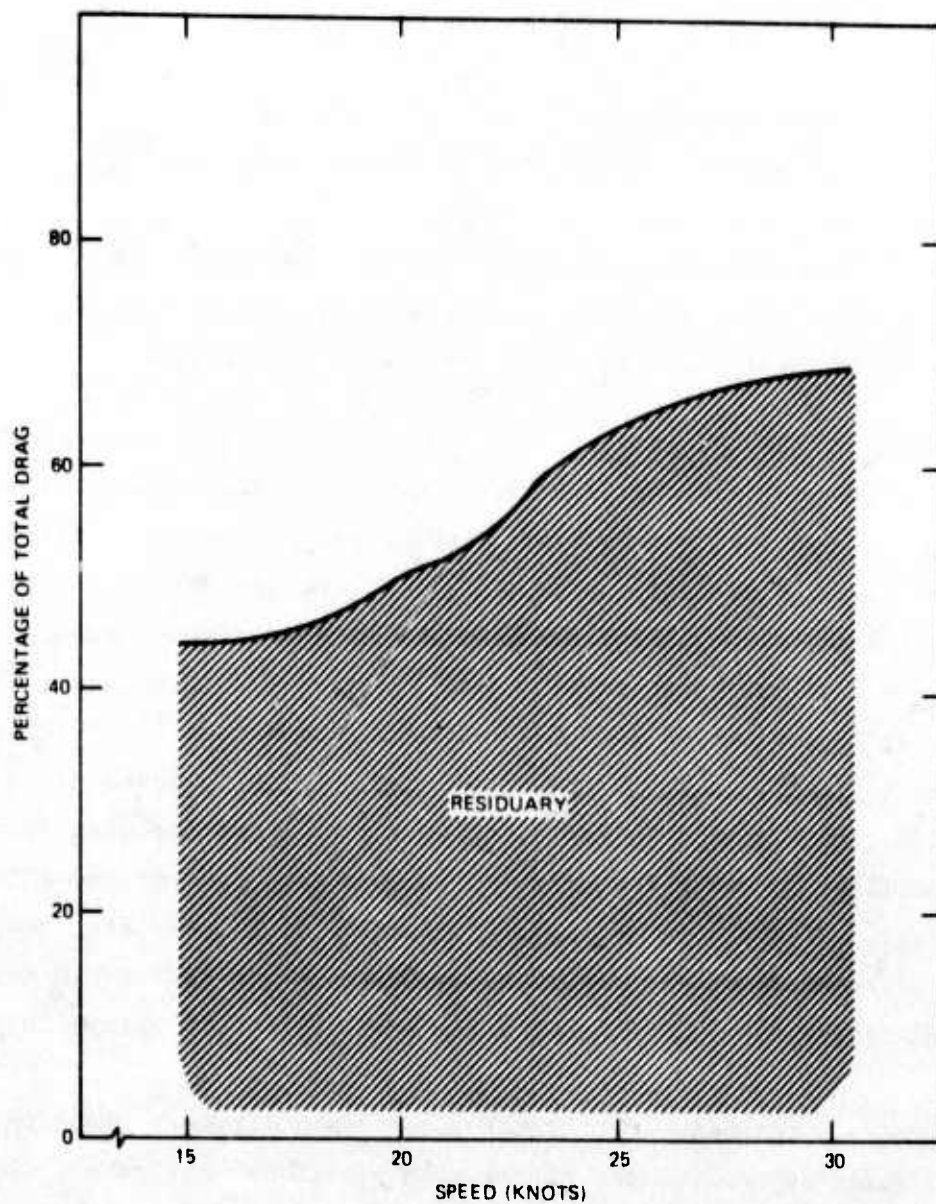
Figure 5 -- Residuary Drag as a Percentage of Total
Drag for a 2000-Ton Monohull Combatant
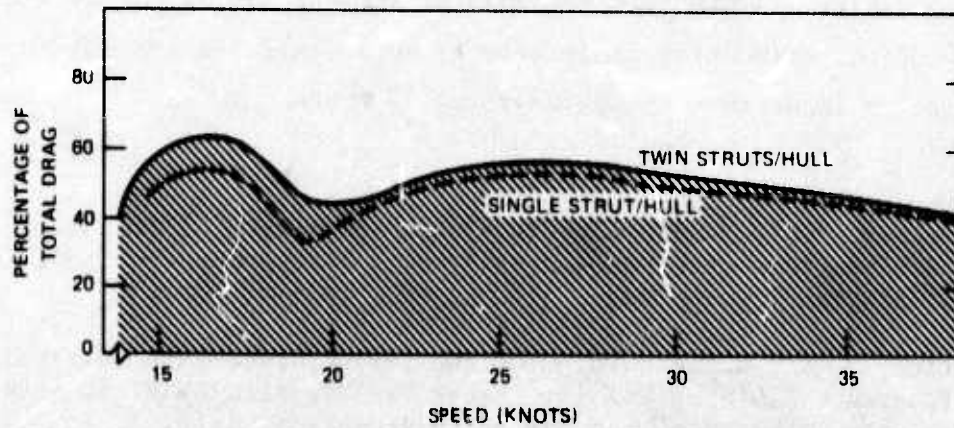
Figure 6 -- Residuary Drag as a Percentage of Total Drag
for Conceptual 2000-Ton SWATH Combatants

The reduced contribution of wavemaking resistance to SWATH powering requirements is brought about partly because both designs have about 80 percent greater frictional resistance than the monohull. But, in fact, compared to the monohull, the absolute magnitude of wavemaking resistance is lower for the two SWATH designs, over the upper portion of their speed range. One point illustrated by this comparison of monohull and SWATH powering characteristics is that per se their residuary resistance coefficient values are not a meaningful measure, given the big difference in their wetted areas for equal displacements.

Referring back to Figure 4, it should be emphasized that the selected hull proportions for the "best" SWATH forms used as the basis for performance predictions varied considerably depending on displacement and the value of the speed-length ratio at design speed. This means that the maximum speeds predicted for a SWATH ship of a certain displacement with different installed power levels may be based on two quite different designs; slenderness is advantageous for higher speeds (see Figure 7) whereas reductions in the amount of wetted area are relatively more important at low speeds. One can carry the implications a step further by stating that at levels corresponding to a small fraction of installed power, a good high-speed SWATH ship will usually fall short of the speed performance predicted for its displacement in Figure 4. Moreover, the speed capabilities of many, if not most, SWATH ships would depart from this norm because of higher wavemaking drag resulting from the less-than-ideal hull proportions forced on them by practical design constraints.

Single versus Tandem Strut Configurations

Design constraints are responsible for the differences in predicted powering characteristics between single and twin struts-per-hull SWATH forms at low to moderate operating speeds (see Figure 8). Although the example selected may appear extreme, it is "real" in the sense that it is the preliminary result of the NAVSEC attempt to design alternative 2000-ton SWATH forms for the same mission. The difference in

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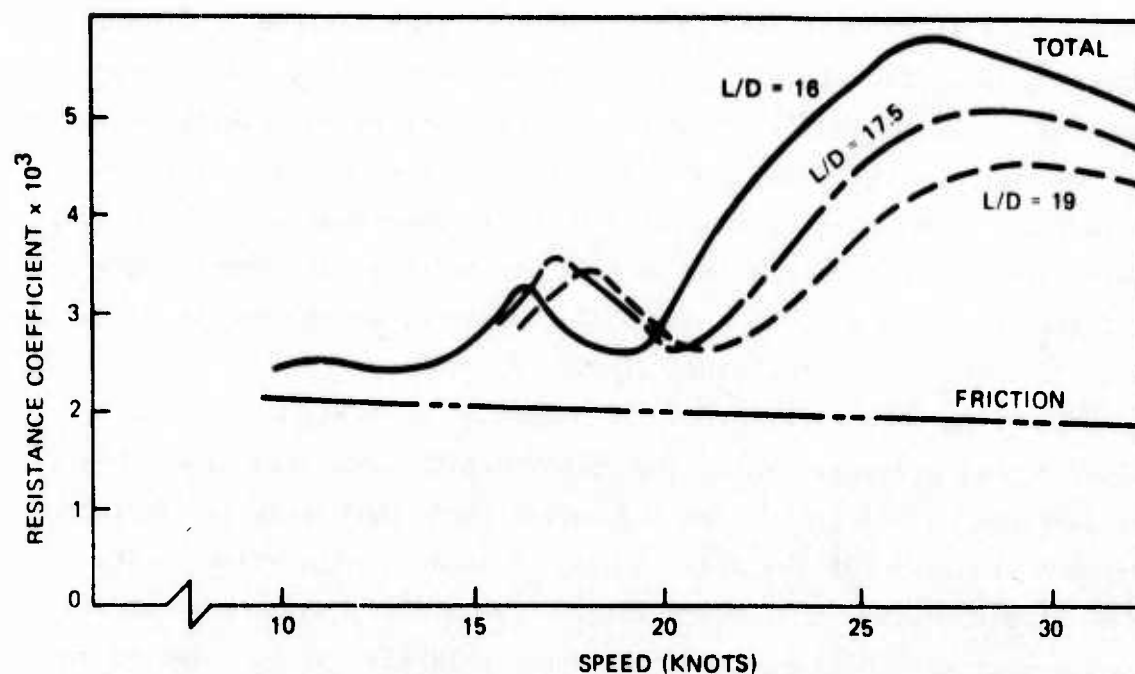
Figure 7 -- Effect of Increased Hull Slenderness on the Drag
Coefficients Predicted for Three 5500-Ton SWATH
Ship Configurations
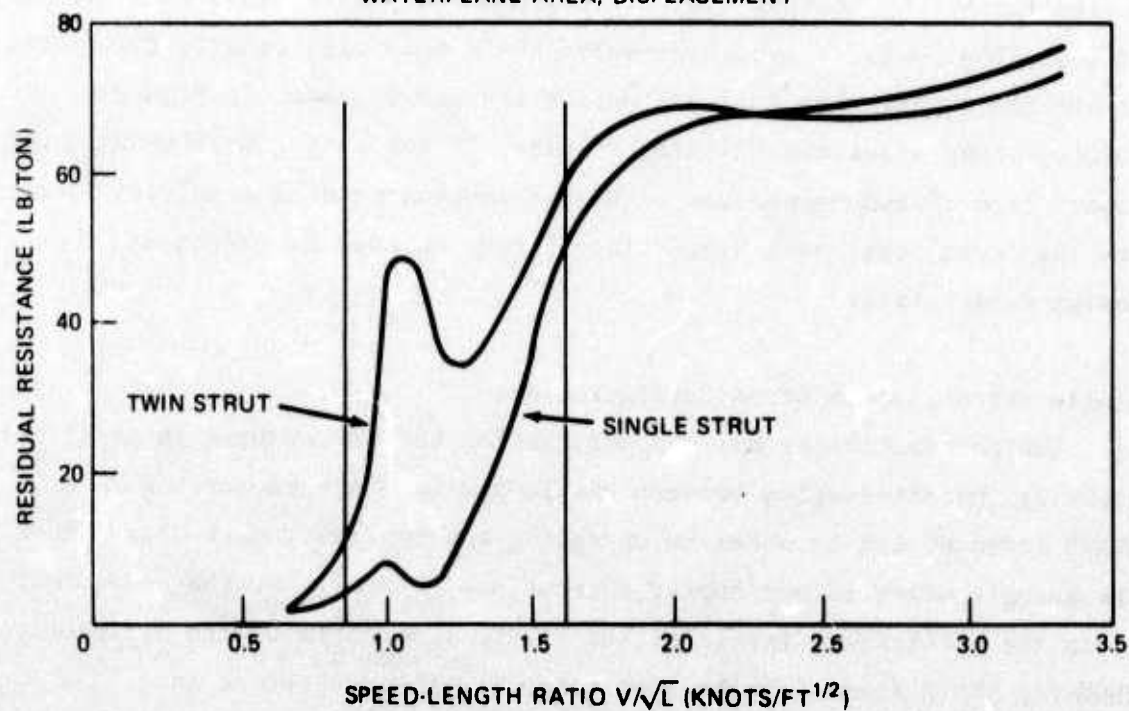
Figure 8 -- Effect of Strut Configuration on Total Residuary
Resistance for Representative 2000-Ton Designs

(Speed-length ratio based on lower hull length;

from Hawkins and Sarchin[18])

TABLE 2 -- PARTICULARS OF THE THREE SWATH CONFIGURATIONS
USED TO STUDY THE SENSITIVITY OF C_R TO HULL SLENDERNESS

Length-to-Diameter Ratio	16	17.5	19.0
Displacement/long tons	5500	5460	5460
₵ Hull Spacing/ft	83.5	81.0	81.0
Lower Hull Length/ft	320	340	360
Lower Hull Diameter/ft	20.1	19.44	18.9
Strut Length/ft	253	269	285
Max. Strut Thickness/ft	8.93	7.85	7.4
Waterplane Area Coefficient	0.754	0.754	0.755
Total Waterplane Area/ft^2	3338	3180	3184
Design Draft/ft	31.7	31.0	30.5
Total Surface Area/ft^2	43,70	44,720	46,545

wavemaking resistance characteristics is due largely to the difference
in strut waterline length and fullness. As one would expect, the length
of each strut in a tandem-strut design is usually less than one-half
that for a single-strut design of the same displacement and waterplane
area.

Theory and tests have shown that the last peak in C_R (residuary
resistance coefficient) curves for surface displacement ships occurs at
a Froude number of about 0.50* based on waterline length. Both the
strut length and the lower hull length are relevant for SWATH ships, the
latter because it is sufficiently near the free surface to generate
waves. Good wavemaking resistance characteristics with a SWATH form are
thus necessarily dependent on a degree of cancellation and a minimum of
reinforcement between the wave trains generated by its lower hull and
strut(s). But for a tandem-strut design the maximum Froude number of an
individual strut is substantially higher** and the C_R peak due to this
strut will occur at a lower speed. In addition, a second C_R peak may be
present at some higher speed because of reinforcement between the wave

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*Equivalent to a value of about 1.68 for the speed-length ratio (in
knots per foot$^{1/2}$).

**By a factor of roughly $\sqrt{2} = 1.414$.

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train of the aft strut and that of the forward one. A third and broader peak will occur at a still higher speed, characteristic of the wave train generated by the submerged lower hull. By the same token, single strut SWATH designs tend to have one less "hump" in their C_R curves.

It also needs to be pointed out that the amplitude of the local C_R peaks at lower Froude numbers depends on the rate of change in the width along the length of the struts and lower hull. Because the struts of a tandem-strut design are necessarily stubbier (to provide the same total waterplane area as a single strut), the low-speed C_R peaks they cause will generally be considerably higher. On balance, for displacements of 2000 tons and greater, the drag characteristics of a tandem strut SWATH over the entire speed range of interest are usually inferior to those for a comparable single strut SWATH.

However, Chapman[19] has shown that, at least for widely spaced tandem-strut forms, measures can be taken to reduce markedly the amplitude of the C_R peaks at lower Froude numbers. Basically, what is involved is the maintenance of constant cross-sectional area in the gap between the tandem struts by bulging out the lower hull in this region. But it has not as yet been verified that analytic predictions of wave-making drag based on potential theory remain valid when the Chapman design modification is applied to SWATH forms with closely spaced tandem struts. The principal source of doubt in the latter case arises from the inability of present theory to account for disruption by the nearby aft strut of the wave train generated by the forward strut. From the viewpoint of the aft strut, when the two struts are in proximity, the incoming flow does not correspond to the initially-calm water surface assumed by drag prediction theories.

To summarize the present state-of-the-art in this particular area, the drag characteristics of single strut SWATH forms are generally

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[19]Chapman, R.B., "Drag Measurements on Models of SWATH Ships and Basic SWATH Components," Naval Undersea Center TN 984 (Apr 1973).

better and their hulls easier to design. In addition, their drag can
be predicted with more confidence than for complex tandem-strut forms.

Parameters that Affect the Drag of
Single Strut Forms

A framework can be provided for the discussion which follows by
explaining at the outset that SWATH ships appear to have two distinct
Froude number regimes characterized by differing sensitivity of C_R
values to various parameters. The approximate dividing point occurs at
a speed-length ratio of 1.20, which is equivalent to 0.36 for the
Froude number. The following conclusions have been drawn:

· Below $V/\sqrt{L}$ = 1.20 knots/ft$^{1/2}$ the bluntness of the strut bow
and stern is important, even if the maximum strut thickness stays
the same and only the fullness (waterplane area coefficient) is increased.
This sensitivity was demonstrated in drag tests* at NSRDC on "SWATH
V," a demihull on which two different struts were tried out. Both
struts had a maximum thickness-to-diameter ratio of 0.331 but the
waterplane area coefficient values were 0.518 for one and 0.706 for the
other. As may be seen in Figure 9, at a speed such that $V/\sqrt{L}$ =
1.04 knots/ft$^{1/2}$, the measured value for the residuary resistance
coefficient (C_R) of the fuller strut was slightly more than double that
for the fine strut. In the speed regime above $V/\sqrt{L}$ = 1.20 knots/ft$^{1/2}$,
on the other hand, the peak C_R value for the fuller strut was only
10 percent higher than for the fine one.

· Another way of decreasing wavemaking drag peaks below $V/\sqrt{L}$
= 1.20 knots/ft$^{1/2}$ is to increase the design draft (T). This is borne
out by some other drag measurements on the SWATH V model, as summarized
in Figure 10. Despite greater wetted surface area (and displacement)
at deeper drafts, the total effective horsepower (ehp) from the
combined effects of frictional and wavemaking drag was found to decrease
at values up to 1.20 knots/ft$^{1/2}$ for the speed-length ratio, Table 3
compares measured ehp requirements at various drafts and speed-length
ratios for the SWATH V model scaled up to a length of 260 ft.

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*Reported informally in NSRDC Technical Note 396-H-12 (Sep 1973).
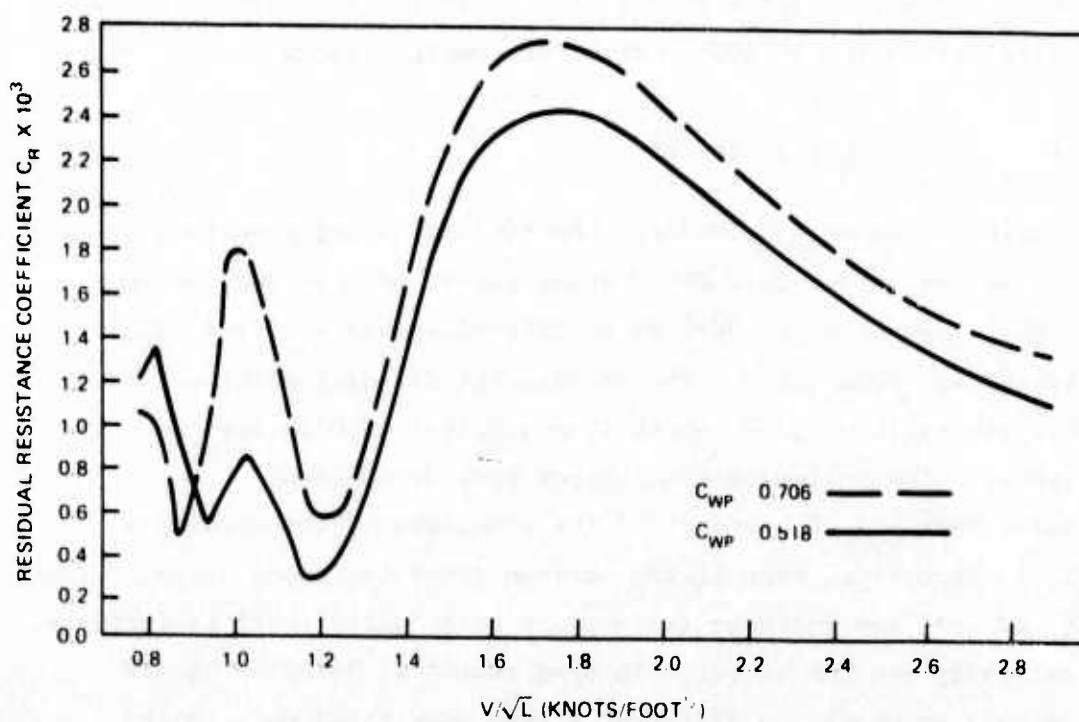
Figure 9 -- Effect of Increased Strut Fullness on the Residuary
Resistance Coefficient of the SWATH V Demihull
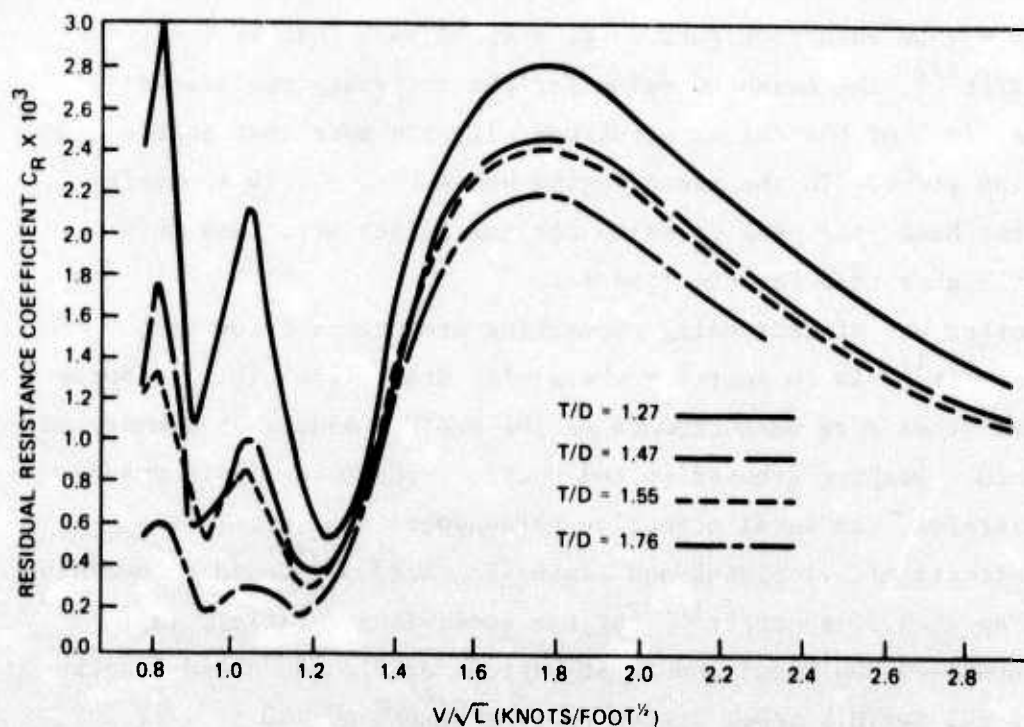
Figure 10 -- Comparison of Residuary Resistance Coefficients
at Four Draft-to-Diameter Ratios for SWATH V as
Predicted by Model 5301

TABLE 3 -- EFFECT OF DRAFT ON THE MEASURED FULL-SCALE
EFFECTIVE HORSEPOWER FOR THE SWATH V MODEL

(Ratio is given as knots/ft$^{1/2}$)

Demihull Displacement, Tons	2,051	2,128	2,161	2,244
Draft-to-Dia. Ratio, T/D	1.27	1.47	1.55	1.76
Speed-Length Ratio	ehp	ehp	ehp	ehp
0.835	1,585	1,335	1,235	1,050
0.90	1,540	1,350	1,340	1,240
0.965	1,655	1,440	1,440	1,350
1.03	2,280	1,500	1,890	1,690
1.09	2,840	2,335	2,250	2,040
1.16	2,725	2,485	2,415	2,350
1.22	2,700	2,580	2,595	2,665
1.285	2,945	3,060	3,190	3,325
1.35	3,735	3,900	4,090	4,330
1.415	5,170	5,270	5,445	5,700
1.54	8,465	8,490	8,800	9,170
1.67	11,730	11,990	12,285	12,810

By the same token, it is also evident at speeds above this point
that ehp increased at deeper drafts. Faced with these conflicting
trends, a tradeoff must be made on the basis of the most important
speed-length ratios for a particular ship size and mission requirement.
Minimizing draft is desirable for high-performance SWATH combatants
that displace 2000 to 5000 tons. The main constraint on draft was
found to be the occurrence of "air drawing" into the propellers with
the ship operating in a seaway.* For the model of a 4000-ton ship
that was tested, avoidance of this phenomenon required a strut immersed
depth of no less than 65 percent of the hull diameter, i.e., a draft-
to-diameter ratio of 1.65.

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*Reported informally in NSRDC Evaluation Report 396-H-08.

• A third influence on wavemaking drag in the low speed regime, particularly for $V/\sqrt{L} = 0.85$ knots/ft$^{1/2}$ is the amount of strut setback (distance from the nose of the lower hull to the leading edge of the strut); see Figure 11. This effect is analogous to that of bulbous bows on conventional displacement ships. Preliminary analytic drag predictions have been carried out over a range of speeds for conceptual SWATH ships from 3000 to 15,000 tons displacement with various strut setbacks. Although it is difficult to generalize these findings, they do point out the need to include strut setback in future parametric powering optimization studies. The amount of setback should also be held constant when examining the sensitivity of drag to another parameter.

• Still another factor that is most important in the low-speed regime ($V/\sqrt{L}$ from 0.95 to 1.15 knots/ft$^{1/2}$) but is also felt at higher speeds is the difference in wavemaking drag humps and hollows between SWATH forms with equivalent circular and elliptical lower hulls of equal length and displacement. Although this sensitivity has yet to be tested by drag measurements on appropriately configured models, it is reasonable that such would be the case because the wave trains generated by elliptical and circular lower hulls would be different.

• In the high-speed regime, on the other hand, a substantial decrease in the amplitude of the last C_R "hump" for a particular SWATH design can only be achieved by making the lower hulls more slender, as expressed by the length-to-diameter ratio. Figure 12 is a comparison of predicted C_R curves for three single-strut demihulls with different L/D ratios but identical strut size, shape, and immersion. The lower hull lengths, strut lengths, and strut setback were also kept equal. The effect on C_R magnitudes of increasing the L/D ratio (achieved by decreasing the hull diameter) may be seen to override any drag penalty arising from accompanying increases in the strut thickness-to-diameter ratio. There is also a less pronounced beneficial effect on low-speed C_R values.

Of course, the high L/D forms in this example had less displacement because they had smaller diameters. The issue of whether they
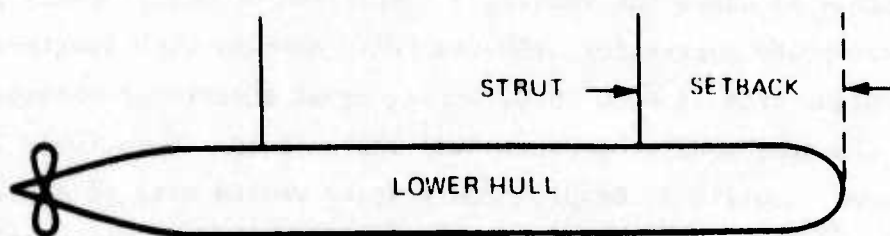
Figure 11 -- Definition of Strut Setback
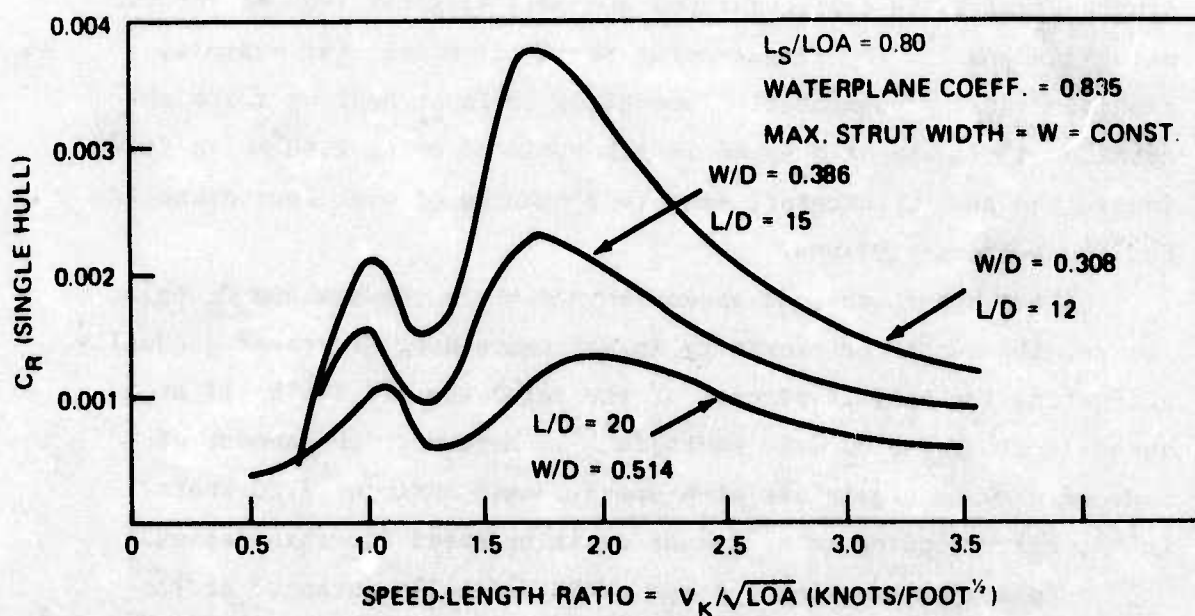
Figure 12 -- Sensitivity of C_R to Length/Diameter Ratio for
Constant Strut Size and Immersion

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would still be better if their dimensions were increased such that the displacements of the three models were equal was resolved in a separate study. Figure 13 shows the result, a comparison of analytically predicted speed-power curves for 5500-ton SWATH designs with length-to-diameter ratios from 15.9 to 19.0, having equal amounts of waterplane area, and the same spacing between hull centerlines. (See Table 2 for design particulars.) Despite the greater wetted area of slender hulls compared with shorter, more blunt SWATH forms of equal displacement, the former usually require less power at speed-length values of 1.20 knots/ft$^{1/2}$ or more. Below this point, however, a more slender SWATH ship would incur a frictional drag penalty that may or may not be significant, depending on its size and the cruising speed required for its mission.

· Induced residuary drag resulting from displacement of the flow between two hulls in relatively close proximity is substantial for single-strut SWATH configurations and only slightly less so for twin-strut designs.[19] The single-strut SWATH III model, for example, experienced drag augmentation amounting to 25 percent of twice the total demihull ehp at a speed-length ratio of about 1.60 knots/ft$^{1/2}$ (where the peak C_R occurs), despite a spacing of over four diameters between hull centerlines.

On the other hand, at speeds beyond where the maximum C_R value occurs, the amount of proximity interference drag decreased gradually, accounting for only 12 percent of the total ehp for SWATH III at a speed-length ratio of 2.20 knots/ft$^{1/2}$. Moreover, the amount of induced drag is negligible at a speed-length ratio of 1.20 knots/ft$^{1/2}$, corresponding to a 20-knot cruising speed for this design.

· Cambering two single-strut SWATH demihulls outboard at the fore and aft ends has been shown by the SWATH IV model tests to be ineffective in decreasing the amount of viscous proximity interference drag at high speeds. Consequently, this approach is no longer being considered even though camber is somewhat beneficial at speed-length ratio values of 1.20 knots/ft$^{1/2}$ or below.
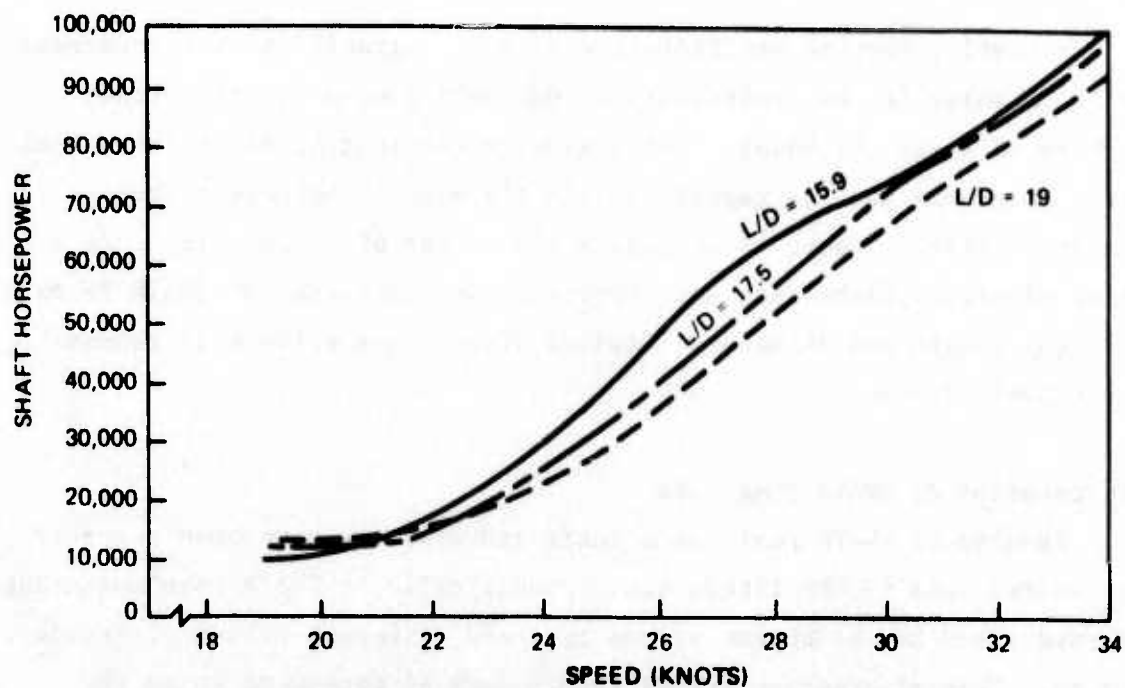
Figure 13 -- Effect of Length-to-Diameter Ratio on Powering
Requirements for Comparable 5500-Ton SWATH Ships
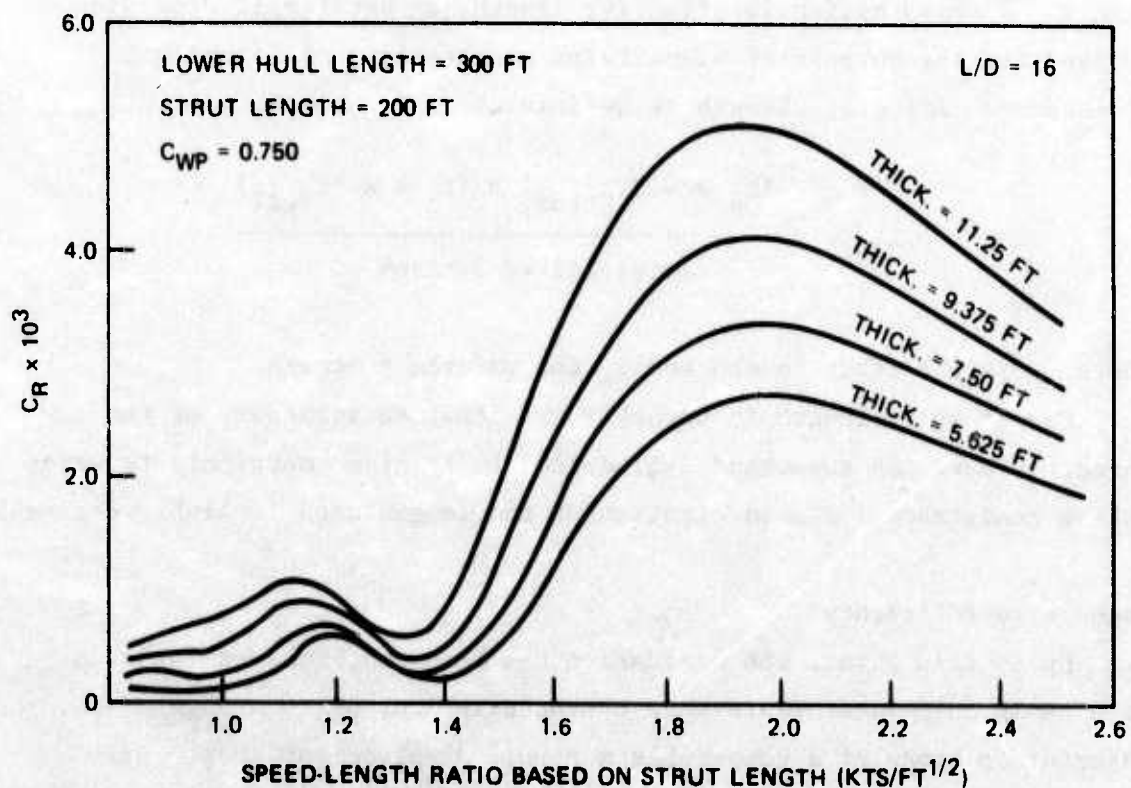
Figure 14 -- Effect of Strut Thickness on the Residuary
Resistance Coefficient of a Single-Strut SWATH of
18.75-Foot Diameter

· Lastly, another manifestation of the desirability of slenderness in SWATH ships is the sensitivity of wavemaking drag at high Froude numbers to strut thickness. For a given strut length, it is the actual strut thickness that is important, not the strut thickness-to-hull diameter ratio. Figure 14 indicates the extent of sensitivity over a range of strut thicknesses for representative single-strut SWATH forms of equal length and diameter. Similar effects are evident in tandem-strut SWATH forms.

Presentation of SWATH Drag Data

Results of SWATH resistance tests and analyses have been reported in various ways in the literature. Specifically, a SWATH form operating at some speed may be characterized by three different values of Froude number. This discrepancy arises from a lack of agreement as to the characteristic length of a SWATH hull.

Two possibilities are obvious: strut length and submerged body length. A third option is effective length, an artificial dimension derived for the purpose of simplifying computations of frictional resistance. Effective length is defined as

$$L_{eff.} = \frac{(L_s \times W.S._{Strut}) \times (L_h \times W.S._{Hull})}{\text{Total Wetted Surface}}$$

where L_s is the strut length and L_h the underbody length.

Use of strut length is probably the least satisfactory of the three, because the submerged cylindrical hulls also contribute to wave-making resistance. Standardization of the length used is highly desirable.

Propulsive Efficiency

Up to this point, the discussion has been concerned exclusively with SWATH calm-water resistance characteristics, which are generally inferior to those of a comparable monohull displacement ship. With

few exceptions, the drag characteristics of a SWATH ship will be fully competitive only at or above the maximum economical design speed for an equal-displacement monohull. The SWATH wavemaking resistance "barrier" is displaced or less pronounced relative to that for a monohull. Usually, a SWATH ship encounters the C_R peak at a lower Froude number because a SWATH ship will be about 25 percent shorter than a comparable monohull, which makes the Froude number of the SWATH higher at each speed. In any case, SWATH ships will have higher drag at most speeds in calm water.

The second determinant of speed-power performance is the propulsive coefficient (P.C.) which must be determined from model tests and is defined as:

$$P.C. = \frac{\text{effective horsepower}}{\text{propeller horsepower}} = e_h \cdot e_{rr} \cdot e_p$$

where e_h = hull efficiency

e_{rr} = relative rotative efficiency

e_p = open-water propeller efficiency

Figure 15 is representative for a single-strut SWATH ship of the variation to be expected in P.C., and its component efficiencies, with the value of speed-length ratio. The P.C. of this SWATH model remained within the band from 0.69 to 0.79, reaching its maximum at a speed-length ratio of 1.05 knots/ft$^{1/2}$ and its minimum at $V/\sqrt{L}$ = 1.5 knots/ft$^{1/2}$. Most of the decrease in the value of P.C. was due to a decrease in open-water propeller efficiency at the latter point.

Although it is recognized that the relationship between the three component efficiencies is complex and largely unknown for SWATH ships, there is a potential for still higher propulsive coefficients. The more deeply submerged SWATH hulls, when combined with compact planetary reduction gears, may permit more efficient (larger, slower turning) propellers to be used. More important, favorable wake conditions
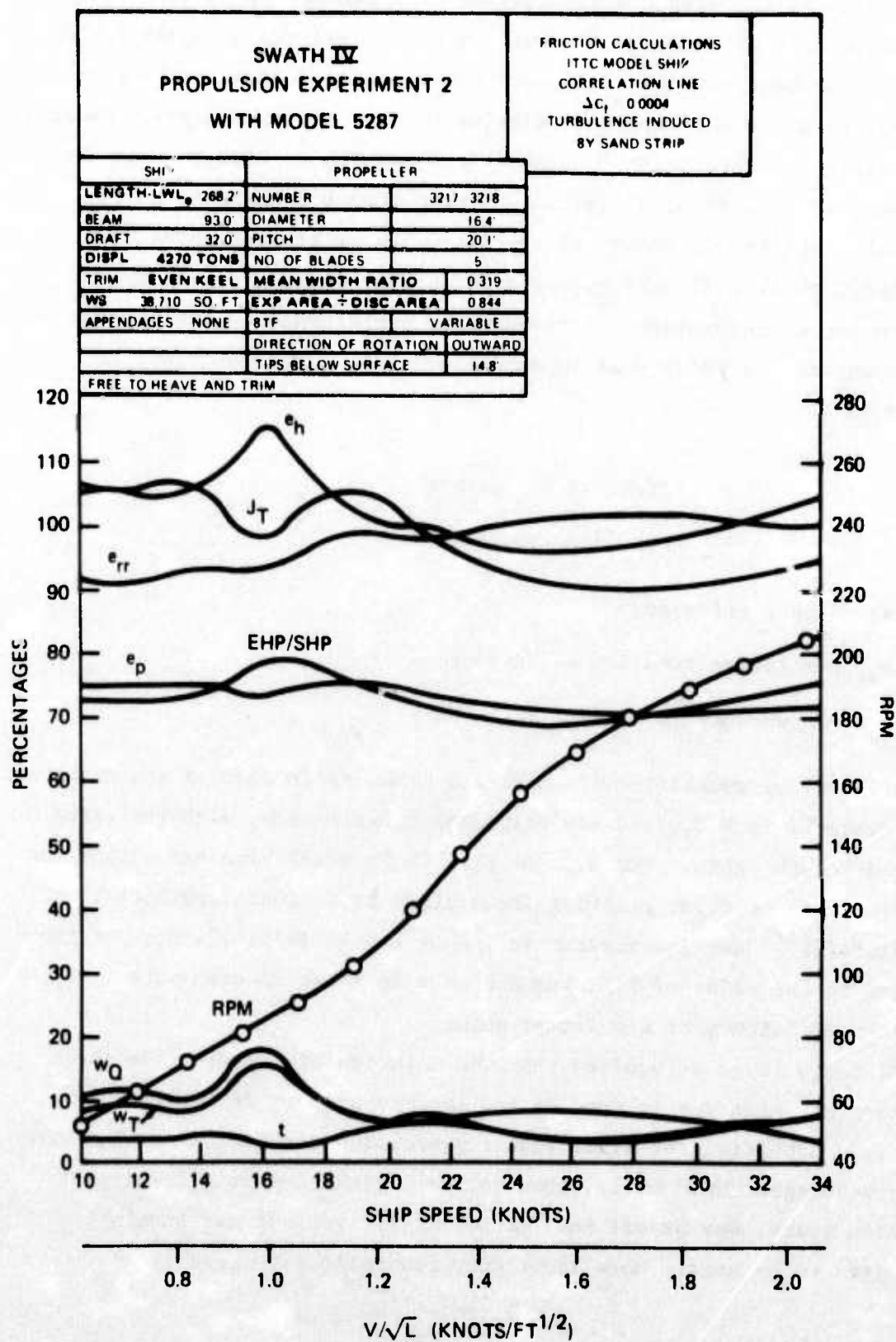
Figure 15 -- Measured Variation in Propulsive
Coefficient for a Single-Strut SWATH Ship
as a Function of Speed-Length Ratio

behind these cylindrical lower hulls will tend to produce higher hull and relative rotative efficiencies. Additional propulsion tests, particularly wake surveys, should make it possible to design SWATH ships which have their peak P.C. at the speeds of greatest operational importance, e.g., 20 knots and above.

Even as things now stand, it has been demonstrated that SWATH ships will have higher propulsive efficiency than a comparable monohull, especially a twin-screw monohull. Table 4 is a comparison of representative P.C. values at high speeds for single- and twin-screw monohulls and single screw-per-hull SWATH ships.

TABLE 4 -- COMPARATIVE PROPULSIVE EFFICIENCIES OF
SWATH AND MONOHULL SHIPS

(From Hawkins and Sarchin[18])

Monohull	SWATH
High speed-length ratio $(V/\sqrt{L} > 1.2 \text{ kts/ft}^{1/2})$ Twin or single screw	Single screw on each demihull
P.C. = 0.62-0.67	P.C. = 0.72-0.76

A unique attribute of SWATH ships is their high directional stability which makes it feasible to propel them at cruise speeds on one propeller with the other feathered; only a small rudder deflection is required to maintain heading. Despite a powering increase of 15 to 25 percent because of the additional drag of the feathered propellers, this mode of operation results in a net decrease in fuel consumption for SWATH ships with one large geared gas turbine in each hull. This apparent anomaly is caused by the poor fuel consumption characteristics of marinized aircraft gas turbines at low outputs. An alternative approach, and often a better means of increasing endurance, is to add two small cruise turbines, one driving each propeller.

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SHIP PERFORMANCE IN WAVES

To summarize the foregoing, comparison studies have revealed that
the maximum calm-water speeds of well-designed SWATH ships can be as
much as 2 knots slower than a comparable monohull for the same installed
power and that they also may possibly require 5 percent greater dis-
placement to provide equal range capability. This is in marked contrast
with the behavior in even modest waves where the same SWATH ship will be
capable of higher sustained speeds than its monohull counterpart.

The problem with conventional displacement ships is not that they
are power-limited in the face of added wave drag but that their large
motions and high accelerations force "voluntary" acts of slowing down or
changing course to ameliorate the situation. Whether precipitated by
excessive slamming or deck wetness, the speed is reduced in these cir-
cumstances to between one-half and two-thirds of calm-water speed,
depending on wave severity and ship size. The need to change course
will usually be brought on by excessive rolling or pitching. Figure 16
is a comparison of the analytically predicted maximum speed with acceptable
bow bottom slamming for U.S. and Soviet destroyers in rough head seas.
The criterion used was that no ship should experience more than one slam
per minute.

Even short of the point at which a conventional ship will voluntarily
slow down, it will experience loss of speed (or increased power will be
required to maintain a given speed) due to a combination of factors:
(1) increased drag from ship motion and wave interaction and excessive
rudder activation for control and (2) decreased propulsive efficiency
because air drawing accompanies propeller emergence in rough seas. These
same factors, less evident because of reduced motions, are usually
responsible for the smaller speed loss a SWATH ship experiences in
moderate waves.

Exceptions occur when, relative to the cross-structure clearance
height, the waves encountered are sufficiently high to cause slams of
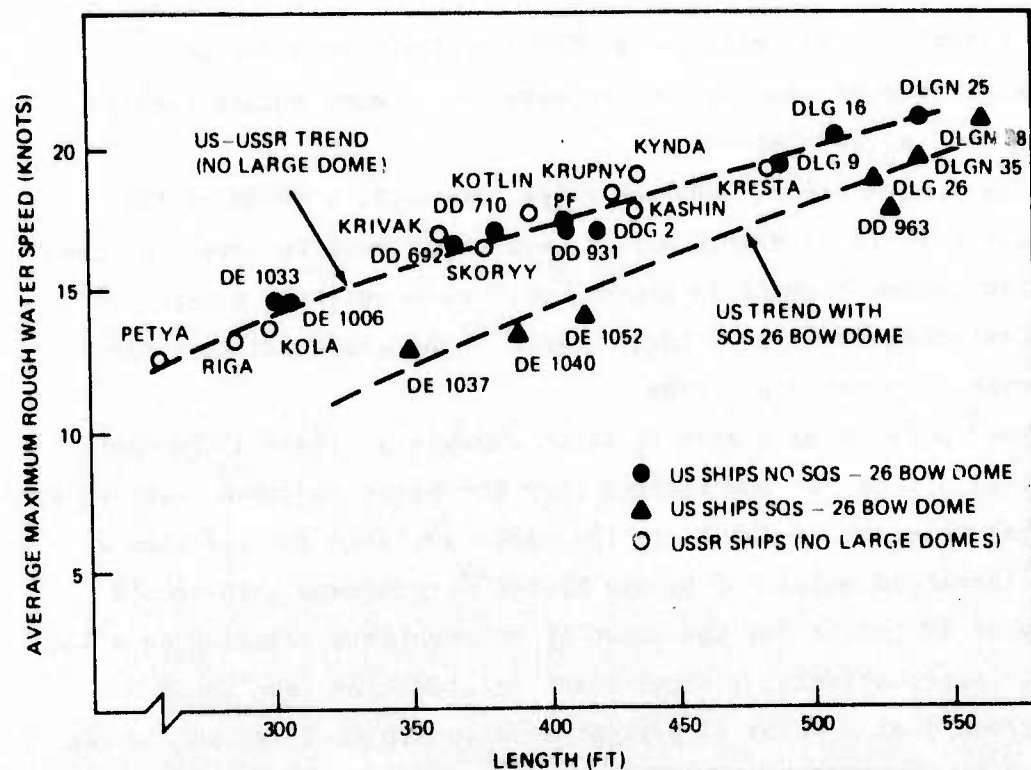
Figure 16 -- Comparison of Slam-Limited Speed in Head
Seas of U.S. and Soviet Destroyers

(From Kehoe[3])
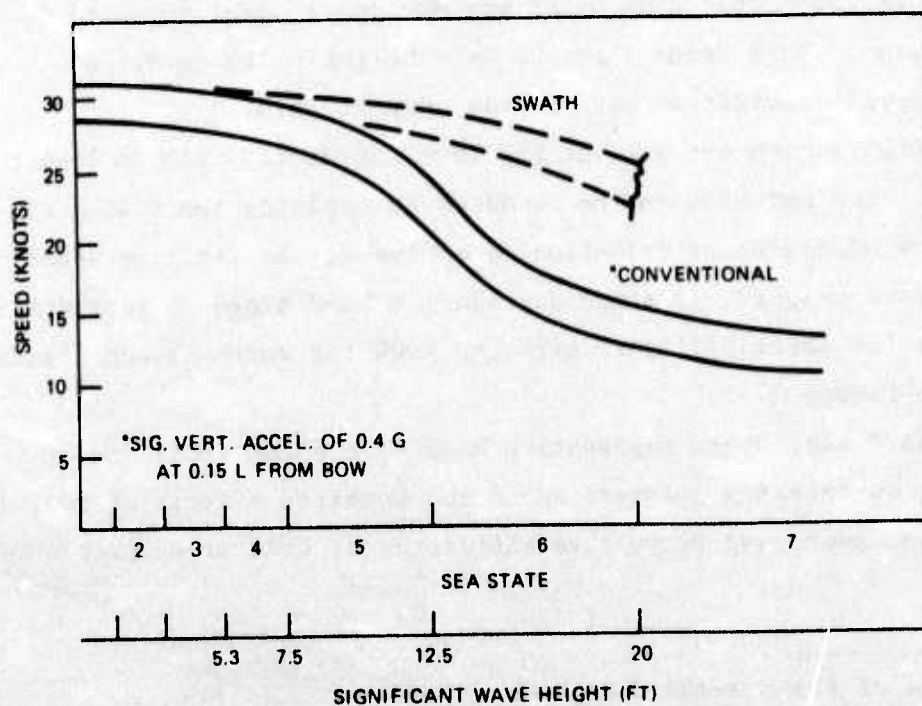
Figure 17 -- Typical Operating Speed Envelopes for
4000-Ton Ships in Head Seas

varying severity. For example, a 3000-ton SWATH in mid-State 7 (30-ft significant* wave height) or worse seas must substantially reduce speed, as do monohulls.

Unlike conventional 3000-ton ships, however, a SWATH of this size, with a 20-ft clearance height, would not need to have its power reduced or course changed in State 5 or 6 seas except, perhaps, at stern-quartering headings. Larger SWATH ships could maintain speed and course even in mid-State 7 seas.

Kehoe[3] defined as a slam an event wherein at least 15 percent of the keel aft of the bow emerges from the water and then reenters with a vertical velocity (relative to the water surface) greater than a certain threshold value. Ochi and Motter[20] recommend a threshold velocity of 12 ft/sec for the onset of unacceptable slamming on a 520-ft ship. Alternatively, a significant acceleration level of 0.4 g (12.9 ft/sec^2) at a point 15 percent of ship length from the bow was suggested for determining the ship speed above which the slam threshold velocity will be exceeded. Figure 16 is based on the Kehoe definition of rough head seas for each ship as that significant wave height, or sea state, in which that ship under maximum power first exceeded 60 slams per hour. This means that the wave height which causes a specified speed degradation varies from ship to ship.

This figure does not present the level of degradation in lesser sea states. The omission can be remedied by applying the 0.40 g significant bow acceleration criterion to arrive at the limiting speed for other wave heights. A speed degradation band based on acceleration predictions for three different existing 4000-ton monohull combatants is shown in Figure 17.

The SWATH ship speed degradation band also shown in Figure 17 is based on engineering judgment as to the combined effects of additional wave drag and decreased propulsive efficiency as well as on probable

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*Average of the one-third highest.

[20]Ochi, M.K. and L.E. Motter, "Prediction of Slamming Characteristics and Hull Responses for Ship Design," Trans. SNAME, Vol. 81 (1973).

voluntary slowdowns due to wave impacts on the cross structure in low
State 7 and higher seas. (Tests of the SWATH VI model showed that a
3000-ton SWATH would have only 0.30 g significant bow acceleration at
20 knots in head or bow seas with a significant wave height of
21.5 ft.*)

Even with zero vertical motion, a SWATH ship will have slams on
the underside and frontal areas of the cross structure in waves above
a certain amplitude, depending on the amount of clearance provided.
When scaled up to 3000 tons, the SWATH VI model had 20 ft of cross-
structure clearance. Nevertheless, it did not take a 40-ft wave height
(20-ft amplitude) to cause slamming. Impacts were experienced in
mid-State 7 seas characterized by a 30-ft significant wave height.
Statistics predict that the average of the 1/10 highest waves in this
sea would be about 38 ft. Moreover, because SWATH ships in such con-
ditions have peak-to-peak heave amplitudes on the order of 15 to
20 ft, cross-structure slamming can occur in less severe low State 7
seas, in which the average height of the 1/10 highest wave would be 28
to 30 ft. It is principally because of cross-structure slamming that
the speeds of a 3000-ton SWATH ship may have to be reduced to the same
extent as a monohull in State 7 head seas.

From the standpoint of operational planning, comparisons of speed
capabilities between conventional and SWATH ships should take this
discrepancy in seaway speed degradation into account. To do so requires
that the speed capability of each ship in seas of various wave heights
be weighted by the fraction of time that wave height will, on the average,
be found in the intended operating area. The net result can be termed
the average maximum expected sustained speed. Table 5 is a sample
calculation for North Atlantic head seas. For illustrative purposes,
a "worst case" is assumed in that the SWATH ship has a maximum calm-
water speed 2 knots lower than the monohull. Even so, its average
maximum sustained speed is higher.

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Report in preparation.

TABLE 5 -- SAMPLE COMPARISON OF EXPECTED YEARLY AVERAGE
SUSTAINED SPEED IN NORTH ATLANTIC HEAD SEAS

(Based on Figure 17)

Sea State	Av. Percent Occurrence	4000-Ton Monohull		4000-Ton SWATH	
		Max Speed	Product	Max Speed	Product
1 and 2	7.0	30.0	2.10	28.0	1.96
3	21.5	29.25	6.29	27.9	6.00
4	21.5	28.5	6.13	27.75	5.97
Low 5	20.0	26.5	5.30	27.6	5.52
High 5	11.5	24.5	2.82	27.3	3.14
Low 6	8.5	19.5	1.66	27.0	2.30
High 6	5.7	14.5	0.82	26.0	1.48
7	4.3	13.0	0.56	20.0	0.86
Total	100.0	Av Speed	25.7	Av Speed	27.2
Ratio		$\dfrac{\text{Av Speed}}{\text{Max Speed}} = 0.855$		$\dfrac{\text{Av Speed}}{\text{Max Speed}} = 0.97$	

Scope of Completed Seakeeping Tests
on SWATH Models

Reference was made previously in this report to some results of
seakeeping tests on the SWATH VI model, which was described as representing
a configuration being considered for a 3000-ton SWATH ship. Prior to
discussing SWATH ship motion characteristics in greater depth, it seems
prudent to summarize what model test evidence did exist at the close of
FY75 that provides the basis for the conclusions to be drawn. Table 6
was prepared as a concise, comprehensive list of all SWATH model sea-
keeping tests completed to date by the Navy.

For reasons which will soon be elaborated on, the series of tests
of the self-propelled SWATH VI model, with three different strut con-
figurations, provides the best foundation for making general statements
about the motions of SWATH ships in various wave conditions. Test
results for all other SWATH models must be qualified or even discounted
to some extent. Unfortunately, only preliminary data from the SWATH VI
test are now available (in unpublished form).

TABLE 6 -- SWATH MODELS FOR WHICH MOTION CHARACTERISTICS HAVE
BEEN DETERMINED BY TESTING

Designation	Model Numbers	Displ. L. Tons	x-Struct. Included	Control Surfaces Included	Speed Knots	Headings Deg	Type of Waves
SWATH I	NSRDC 5226	23,500	No	No	0, 22, 27	180	Reg.
SWATH II	NSRDC 5266	101,000	No	No	0, 15, 30	180, 135 90, 45, 0	Reg. and Irreg.
SWATH IV	NSRDC 5287	4,000	Yes	Yes and No	0, 10, 20 32	180, 90 45, 0	Reg. and Irreg.
SWATH VI A-C*	NSRDC 5337	3,000	Yes	Yes	0, 20, 28	180, 135 90, 45, 0	Reg. and Irreg.
SSP	NUC-RC 1	150			0, 10, 15 20, 25	180, 135 90, 45, 0	Reg.
SSP	NUC-5' R/C**	190	⟶	⟶	0, 10, 20	180, 135 90, 45, 0	Reg. and Irreg
7'-R/C A and B*	NUC-RC 2	3,000	⟶ Yes	⟶ Yes	0	90	Reg.
Segmented	NSRDC-Struct.	3,050	Yes	Yes	0	180, 135 90	Reg. and Irreg.

*Single- and tandem-strut versions.
**Tested at NSRDC.

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The SWATH I model, with a single strut per hull, was the first configuration built at DTNSRDC. Funded as part of an investigation of small attack carriers, it was tested only in regular head waves and did not have any control surfaces or a cross structure (two steel beams connected the hulls). A third serious deficiency was that this model was tested at too shallow a draft; the draft-to-diameter ratio of only 1.30 was not satisfactory from a propulsion standpoint.

The SWATH II model is unique both for the elliptical cross section and ducktail stern of its lower hulls and for the size ship it represents-- 101,000 tons. To be more useful, these results have to be scaled down to the smaller sizes now being investigated, and that entails considerable cost. Moreover, scaled SWATH II motions must be interpreted with caution because the model was tested without a cross structure and so slamming did not occur. Another complication caused by the design full-scale size is that the maximum Froude number utilized was fairly low; thus pitch instability was not reached although the model had no control surfaces. A smaller version of SWATH II could require the addition of control surfaces and it would then have different motion behavior.

FY74 tests of the SWATH IV model (also single strut) were comprehensive and included a substantial part of the matrix defined by four speeds, four headings, and three drafts for the basic hull as well as for the hull with various appendages. Trends can be deduced from these results, but the motion amplitudes were probably distorted by the change in cross-structure clearance that accompanied a change in model draft. As the draft corresponding to a nominal displacement of 4000 tons was increased from 28 to 32 ft, the cross-structure clearance was reduced from 19 to 15 ft. The difference in motion responses at the two drafts was affected to an unknown extent by the much more prevalent wave impacts accompanying the 15-ft clearance, which was clearly insufficient for State 6 seas.

Results from seakeeping tests of the two radio-controlled models
of similar small, tandem-strut SWATH craft appear to be valid but of
limited applicability. Because of their resistance characteristics,
neither configuration would be chosen for a SWATH ship displacing
2000 tons or more.

NUC tested their 7-ft model of a different 3000-ton SWATH design
at 0 speed in regular beam waves to measure differences in roll,
transverse bending moment, and side load between single-strut and
tandem-strut SWATH ships of the same length and hull spacing. However,
the general meaning of these differences must be assessed in the light
of the fact that the single-strut configuration had about 50 percent
greater waterplane area than the tandem-strut configuration.

DTNSRDC used a segmented model to measure the magnitude and distri-
bution of maximum wave-induced loads on a single-strut SWATH in simu-
lated seas up to State 8 at several headings, but only for the stationary
condition. Although useful, these data are not amenable for ex-
trapolation to predict motions and loads at various speeds.

SWATH VI was a self-propelled model representing a 3000-ton
developmental/oceanographic research ship with a cross-structure
clearance of 20 ft. Comprehensive motion measurements were made at a
range of speeds for principal and oblique headings in regular waves
as well as simulated extreme sea conditions (low State 7: 22-ft sig-
nificant wave height). Three different strut configurations were tried
out with the same lower hull to determine the desirability of greater
pitch stiffness. Two were single-strut configurations and the third
was a tandem strut. The latter had approximately the same pitch
stiffness as the longer of the two single-strut designs to enable a
comparison of the importance of strut configuration versus similar
dynamic characteristics. All three versions of SWATH VI were equipped
with fixed horizontal fins of appropriate sizes forward and aft to
decrease their peak relative bow motion responses to approximately
equal levels. A report on these results is now in preparation.

Relation of Bare-Hull Motions to
Static/Dynamic Stability

The character of the vertical motions (heave, pitch, roll) of a
SWATH ship without submerged horizontal appendages is that of under-
damped forced periodic oscillations excited by the waves it encounters.
The response of a ship to a particular wave depends on the mass,
restoring force (stiffness), and damping of the ship, but the most
important factors are the magnitude and phasing of the wave excitation
force. The latter two factors, in turn, vary with the amplitude, length,
and period of the wave encountered. The accompanying accelerations are
a function of response amplitude times the square of the frequency
with which motions occur.

The natural motion frequencies of a ship are a function of the
ratio of its heave, pitch, and roll stiffness to its inertial mass.
The smaller the stiffness relative to a given amount of inertia, the
lower the natural frequency and, correspondingly, the longer its
natural period.* If the heave, pitch, and roll natural frequencies
could be made substantially lower than the frequency of any wave likely
to be encountered at sea, then there would be little motion excitation
of a stationary ship by waves. But, in practice, such complete
detuning of SWATH ship response cannot be achieved because requirements
of static stability do not permit reducing waterplane area and inertia
to the extent necessary.

The motion stiffness of a ship is a function of its hydrostatic
restoring force and moments; these depend on the distribution as well
as amount of waterplane (horizontal cross section) area in relation to
ship mass and draft. The magnitude of wave exciting force also depends
on the same elements of ship geometry. The potential for improved sea-
keeping with a SWATH ship arises from its relatively small waterplane
area and inertia.

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*$T = 2\pi/\omega$ where T is the period and ω the frequency.

Available documentation for the lesser wave excitation forces on SWATH ships[21] compares predicted wave forces based on strip theory for nominal 750-ton monohull and SWATH craft at zero speed in regular head waves. Figure 18 compares their heave excitation forces versus wave length, and Figure 19 compares their pitch excitation. The SWATH ship has no more than 1/4 the heave excitation and, generally, from 1/10 to 1/15 of the pitch exciting forces.

Because the excitation force and moment generated on a SWATH ship by a particular wave is relatively small, substantial motion will result only when the wave force is applied periodically at a frequency close to one of the ship natural frequencies, and with the proper phasing. However, the hydrostatic restoring forces generated as a SWATH ship moves up and down are also small compared with values for conventional ships. This suggests that although only relatively large waves will have sufficient energy to excite heave and pitch motions, once a SWATH ship without appendages is excited, its motions may be comparatively large.

It follows that undesirable motions will sometimes occur. What the naval architect should infer from this is that substantially reduced waterplane area (and inertia) is a necessary, but not a sufficient, requirement for ensuring that a SWATH ship design will have superior seakeeping. He must be concerned not only with minimizing the likelihood of motion excitation but also with increasing the damping of various motions in those relatively rare combinations of ship heading, speed, and wave length where substantial response is excited. A disadvantage of the SWATH configuration from the latter standpoint is that the amount of wavemaking damping is less than for monohull displacement ships.

Nevertheless, there is a crucial qualitative difference in the motions of SWATH ships and monohulls: a SWATH ship moves much more

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[21]Baitis, E. et al., "A Seakeeping Comparison between Three Monohulls, Two SWATH's, and a Column-Stabilized Catamaran Designed for the Same Mission," NSRDC Evaluation Report SPD-622-01 (Apr 1975).
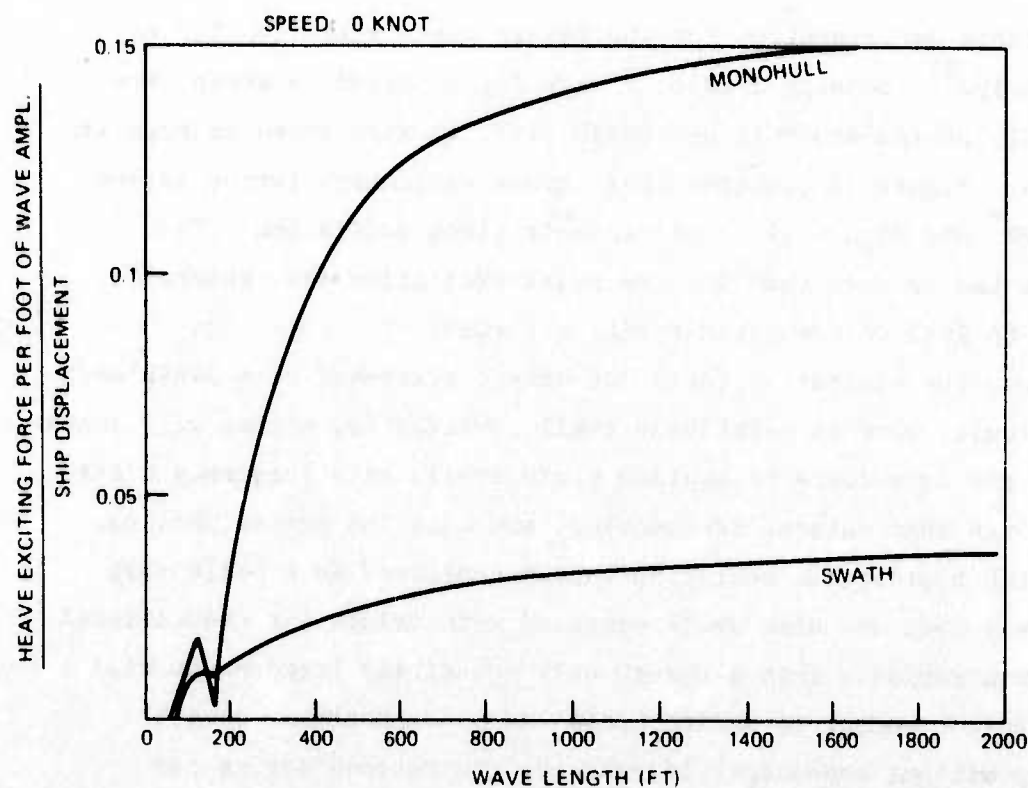
Figure 18 -- Wave-Exciting Heave Force as a Function of
Wave Length for Conventional and SWATH Craft at
Zero Speed in Head Waves

(From Baitis et al.[21])
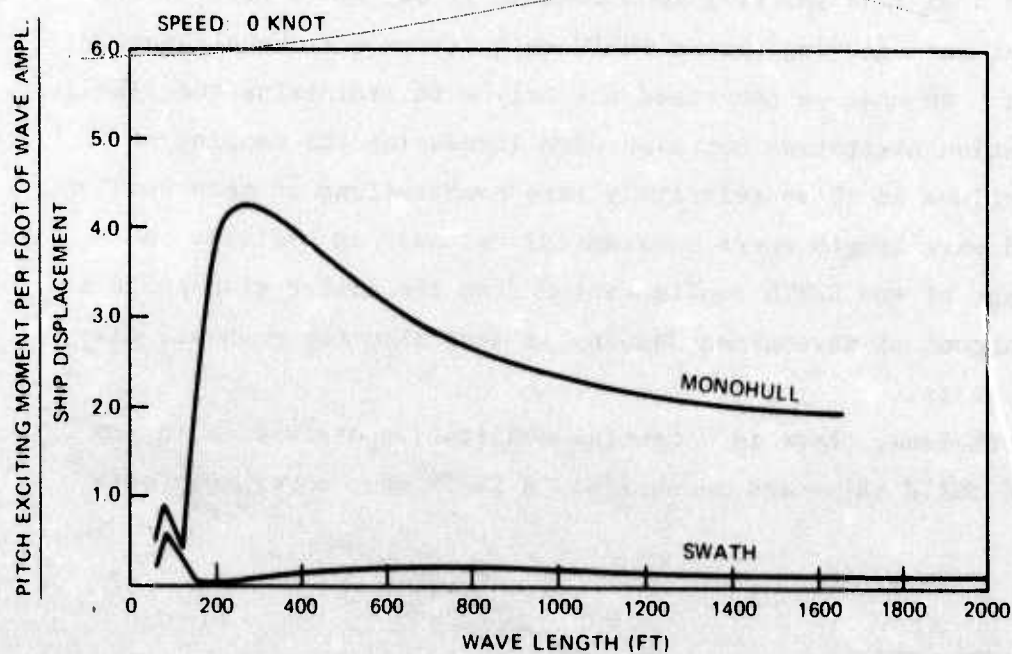
Figure 19 -- Wave-Exciting Pitch Moment as a Function of
Wave Length for Conventional and SWATH Craft at Zero
Speed in Head Waves

TABLE 7 -- PRINCIPAL CHARACTERISTICS OF
THE CANDIDATE WORKBOATS FOR THE
PACIFIC MISSILE RANGE

Parameters	Monohull	SWATH
Length, ft	200	155
Beam, ft	8.25	49.5
Draft, ft	9.35	16.5
Clearance, ft		12.0
Freeboard, ft	17.65	
Displacement, tons	741	785
Design Speed, knots	20	15
Waterplane Area, ft	4404	1166
GM_L	-	20.0
GM_T	4.0	4.0
T_H	4.8	6.6
T_R	6.8	19.5
T_P	7.7	12.5

slowly. The cause is the disparity in their motion response stiffness; a conventional destroyer is about five times stiffer than a SWATH in heave and about 10 times stiffer in pitch. Consequently, the monohull has a natural heave period about one-half that of the SWATH, and a pitch period about one-third as long. The fact that shorter periods result in higher velocities and accelerations suggests monohulls would benefit from decreased heave and pitch stiffness; it is unfortunate that little progress is possible in this direction. Heave stiffness is proportional to the amount of waterplane area; this area cannot be reduced much on monohulls because it is the sole source of transverse inertia needed for roll stability. The pitch stiffness of a conventional ship results from the fact that its large waterplane area is distributed over the greatest length possible in order to minimize wavemaking resistance. The resulting longitudinal waterplane inertia is excessive.

Besides increasing the likelihood of heave and pitch excitation, greater waterplane area causes larger exciting and restoring forces, both of which make the pitch and heave motions of monohulls exceedingly difficult to dampen or control.

Easily Controllable SWATH Ship Motions

By the same token and precisely because the forces involved are smaller, there exists a genuine potential for controlling the slower SWATH motions. To counteract forces that cause ship motions, an opposing force of comparable magnitude must be applied to the hull. The requisite pitch control forces are prohibitively large for conventional ships, but they can be generated for SWATH by submerged hydrofoils of reasonable size provided the ship is moving at moderate speed. This was the conclusion drawn by Lee and Martin[22] on the basis of a numerical example for a 2000-ton SWATH ship. Effective control of the stiffer heave motions was judged to require considerably larger fins.

A rule of thumb for evaluating the seakeeping behavior of any ship is that the motion mode with least damping is the critical one.

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[22]Lee, C. and M. Martin, "Determination of Size of Stabilizing Fins for Small Waterplane Area, Twin-Hull Ships," NSRDC Report 4495 (Nov 1974).

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It may be seen from Figure 20 that the typical struts and circular submerged hulls of destroyer-size SWATH ships provide very little damping, particularly for heave motions. The ordinate is termed the damping ratio. Critical damping is that value at which motion is not vibratory but rather a vertical displacement followed by a slow return to equilbrium. Assuming a single degree-of-freedom system, the critical damping in heave is

$$B_c = 2 (M + A_{33}) \omega_{OH}$$

where M   is the ship mass,

A_{33} is the heave added mass, and

ω_{OH} is the undamped natural frequency for the heave mode.

An equation for the damping ratio of uncoupled heave motion, employing coefficients of the equations of motion, was derived in Lee and Martin[22] as

$$\zeta_{h0} = \frac{B_{33}}{2} [(M + A_{33}) C_{33}]^{-1/2}$$

where the heave damping coefficient B_{33}, the heave added mass A_{33}, and the heave restoring force coefficient C_{33} are defined by equations given in their report.

Figure 21 illustrates the marked increase in the heave damping ratio computed for higher speeds of the SWATH IV model which has relatively small, fixed stern fins. The entire increase is due to greater lift from the fins. Damping of the hull itself was only 2 percent of critical.

Similarly, the equation for the damping ratio for uncoupled pitch motion was expressed in the form

$$\zeta_{p0} = \frac{B_{55}}{2} [(I_5 + A_{55}) C_{55}]^{-1/2}$$
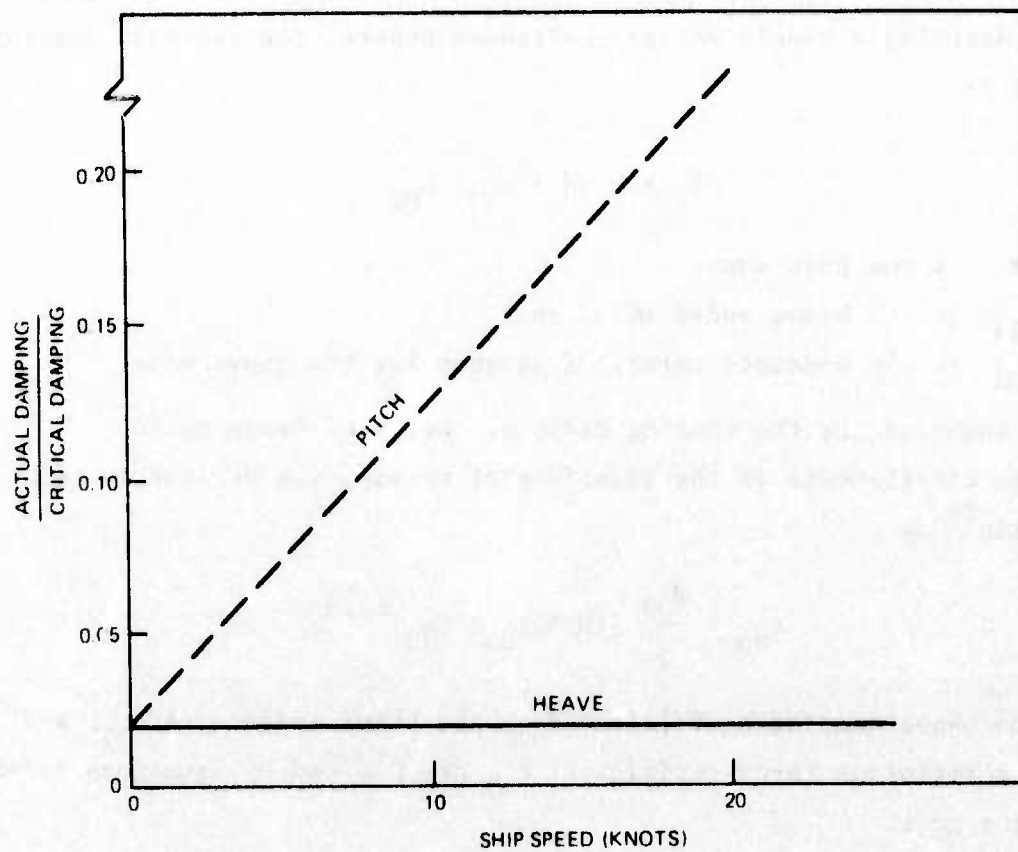
Figure 20 -- Effect of Speed on the Bare-Hull Heave
and Pitch Damping of the SWATH IV Configuration
(From Lee and Martin[22])

Figure 21 -- Predicted Effect of Speed on the Heave
Damping Ratio of SWATH IV with and without Passive
Stern Fins Located Inboard on Each Hull

(From Lee and Martin[22])

Here the pitch damping coefficient B_{55}, the coefficient of added inertia of the bare hull A_{55}, and the pitch restoring moment coefficient C_{55} are defined by equations given by Lee and Martin.[22] I_5 is the ship mass moment of longitudinal inertia about the y axis.

Figure 22 shows that damping of the bare hull is more significant for pitch, being approximately equal in magnitude to that of the fins. (Recent unpublished motion measurements on the SWATH VI model demonstrated that passive fins provide even greater damping than this prediction shows.) The larger damping ratio in pitch is mostly a consequence of the fact that the natural pitch frequency for SWATH IV is 60 percent lower than the heave frequency. This follows because the critical damping value is inversely proportional to natural frequency. Another SWATH ship of equal tonnage but stiffer pitch, i.e., higher natural frequency, would have a lower damping ratio for the same size fins and lever arm.

If both the heave and pitch modes have low damping ratios, then curves that show vertical motion response as a function of wave encounter frequency will have two resonant peaks occurring at the natural frequencies for the heave and pitch modes. One qualification is that the resonant frequencies must be reasonably well separated. When they are close together and the damping is low, a single sharper resonance peak is possible. The ratio of wave encounter frequency to a natural frequency is called the tuning factor (Λ).

The effectiveness of fixed stern fins alone in decreasing both heave and pitch motion amplitudes was demonstrated at DTNSRDC by testing the SWATH IV model in waves with and without these fins. Figure 23 indicates the resulting motion responses in regular head waves obtained by Kallio and Ricci.[23] Compared to magnitudes for the bare hull, stern fins decreased the pitching of SWATH IV by over 50 percent and heave motion about 20 percent at 20 knots; at 32 knots, the measured peak heave motion was about one-third less.

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[23]Kallio, J. and J. Ricci, "Seaworthiness Characteristics of a Small Waterplane-Area, Twin-Hull Ship (SWATH IV), Part I," NSRDC Evaluation Report SPD-620-01 (Mar 1975).
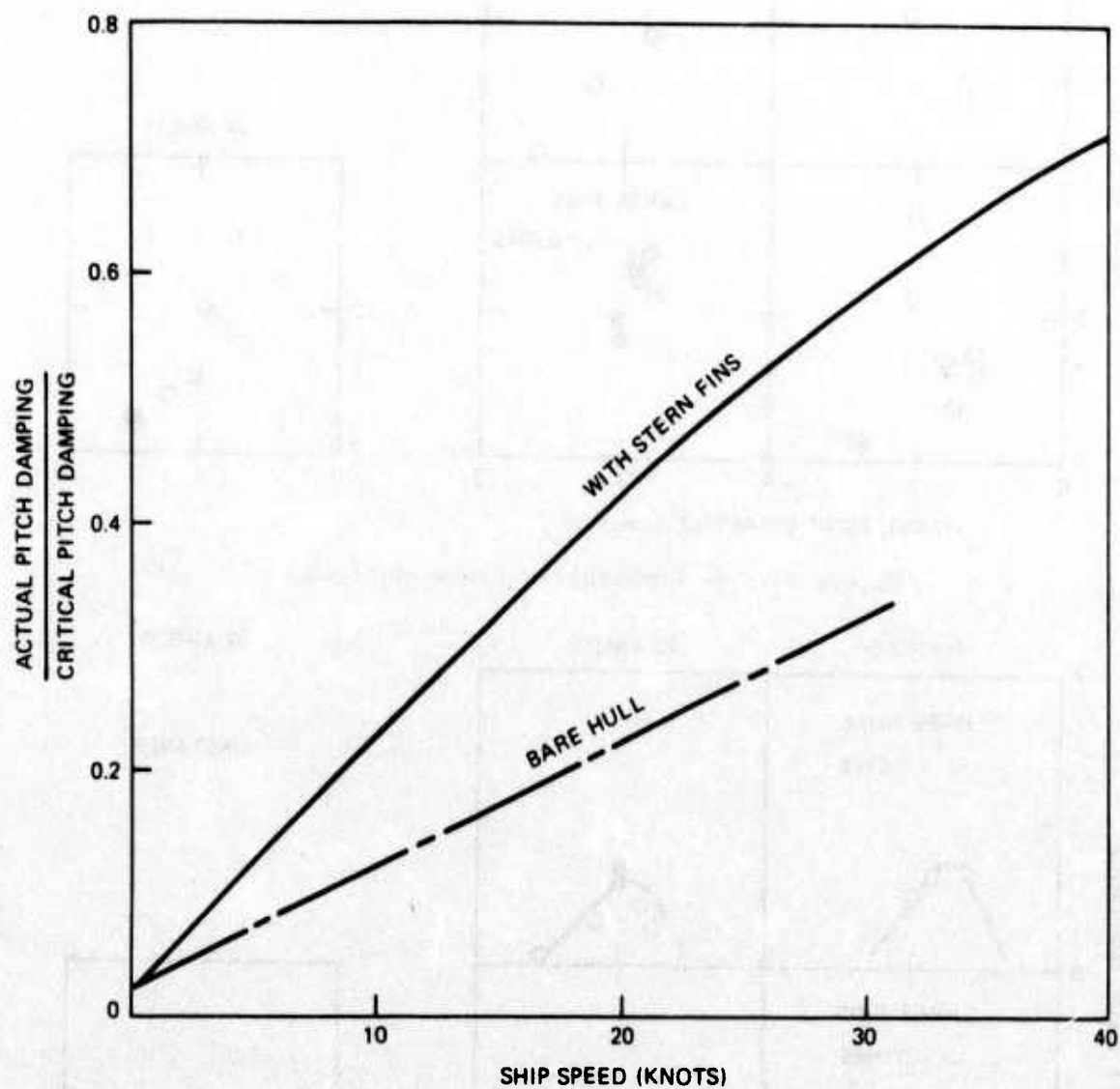
Figure 22 -- Predicted Effect of Speed on the Pitch
Damping Ratio of SWATH IV with and without Passive
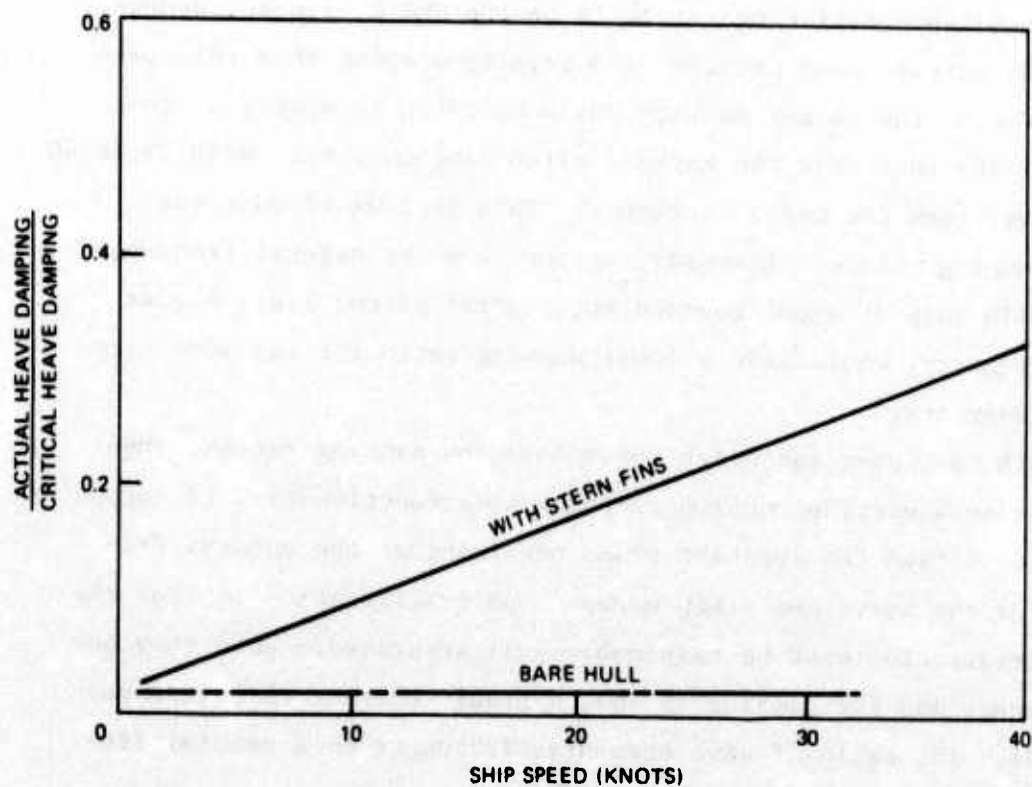Stern Fins Located Inboard on Each Hull

(From Lee and Martin[22])
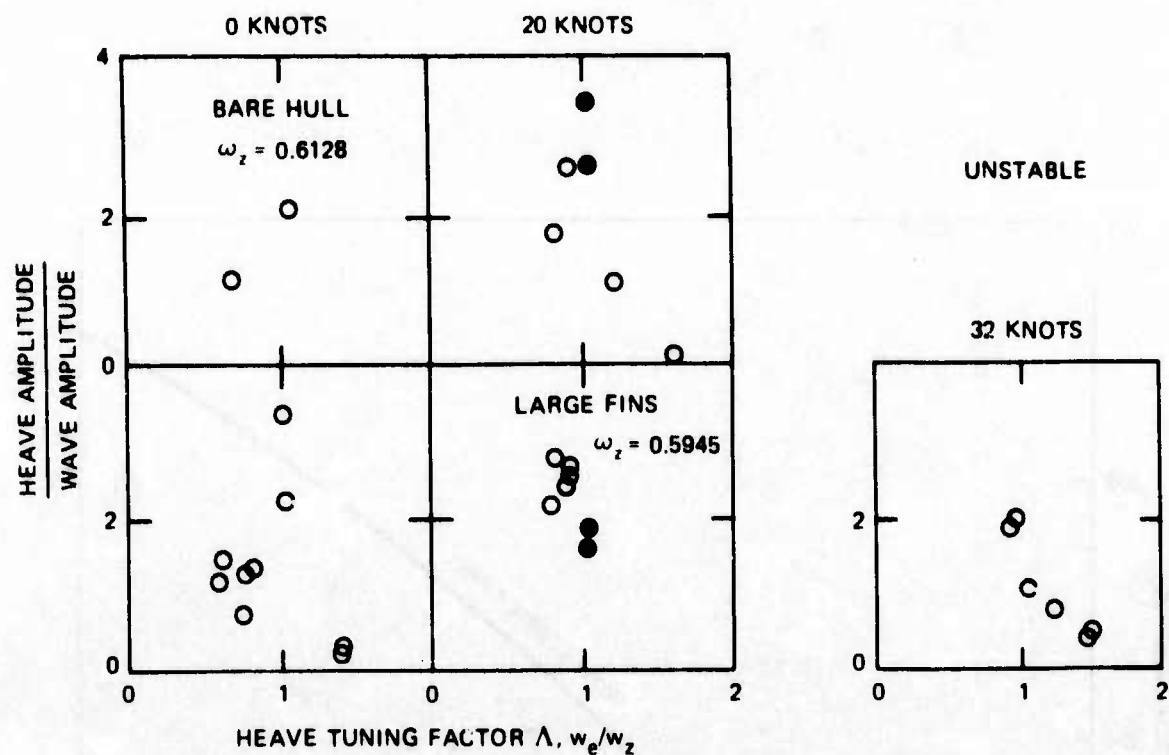
Figure 23a -- Comparative Heave Motions
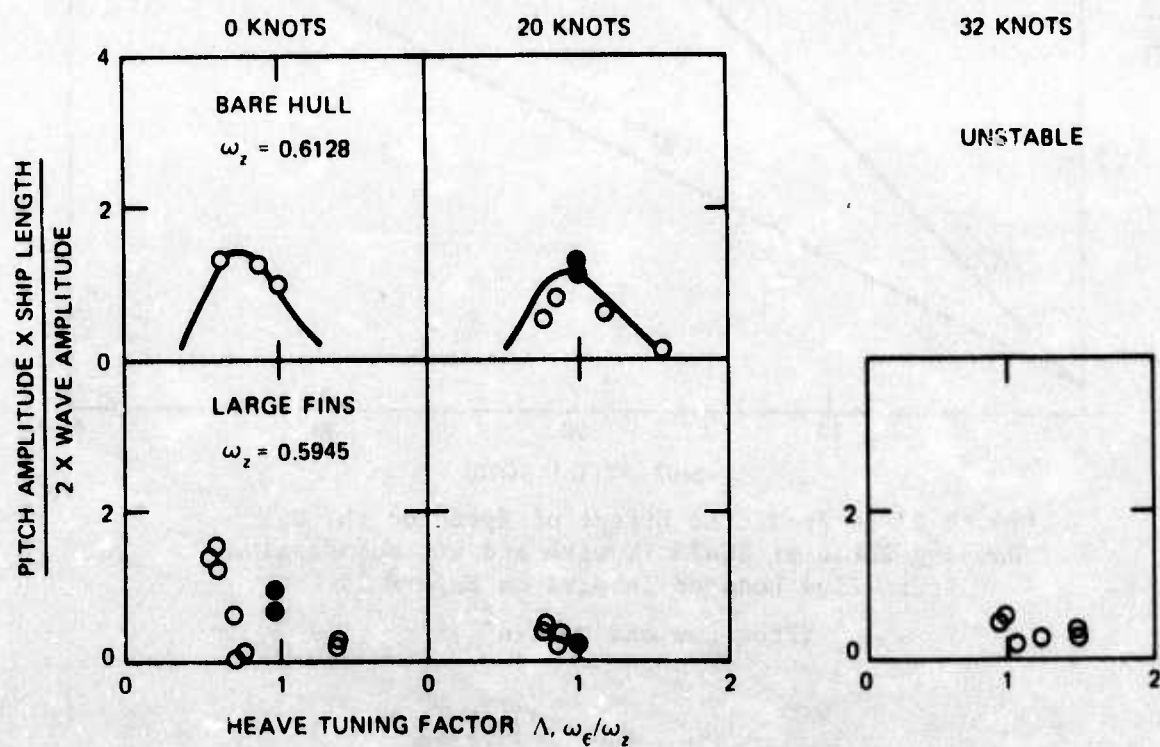
Figure 23b -- Comparative Pitch Motions

Figure 23 -- Comparison of SWATH IV Motions in Regular Head
Waves with and without Passive Stern Fins

(At 32-ft draft; from Kallio and Ricci[23])

Dynamic Pitch Instability

Horizontal stern fins are also desirable from the standpoint of augmenting the pitch restoring moment of a SWATH ship at high speeds. The amount of waterplane area in a typical SWATH configuration is roughly one-fifth of that present in a conventional ship of equal tonnage, but the longitudinal inei la of a SWATH is about one-tenth as great because the SWATH struts have only one-half the waterline length of a comparable monohull and, moreover, are much narrower. The longitudinal inertia of SWATH IV was so reduced that it was merely twice as large as the transverse inertia. This meant that the longitudinal metacentric radius (BM_L) about the center of buoyancy was twice the transverse BM. The net effect was a longitudinal metacentric height (GM_L) of 33 ft above the center of gravity for SWATH IV compared to a transverse GM_T of 8 ft.

The pitch restoring moment of a ship is directly proportional to the GM_L value; it is given by the expression

$$R.M. = \Delta \ GM_L \ \sin \theta$$

where Δ is the ship full-load displacement and θ is the pitch angle. The greater the GM_L, the stiffer the ship in pitch. Stiffness, in turn, has the effect of decreasing the ship natural pitch period. This is why a conventional 4000-ton destroyer has a pitch period of about 6 sec whereas the period for a similar size SWATH ship can be as high as 20 sec. But a curious fact about the bare-hull natural pitch period of a SWATH is its demonstratedly longer pitch periods at higher speeds, as documented in Table 8 from data of Kallio and Ricci.[23]

What causes the pitch period to lengthen with speed? In part, it is due to the substantial increase in pitch damping. But the major factor is a decrease in the ship pitch stiffness. Because the two lower hulls of a SWATH are fully submerged, they are subjected to the speed-dependent destabilizing Munk moment. This is a pitching couple arising from the pressure distribution on a moving submerged body at

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TABLE 8 -- MEASURED BARE-HULL PITCH PERIODS FOR SWATH IV
SCALED UP TO 4000 TONS AT 28-FOOT DRAFT
(From Kallio and Ricci[23])

Ship Speed	Natural Pitch Period
knots	sec
0	16.21
10	17.16
20	17.61
32	Not measurable

an angle of attack in a fluid.[24] It may be seen from Figure 24* that
the Munk moment acts to increase the angle of attack which the body
presents to the flow. Further, because the moment arises from dynamic
pressures, its magnitude will increase in proportion to the square of
the fluid inflow velocity.

Opposing the Munk moment is the hydrostatic pitch restoring moment
so that the greater the GM_L, the less tendency to become unstable. But
all SWATH ships will become unstable above a certain speed. The approxi-
mate equation derived by Lee[22] for determining the speed for onset of
pitch instability is

$$U_0 = \left[\frac{\Delta \, \overline{GM}_\ell}{\frac{\rho}{2} L^3 M'_w} \right]^{1/2}$$

where Δ = ship full-load displacement

ρ = mass density of water

L = overall ship length

M'_w = coefficient of hydrodynamic pitching moment about
the y-axis

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[24]Munk, M.M., "Aerodynamic Theory of Airships," W.F. Durand, Berlin
(1934).

*Reference 25 mentioned on Figure 24.

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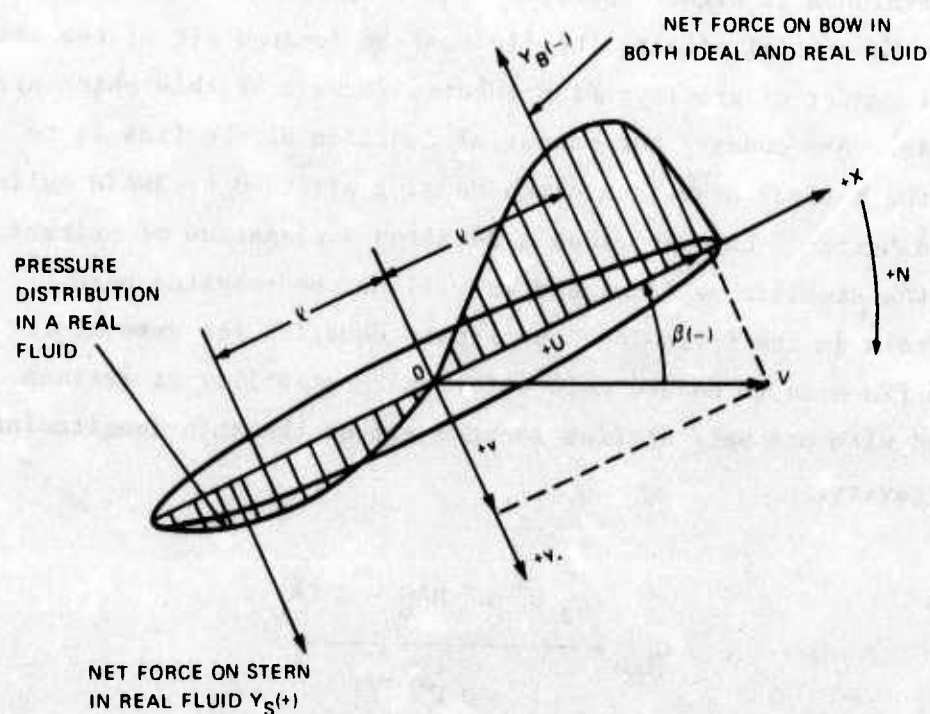
Figure 24 -- Forces Acting on a Submerged Ellipsoid at
an Angle of Attack in a Real Fluid[25]

([25]"Principles of Naval Architecture," SNAME,
New York, N.Y. (1967)).

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For the SWATH IV model configuration scaled up to 4000 tons, and its GM_L of 33 ft, the computed value of U_0 is 27.5 knots. This estimate of the speed for onset of instability was confirmed in the model tests because it was not possible to accelerate up to 32 knots and maintain zero running trim. At 20 knots, the model behaved normally.

The primary function of submerged fins is to ensure dynamic pitch stability by augmenting the ship hydrostatic pitch restoring moment which is diminished at higher speeds by the hydrodynamic Munk moment. To provide this beneficial effect, the fin must be located aft of the ship longitudinal center of gravity; fins located forward of this point are destabilizing. A secondary but essential function of the fins is to supplement the minimal heave and pitch damping afforded by SWATH hulls.

Lee and Martin[22] have provided a detailed explanation of criteria for sizing the stabilizing fins, and it will not be repeated here. Derived therein is the following approximate equation for determining the minimum fin area to ensure calm-water pitch stability at maximum design speed with one pair of fins located aft of the ship longitudinal center of gravity:

$$c\ S\ C_{L\alpha} = \frac{\frac{\rho}{2}\ U^2\ L^3\ M'_w - \Delta\ \overline{GM}_\ell}{\rho\ U^2\ |\ell|}$$

Here C   is the chord and s the span of each fin (assuming it has a rectangular plan form)

$C_{L\alpha}$ is the lift-curve slope for the fin being used

U   is the ship maximum speed

L   is the length of the ship, and

M'_w is the nondimensional coefficient of pitch moment due to heave velocity.

The quantity $|\ell|$ designates the absolute value of the X coordinate of the quarter-chord point of the fin relative to the ship longitudinal center of gravity.

Generally, a pair of stern fins of this minimum area will not provide the extent of additional heave damping desired. For greater heave damping, fin area should be distributed both forward and aft rather than concentrated in a single pair of aft fins. With this recommended approach, however, care must be taken to ensure that the aft fins are sufficiently larger than the forward ones to provide the necessary calm-water pitch stability augmentation. Since forward fins are destabilizing, whatever fin area is added forward must also be added aft so there will be no net change in high-speed pitch stability. Thus, it is not unusual for a SWATH design to have as much as twice the total combined fin area as the minimum for stability predicted by the equation.

Analogy of Heave, Pitch, and Roll to
Mechanical Vibrations

To delve more deeply into these matters, it is convenient to separate ship motions into their six components: surge, sway, heave, roll, yaw, and pitch. The first three describe translational motions and the latter three apply to rotational motion. Since SWATH ships have port-and-starboard symmetry, it is reasonable to assume that motions in the vertical plane are decoupled from the horizontal-plane motions in head and following seas. In other words, surge/heave/pitch motions will be independent of sway/roll/yaw motions. Also, because SWATH hulls are slender, one can assume further that heave/pitch motion will be decoupled from surge motion.

The natural pitch period of a SWATH ship will generally (except for some tandem-strut designs) be considerably longer than the heave natural period. If this is the case, then one more simplification can be made: to a first approximation, heave motions of an unappended SWATH ship can be assumed to be independent of pitch motions. This assumption appears valid because regular-wave tests of unappended single strut-per-hull SWATH models demonstrated large motions with very little pitching, at least for slow speeds;[26] see Figure 25.

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[26] Kallio, J. and J. Ricci, "Seaworthiness Characteristics of a Small Waterplane-Area Twin-Hull Ship (SWATH IV), Part II," DTNSRDC Evaluation Report SPD-620-02 (Mar 1975).

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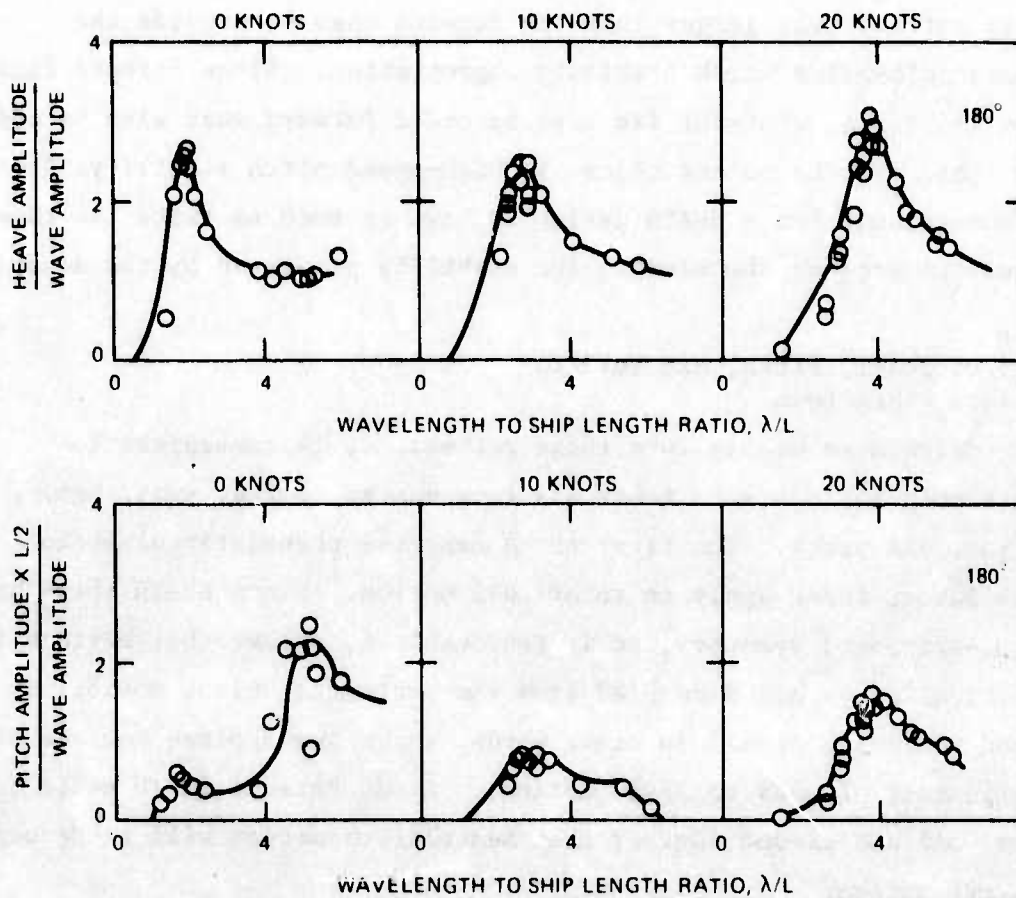
Figure 25 -- Head Sea Motions of the Unappended SWATH IV Model
as a Function of Wave Length-to-Ship Length Ratio

(From Kallio and Ricci[26])

The net result of these simplifications is to reduce the differential equation of vertical motion for a SWATH ship without control surfaces in regular sinusoidal waves to

$$(M + A)\,\ddot{Z} + B\,\dot{Z} + C\,Z = F_0\,\sin(\omega t + \beta)$$

where $Z(t) = Z_0\,\sin(\omega t - \phi)$ is the heave motion of the ship as a function of time, with Z_0 the peak amplitude, and ϕ the phase angle of peak upward heave motion with respect to a wave crest located above the ship longitudinal center of buoyancy. In addition:

$\ddot{Z}$ = heave acceleration

$\dot{Z}$ = velocity

M = ship mass

A = mass of entrained water

B = combined wavemaking and viscous damping coefficient

C = hydrostatic restoring force coefficient

F_0 = amplitude of the sinusoidal wave exciting force

ω = angular frequency of oscillation

β = phase angle with respect to wave motion about the longitudinal center of mass of the ship

This equation suggests that the heave motion of a SWATH ship in regular head waves is analogous to the forced periodic oscillation of a simple mass/dashpot/spring mechanical vibration system. Such an analogue is helpful in pointing the way toward valuable insights. To begin with, it can be shown[27] that the heave amplitude is defined by the equation

$$Z_0 = \frac{F_0}{\sqrt{(B\omega)^2 + [C - (M + A)\,\omega^2]^2}}$$

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[27] Den Hartog, J.P., "Mechanical Vibration," McGraw-Hill, Inc., New York, N.Y. (1947).

Expressed in nondimensional form, the heave amplitude is shown to be a function of the tuning factor (ω/ω_n) and the damping ratio (B/B_c) where B_c is the critical damping magnitude and ω_n is the undamped heave natural frequency.

$$Z_0 = \frac{F_0/C}{\sqrt{\left(1 - \frac{\omega^2}{\omega_n^2}\right)^2 + \left(2 \frac{B}{B_c} \frac{\omega}{\omega_n}\right)^2}}$$

For mechanical vibration systems, the quantity F_0/C can be interpreted as the stiffness, i.e., the deflection of a spring when acted on by the force F_0. The peak magnitude of the forced vibration may be larger or smaller than the static deflection, depending on the values of the tuning factor (ω/ω_n) and damping ratio;[27] see Figure 26.

Similarly, the equation for the response phase angle is

$$\phi = \arctan\left[\frac{2\left(\frac{B}{B_c} \frac{\omega}{\omega_n}\right)}{1 - (\omega^2/\omega_n^2)}\right]$$

Well below resonance, the wave-exciting force and resultant ship motion response are in phase ($\phi = 0$) for simplified single degree-of-freedom ship motions with no damping. Well above resonance, the motion response is 180 deg out of phase with the crest of the exciting wave. Consequently, a phase-angle curve shows an abrupt shift at a tuning factor of unity.

The addition of damping in a single degree-of-freedom system produces a smooth curve for the variation in response phase angle as a function of tuning factor. Typically, heave damping for an unappended SWATH hull oscillating at a frequency close to ω_n with zero forward speed is on the order of 2 percent of the critical value if the hull

Figure 27 -- Phase Angle between Force and Displacement as a Function of Frequency for Various Values of Damping (From Den Hartog[27])

Figure 26 -- Amplitudes of Forced Vibration for Various Damping Ratios

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is circular in cross section.* For an elliptical hull with horizontal
(major) axis slightly less than twice the minor axis, the resonant
heave damping is about 7 percent of critical. However, bare-hull
damping increases somewhat with forward speed. In general, the resonant
heave response of SWATH ships should lag the exciting wave by roughly
90 deg.

If $\omega = \omega_n$, corresponding to resonance, the heave amplitude is
defined by the equation

$$Z_{0(Res)} = \frac{F_0/C}{2B/Bc}$$

In other words, the peak heave amplitude at resonance will be inversely
proportional to the restoring force C and the damping ratio.

One disadvantage of the SWATH configuration, particularly at zero
speed, is that both the hydrostatic restoring force and wavemaking
damping terms are smaller than for conventional displacement ships,
thus the peak freebody heave amplitude at resonance will be considerably
greater. The decreased hydrostatic restoring force of SWATH ships
is a consequence of their greatly reduced waterplane area, and decreased
wavemaking damping is caused primarily by the submergence of most of
the buoyant volume an appreciable distance below the water surface.

Although the foregoing technical background was presented in
terms of SWATH heave response, the method of analysis and conclusions
drawn apply equally well to roll responses. SWATH ship pitch behavior,
on the other hand, is different in one important respect, the existence
of a speed-dependent destabilizing moment.

Motions Prediction Techniques

Because of their complexity, ship motions were, until recently,
given only cursory consideration in the exploratory feasibility stage
of design. Before the advent of computer programs for analyzing ship

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*Reported informally in NSRDC Report 396-H-14.

response to waves, the prediction of ship motions had been made manageable by breaking the task down into two phases: (1) testing models to measure motions in regular sinusoidal waves and (2) applying the principle of superposition to predict the ship response to irregular seas by summing individual responses to regular waves of the appropriate frequencies and amplitudes.

On the other hand, the model test approach is generally too costly for exploratory feasibility studies in which many alternative designs are to be evaluated. Accordingly, DTNSRDC developed a more practical analytical method of predicting heave, pitch, sway, roll, and yaw motions for a monohull ship advancing at constant speed in regular waves.[28,29] This method is basically the strip theory originated by Korvin-Kroukovsky, but with different forward-speed correction terms. Strip theory approximates hydrodynamic added mass and damping coefficients by computing them for a limited number of transverse ship sections and then integrating these over the length of the ship. The hydrodynamic effect on each transverse ship section (or strip) is computed as if that section were two-dimensional and had negligible longitudinal variation.

In the early 1970's, the strip theory approach was extended to parallel, twin, heaving cylinders of arbitrary section shape. As a result, the motion response of unappended SWATH forms in regular head or following waves can now be predicted on a rational basis except for the peak amplitudes in near-resonant conditions. This exception arises from the very small wavemaking damping of SWATH forms which, if assumed to be the only type of damping present, results in an overprediction of peak heave/pitch amplitudes. It has been found necessary, therefore, to increase the damping estimates for heave and pitch to account empirically for the presence of viscous effects not predicted by potential theory.

[28]Salvesen, N. et al., "Ship Motions and Sea Loads," Trans. SNAME, Vol. 78, pp. 250-287 (1970).

[29]Frank, W. and N. Salvesen, "The Frank Close-Fit Ship Motion Computer Program," NSRDC Report 3289 (Jun 1970).

Beyond this, theoretical work[30] recently completed by MIT under contract will permit the present two-dimensional analytical tool to be extended to a three-dimensional one of greater accuracy because forward speed effects on hydrodynamic coefficients will be taken into account.

During FY76 the existing motions computer program will be transformed so that it will have additional capabilities for predicting heave, pitch, roll, and yaw motions in oblique seas. Initially, the expanded motions program for oblique seas will be based on 2-dimensional theory.

From the standpoint of practical SWATH ship design, one should not be too concerned over the difficulty inherent in predicting peak responses of unappended SWATH bodies. In most if not all cases, SWATH ships will be equipped with horizontal fins. The damping afforded by control surfaces of the proper size predominates at moderate to high speeds and is quite predictable; thus motion predictions for SWATH ships so equipped become more accurate for the ship underway than at zero speed. Even in resonant wave encounter conditions, the motions of a SWATH ship with control surfaces are approximately linearly proportional to wave height. This was not true of the vertical motions of an unappended SWATH. However, the presence of fins does not eliminate the need to apply empirically derived correction factors to estimates of heave, pitch, and roll damping at zero speed. The unpredictable viscous damping remains significant at zero speed.

Notwithstanding the considerable progress in this area of technology, it has been necessary to employ model tests to accurately predict the magnitude of motion responses for a conceptual SWATH ship in particular seaways. More important, by analyzing the model motion response data in certain ways, it is possible to confirm the underlying vibratory mechanism by which SWATH motions are excited as well as to generalize those wave conditions in which the greatest motion will occur.

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[30]Kim, K.H., "Determination of Damping Coefficients of SWATH Catamaran Using Thin Ship Theory," MIT Report 75-4 (Jan 1975).

Heave and Pitch Response in Head Waves

Referring back to Figure 22, note that head waves on the order of the hull length of 286 ft did not excite either heave or pitch motion of a 4000-ton SWATH represented by the SWATH IV model. At zero speed, both the peak heave and a secondary peak in pitch response occured in waves of approximately twice the ship length; the most pitching occurred in 1400-ft waves, five times the ship length. At 20 knots, in contrast, maximum pitch and heave responses both shifted to waves four times the model length. But for pitch, only the secondary peak in the response curve at the point of greatest heave was evident at 20 knots. Peak vertical response of this SWATH model over a range of ship speed does not correspond to a particular geometric relationship between a wave profile and the hull. This will be the case for most SWATH ships.

When the same measured freebody responses are replotted as a function of heave tuning factor, the heave motion of an unappended SWATH is found to behave as an underdamped (sharply peaked) vibratory response, but pitch response is more complex; see Figure 28.

At zero speed (as one would expect), heave and pitch responses are greatest at their respective resonant wave encounter conditions (a value of 0.6 for the heave tuning factor corresponds to 1.0 for pitch). But at a full-scale speed of 20 knots, maximum pitching occurred at the resonant wave encounter condition for heave. Because of facility limitations at DTNSRDC, no measurements were taken in waves of about 7.7 times ship length where pitch resonance would be expected to occur at 20 knots. On the other hand, such a 2200-ft-long wave has a small slope and pitch resonance would not be much of a problem. The secondary peak in the pitch response curve for SWATH IV in 1100-ft waves (heave resonance) at 20 knots is of more practical concern. Evidently there is some coupling of heave motion with pitch, presumably because of asymetrically distributed exciting forces.

Because the frequency for pitch exciting moment at heave resonance is different from that for pitch resonance, the response will generally be out of phase with the excitation and thus have reduced amplitude.

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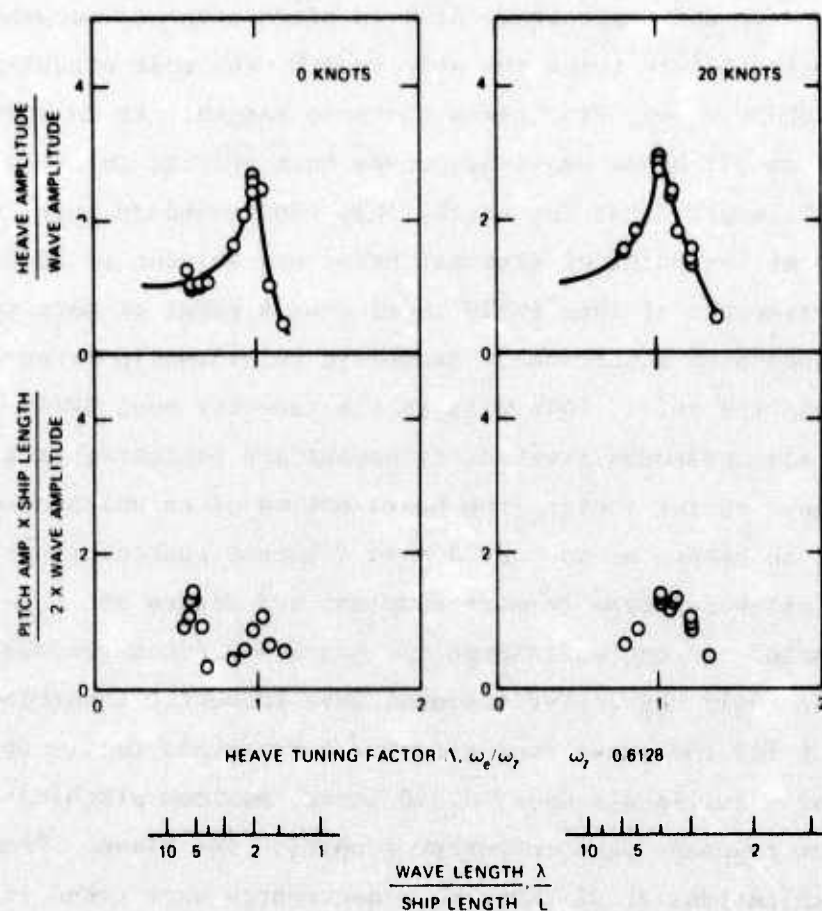
Figure 28 -- Measured Responses for the Unappended SWATH IV
Model as a Function of Heave Tuning Factor

(At 28-ft draft; from Kallio and Ricci[23])

In contrast, the heave excitation at heave resonant conditions is more closely in phase with the ship response so that maximum heave motion results. The difference in phasing is most evident at 20 knots because pitch resonance is not reached. The phase angles presented in Figure 29 for the SWATH IV model were measured relative to the wave profile as it passed the longitudinal center of gravity. A negative value defines ship response as lagging the wave.

A second reason why the head sea pitch response of SWATH IV lagged waves by a greater amount than did the heave response is that at 20 knots, this form had substantially greater damping of pitch motions than of heave (see Figure 20). By the same token, measured peak heave motions on the order of three times the wave amplitude for resonant wave lengths result from the negligible heave damping of unappended SWATH forms of circular cross section, such as SWATH IV.

Effect of Speed on Motions of an Unappended SWATH

It is evident from Figure 28 that when plotted against tuning factor, the heave transfer function curves for SWATH IV have remarkably similar shapes at 0 and 20 knots. At the 28-ft draft, peak bare-hull heave response of 1.5 to 3.0 times the wave amplitude occurred for both speeds at wave lengths corresponding to values between 0.90 and 1.10 for the heave tuning factor. By extension, it is reasonable to conclude that the wave lengths for peak heave response at other speeds will be those at which the tuning factor takes on values between the same limits.

If a ship is heading directly into waves, the encounter frequency with a particular wave may be determined from the equation

$$\omega_e = 2\pi \frac{(V_w + U)}{\lambda}$$

where V_w = wave celerity

   U = ship speed

   λ = wave length

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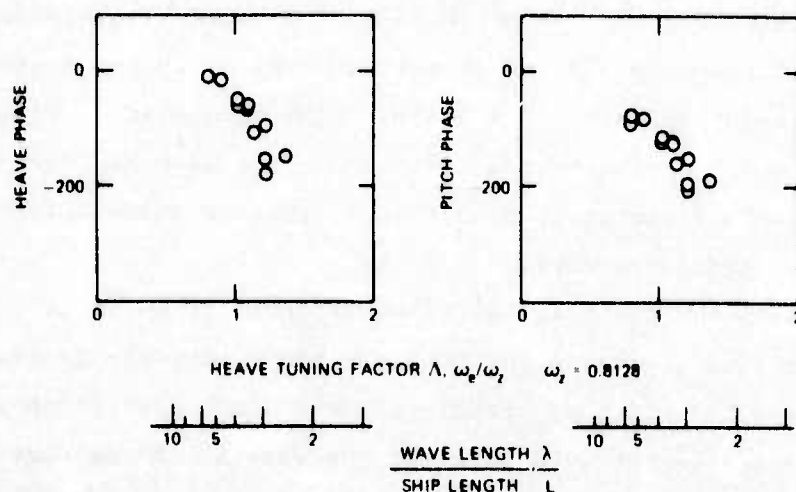
Figure 29 -- Measured Phasing of Responses for the Unappended
SWATH IV Model as a Function of Heave Tuning Factor

(Regular head waves at 20 knots and 28-ft draft;
from Kallio and Ricci[23])
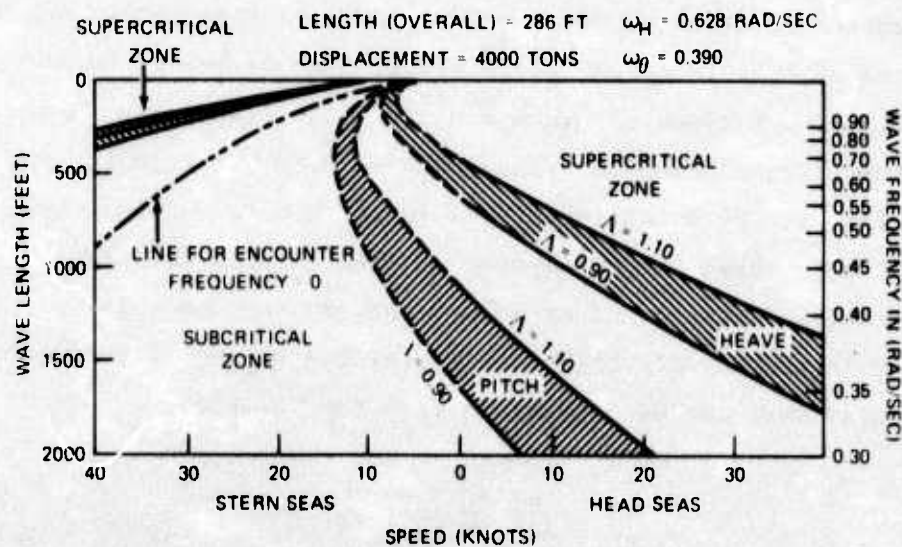
Figure 30 -- Zones of Operation in Regular Seas for SWATH IV--
Heave and Pitch

It is apparent from this equation that the encounter frequency increases at high ship speeds and, if speed is held constant, decreases as waves become longer. By the same token, the encounter period is decreased at high speeds but is increased in long waves.

For our purposes, the wave lengths at which the tuning factor takes on values greater than 1.10 for any ship speed may be termed supercritical, i.e., above resonance. In this context, supercritical denotes a condition wherein the ship operates at speeds high enough so that it has insufficient time to respond to a wave before it has passed by and the next one arrives. The ship speeds required for supercritical operation with respect to heave in regular waves of length λ can be computed from the equation given below:

$$U = \left[\frac{\lambda}{(T_z/1.10)} - V_w \right]$$

This equation was derived by setting $\omega_e = 1.10\ \omega_z*$ and solving for U. Here the subscript z denotes ship natural frequencies and periods with respect to heave motion.

Similarly, wave lengths for which the heave tuning factor takes on values less than 0.90 at any ship speed can be called subcritical. The speeds which satisfy this condition for particular wave lengths can be determined from the inequality

$$U < \left[\frac{\lambda}{(T_z/0.90)} - V_w \right]$$

Subcritical denotes a contouring mode of operation wherein the ship heaves up and down in phase with the wave.

If both calculations are carried out for a wide range of wave lengths, one can cross-plot those speeds defining limits of subcritical and supercritical operation, i.e., wave lengths for which $0.90 \geq \Lambda \leq 1.10$ for ship speeds of interest. By connecting these points, we

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*$\omega_z = 2\pi/T_z$ where T_z is the heave natural period.

thereby delineate zones of minimal and greatest heave response in head
seas, as shown in Figure 30 for a 10-sec heave period; this is the heave
period of the SWATH IV configuration at a displacement of 4000 tons.
When operating at 15 knots, this ship would behave supercritically in
waves up to 825-ft long and subcritically in waves longer than 1250 ft.
The largest heave motion would occur in 1000-ft waves. At 25 knots, in
contrast, a ship with this heave period would be supercritical in regular
waves up to 1050 ft while subcritical operation would become possible
only in waves longer than 1400 ft. The peak heave motion at 25 knots
would take place in 1225-ft waves.

Since the least ship motion is experienced when in supercritical
wave conditions, the utility of Figure 30 lies in depicting the broadened
range of wave lengths that become supercritical when the speed of a
SWATH ship is increased. But a more important implication follows from
the well-known relationship of wave period to wave length:

$$T_w = \left(\frac{2\pi\lambda}{g}\right)^{1/2} = 0.442\ \lambda^{1/2}$$

We know from this equation that the period of a wave increases in
proportion to the square root of its length and that the wave frequency
decreases at the same rate. The wave frequencies corresponding to
various wave lengths are shown on the right ordinate of Figure 30. By
increasing speed in head seas, the operator of a SWATH ship can maintain
greatly reduced vertical motions in waves of longer periods (and shorter
frequencies). Indeed, a speed of 10 knots is sufficient to reduce
motion to minimal levels in head waves with a 10-sec period, the same as
the natural heave period of the SWATH IV.

Too much should not be made of ship motions in regular waves; an
actual seaway consists of waves of many different lengths (i.e., periods)
moving in various directions. The SWATH ship potential for greatly
improved seakeeping ability arises from the relatively infrequent
occurrences of ocean storm waves with long periods. The similarly

long natural periods of a SWATH ship make it possible to avoid motion excitation by appropriate choice of speed, except in uncommonly long head waves and stern or stern-quartering seas.

Freebody Response in Stern Waves

Differences between SWATH ship motions in head and following seas stem mainly from the characteristic ship/wave encounter frequencies at these two headings. In following seas, a ship is traveling in the same direction as the waves and therefore the encounter frequencies are low, i.e., the encounter periods are long. Because the natural pitch period of a SWATH ship is usually much longer than the natural heave period, it seems reasonable to conclude that the principal seakeeping goal in following seas will be to avoid pitch resonance. This can be done only by operating at speeds such that the wave encounter period remains in the subcritical region of pitch response (pitch tuning factor less than 0.80). For a 4000-ton full-scale version of the SWATH IV model with a 16-sec pitch period at zero speed, the minimum encounter period for subcritical operation is (16 ÷ 0.80) or 20.0 sec.

One must also keep in mind that the same following sea encounter period can arise from two sets of wave conditions, one where the ship overtakes the wave and one where a long wave overtakes the ship. This is illustrated in Figure 31. It so happens that the desired subcritical pitch response will be most difficult to achieve in situations where a SWATH ship is overtaking relatively short waves. To explain further, consider the aforementioned 4000-ton SWATH operating in 225-ft-long regular waves that match the strut length of this ship at design waterline. Because a 225-ft wave propagates at 20.1 knots, the ship could be overtaking the wave. The maximum speed for subcritical operation with respect to a 225-ft wave traveling in the same direction as the ship is 26.8 knots, as computed below. This is the first way of ensuring a value of no more than 0.80 for the tuning factor. According to the convention followed by hydrodynamicists, a positive tuning factor denotes a ship overtaking the wave.
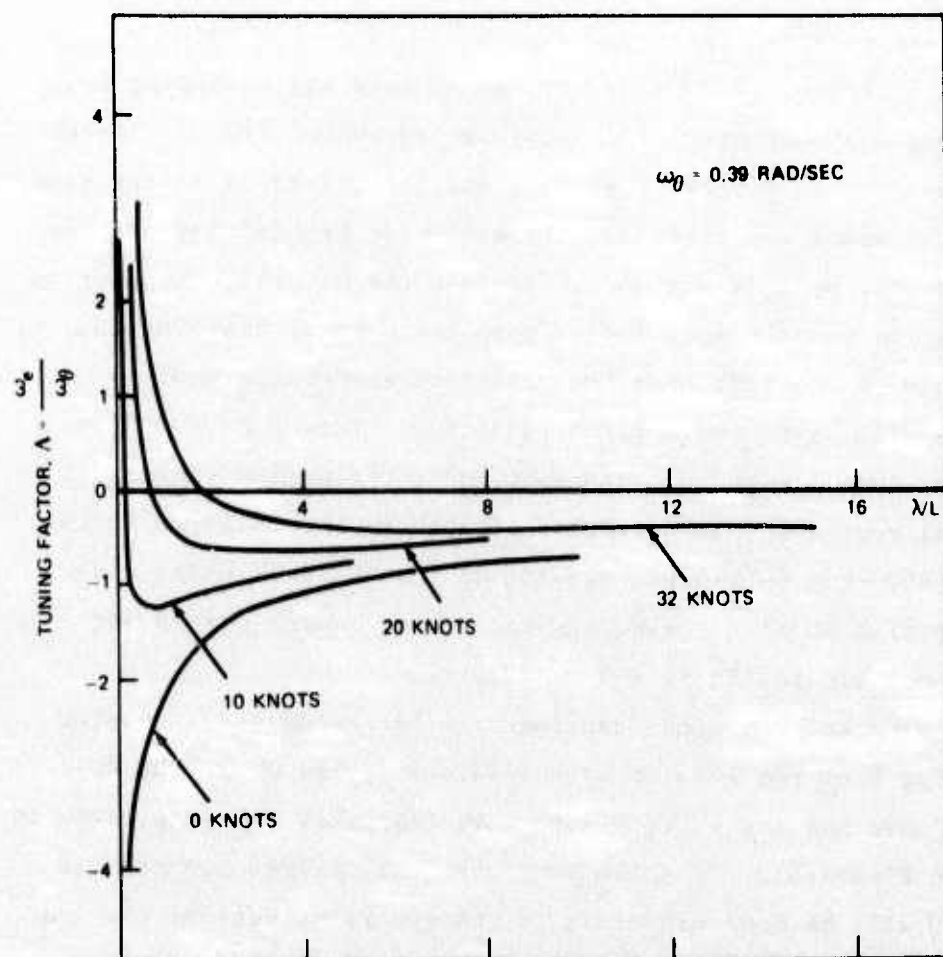
Figure 31 -- Pitch Tuning Factor as a Function of
Wavelength-to-Ship Length Ratio in
Following Seas

$$U_{max} = V_w + \frac{\lambda}{(T_\theta/0.80)} = 34.0 \text{ ft/sec} + \frac{225 \text{ ft}}{(16.0 \text{ sec}/0.80)}$$

$$U_{max} = 45.2 \text{ ft/sec, or } 26.8 \text{ knots}$$

On the other hand, the minimum speed to ensure subcritical operation with the same wave overtaking a slower ship is 13.5 knots:

$$U_{min} = 34.0 \text{ ft/sec} + \frac{225 \text{ ft}}{[16.0 \text{ sec}/(-0.80)]}$$

$$U_{min} = 22.8 \text{ ft/sec, or } 13.5 \text{ knots}$$

For this wave length, ship speeds between 13.5 and 26.8 knots will produce subcritical (contouring) pitch motions. The band of subcritical ship speeds can be computed for other wave lengths in a similar manner. The curves that result from connecting these points are shown in Figure 30.

In short waves, the range of speeds corresponding to pitch resonance is narrow (between 27 and 30 knots for this 4000-ton SWATH in a 225-ft wave); thus supercritical operation with respect to pitch is also possible in these conditions. In long following waves, on the other hand, pitch resonance would occur at ship speeds below 10 knots.

Measured SWATH IV heave and pitch responses in regular stern seas are plotted in Figure 32 as a function of the zero-speed pitch tuning factor. Examination of the results for 0 and 10 knots indicate that the variation found in pitch transfer function values with tuning factor confirmed expectations suggested by the preceding analysis, i.e., peak response occurs at wave conditions corresponding to pitch resonance. But a resonant condition never occurs at 20 knots (the case of the ship overtaking a wave about 100 ft long was not investigated) and no other

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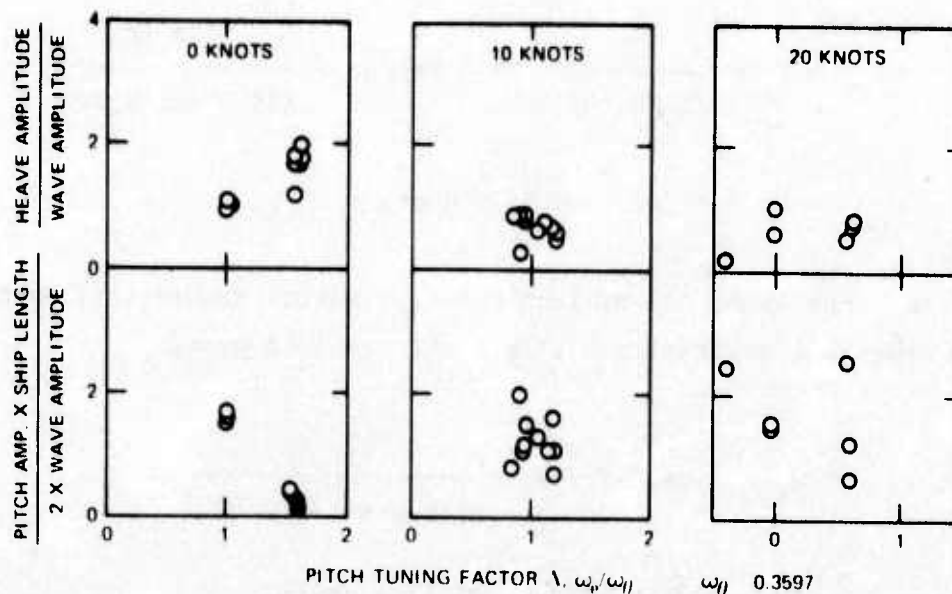
Figure 32 -- Measured Responses of the SWATH IV in Regular Stern Seas
(Bare hull, 32-ft draft; from Kallio and Ricci[23])
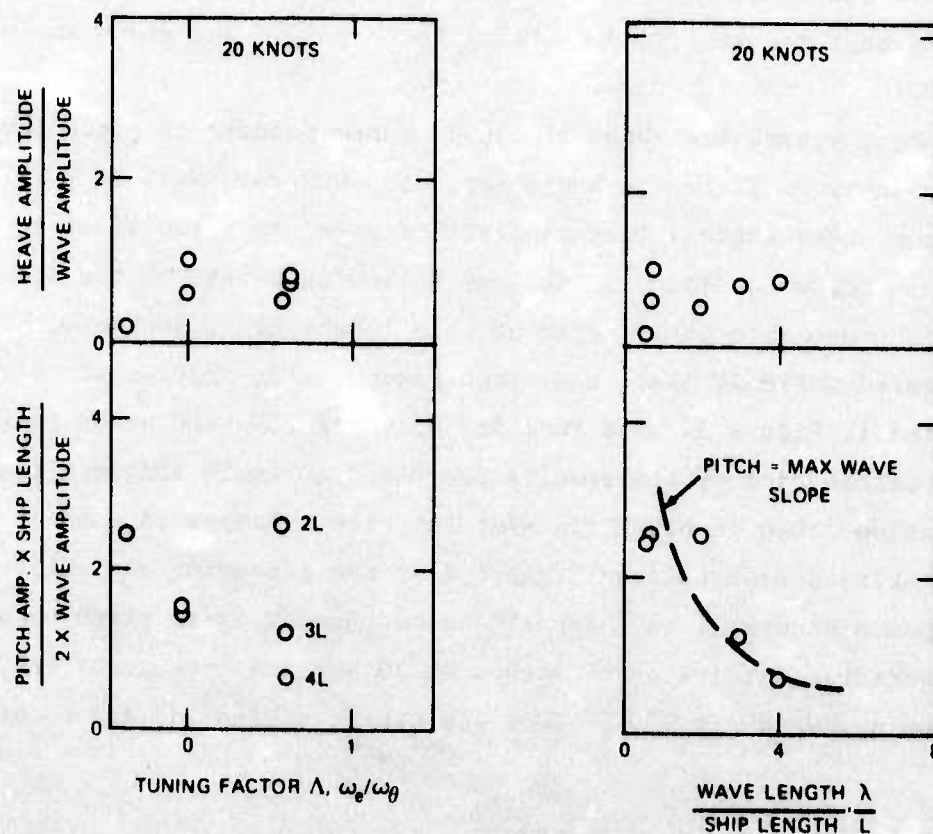
Figure 33 -- Comparison of Alternative Ways to Present Unappended
SWATH IV Pitch Response Data for Stern Seas

(At 32-ft draft)

operative principle governing the amplitude of pitch response is evident. To clarify what is going on, the data obtained at 20 knots are replotted in Figure 33 as a function of the ratio of wave length to ship length.

It seems safe to conclude that the geometrical relationship between SWATH ship length and wave length has a marked effect on these subcritical pitch response amplitudes at 20 knots. The best evidence is that the condition for greatest pitching is at wave lengths that are from one to twice the ship length. In longer waves, moreover, the measured bow motions due to pitch correspond to the bow response for a pitch angle approximately equal to the maximum slope of that length wave. This is exactly what one would expect of the contouring mode of operation implied by a subcritical value for the tuning factor.

The heave and pitch natural frequencies of conventional monohulls are so high that destroyer-size ships can operate subcritically in following seas in waves of virtually any length. However, the geometrical relationship between ship and wave lengths is even more of a problem because monohulls are subjected to larger wave-induced pitching moments and the long encounter periods provide plenty of time for pitching to occur. Additionally, orbital wave velocities cause surging.

Another point illustrated by Figure 35 is that like conventional ships, SWATH's experience some difficulties in following seas when the ship speed is nearly equal to the wave celerity. This condition corresponds to a wave length of about 500 ft for a ship speed of 30 knots and a wavelength of 225 ft for a speed of 20 knots (see Figure 30). In such a situation, the orbital wave velocities will excite substantial surge motion along with pitching, alternately decelerating and accelerating the ship. With monohulls, roll-yaw motion is often induced at the same time, but stern quartering seas are probably needed to cause roll-yaw behavior in a SWATH ship.

Implications for SWATH Response in
the Ocean

From the standpoint of minimizing the likelihood of resonant wave encounter conditions, the beneficial effect of forward speed on SWATH

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head sea motions is limited in the real world by the wide variety of wave lengths present. Recognizing that ship operating speeds will often be constrained by transit range or sonar noise considerations, the natural heave (and possibly the pitch) period of a SWATH displacing 4000 tons will not be long enough to avoid motion resonance when heading into a severe storm or when encountering long swells. The first of these conditions presents the bigger problem.

Although wave length and steepness depend on wind speed and duration as well as on geography, certain bounds can be put on the conditions to be expected. For example, the average length of storm waves varies from less than 300 ft in the Mediterranean Ocean, to about 500 ft in the North Atlantic, to a little over 500 ft in the Pacific Ocean.[31] The periods of these storm waves range from 7.6 sec for 300-ft waves to about 10 sec for a 500-ft-long wave. When heading into even the longest of these "average" waves, slow speeds in excess of 10 knots are sufficient for a 4000-ton SWATH ship with natural periods of at least 10 sec to achieve supercritical heave and pitch response. Nonetheless, this does not mean that Pacific Ocean storms would be of no consequence to such a SWATH ship.

Wave statistics can be misleading if not properly understood. To be more precise, a 502-ft-long "average" storm wave corresponds to the wave period of maximum energy in the low State 6 fully developed sea spectrum which has been found to result from a 25-knot wind acting for at least 15 hr. A widely used representation of such a seaway* shows a Rayleigh distribution of its total energy over a wide range of wave periods (frequencies) with significant energy at wave periods as low as 3.8 and as high as 13.6 sec. Corresponding wave lengths range from 75 to 950 ft. One can use the curve in Figure 30 to determine that a SWATH with a 10-sec natural heave period requires a speed of at least 20 knots to be supercritical when heading directly into a 950-ft wave.

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[31]Kinsman, Blair, "Wind Waves," p. 10, Prentice-Hall, Englewood Cliffs, N.J. (1965).

*Marks, Wilbur, "Wind and Sea Scale for Fully Arisen Sea," NSRDC.

More severe storm conditions, say a 35-knot wind blowing for more than 30 hr, could create a fully developed State 7 sea whose maximum energy is centered around a wave period of about 13.6 sec, with significant energy at wave periods up to 18.5 sec. Component waves could vary in length from 150 to 1750 ft. For the latter wave length, the SWATH ship in question would have to operate at 50 knots to achieve supercritical response. A speed below 30 knots, on the other hand, would result in subcritical heave motion in a 1750-ft-long wave. The problem is that at this slower speed, resonant heave motions would be excited in the shorter waves that are also present in fully developed State 7 seas.

An important lesson from these examples is that, in effect, a SWATH ship heave natural period determines the threshold wave conditions in which its freebody motions start to deteriorate. For any SWATH design with realistic proportions, the pitch and roll natural periods are considerably longer than for heave, and therefore they cause difficulties less often. Only three factors affect the undamped natural heave period of a ship: displaced mass, mass of entrained water (added mass), and amount of waterplane area, as shown in the equation below.

$$\omega_z = \sqrt{\frac{\text{hydrostatic restoring force}}{(\text{mass + added mass})}} = \sqrt{\frac{\rho \, g \, A_{wp}}{(M + A)}}$$

where ω_z = undamped natural heave frequency

   A_{wp} = total waterplane area of the ship

   ρ = density of seawater

   g = gravitational constant

The heave period can be increased either through greater mass for a given amount of waterplane area or through a decrease in waterplane area for the same mass. Both are difficult to achieve from a practical standpoint because they result in decreased transverse static stability

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unless hull spacing is increased at the same time. The accompanying increase in overall beam is often unacceptable for SWATH ships intended to transit the Panama Canal. Another drawback to greater beam is the accompanying increase in enclosed volume beyond required levels.

By the same token, an increase in added mass is permissible because it is a hydrodynamic quantity that does not affect static stability. Two-dimensional vertical oscillation tests* have demonstrated that it is possible to increase the added mass of a SWATH ship from 50 to roughly 100 percent of the displacement by selecting a lower hull with a 2:1 elliptical cross section in place of a circular hull. Such an elliptical hull would have a 15 percent greater natural heave period for the same amount of waterplane area. This means a 15 percent lower heave natural frequency. In reducing the ship natural frequencies, not only is motion excitation by waves made less likely for head, bow, and beam headings but the critical damping magnitude is also decreased as well. Whatever wavemaking and viscous damping exists on unappended or appended SWATH forms is thereby made more effective (because it represents a larger fraction of the critical damping value).

In stern and stern-quartering waves, however, slightly longer natural periods are of little benefit from the standpoint of decreasing the likelihood of heave/pitch excitation. Not only can ship/wave encounter periods in stern seas approach infinity but substantial pitching can also result from the tendency of a SWATH to contour the steep slope of waves only a little longer than ship length. At the same time, the decreased inflow velocity over the ship control surfaces in stern seas will generate less lift for a given ship speed, and therefore less damping will be provided. To decrease the pitch angle of a SWATH ship in stern seas, it is probably desirable to provide greater pitch stiffness. To do so, however, would degrade motions in head waves somewhat. Thus, in designing a SWATH ship, there is a need to compromise on the issue of pitch stiffness to ensure good motions in both head and following seas.

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*Reported informally in NSRDC Technical Note 396-H-14.

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Generally, the addition of appropriately sized horizontal fins to a
SWATH ship has relatively little effect on zero speed responses; as
speed is increased, however, the greater damping present results in
broader, shallower motion response curves (as a function of encounter
frequency). This means that a SWATH ship so equipped will respond to a
wider range of wave lengths for a given ship speed but that the result-
ing motions will be smaller. If the criterion for good seakeeping is
that the response must not exceed 1.5 x the wave amplitude, then the
addition of fins will be found to increase the possible combinations of
ship speeds/heading/wave lengths which satisfy that criterion.

Possible Need for Foil Activation

The presence of submerged horizontal fins on a SWATH ship will be
accompanied by a wave-induced variable vertical excitation force. Even
when the ship is operating at even keel, a time-varying angle of attack
to the inflow velocity will be caused by the vertical component of the
orbital motion of water particles below the wave surface. The ship/foil
position relative to the wave that produces the maximum upward force (F)
on a stern fin is shown for stern seas in Figure 34. Similarly, a position
on the back side of the wave above the trough will produce the maximum
downward force on a stern foil in following seas.

The inflow angle will vary approximately sinusoidally between these
two extremes over the period of encounter with each wave. It so happens
that the period of encounter in head seas is relatively short compared
to the ship heave and pitch natural periods, and the ship will not have
sufficient time to respond to the foil-induced excitation force. But in
following seas, the periods of encounter are characteristically as long
or longer than those of the ship; thus the ship will respond and pitch
motions can be aggravated by the presence of fixed stern or bow fins.
The most serious drawback to this increased wave excitation force occurs
when the ship stern is lifted by one or the other set of fins, causing
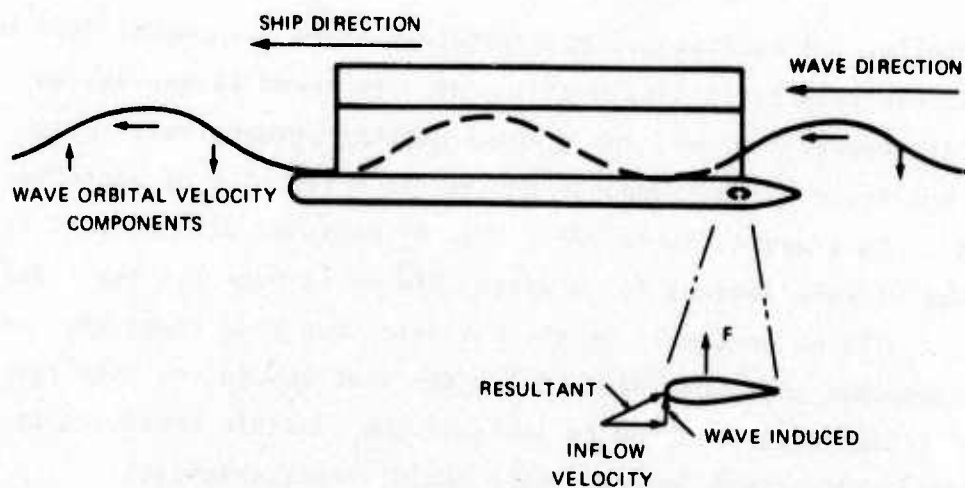the bow to pitch down and possibly dig into the crest of the wave

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Figure 34 -- General Following Wave Condition in Which
Fixed Stern Fins are Subjected to an
Upward Lift Force
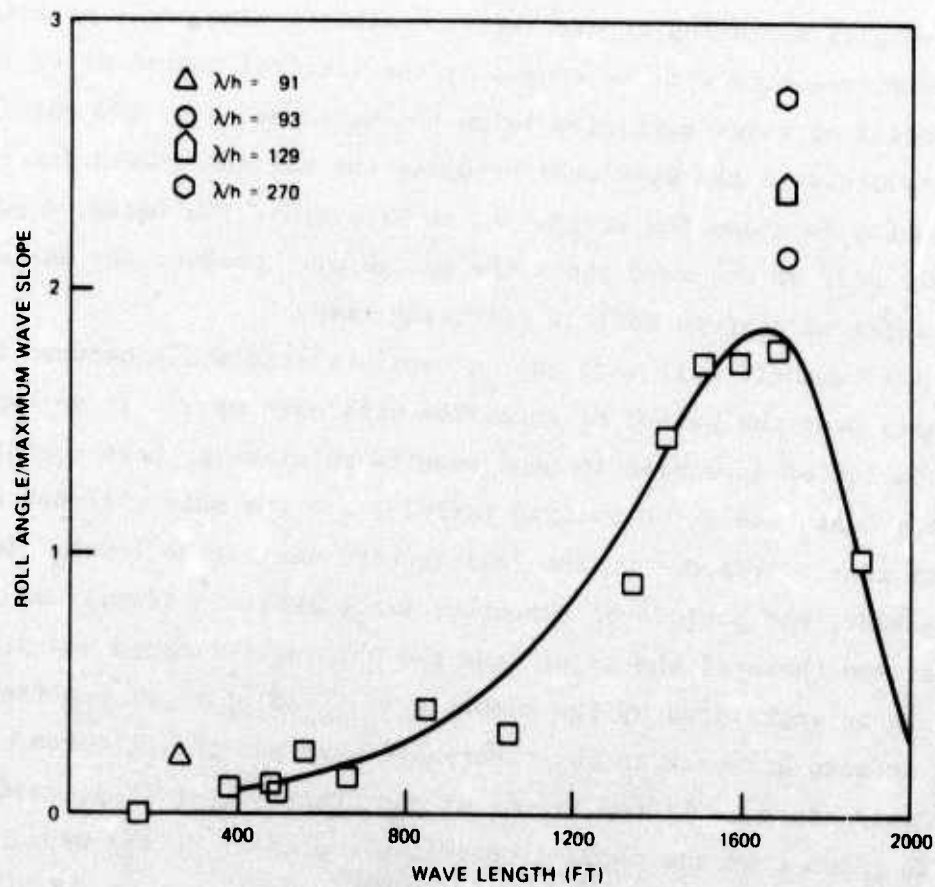
Figure 35 -- Variation in Unit Roll Response Due to Wave
Steepness for the SWATH VI Model Scaled to 3000 Tons

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ahead. This phenomenon presents the greatest problem in steep waves close to ship length and is the principal reason why fixed stern fins could be less than satisfactory from a seakeeping standpoint. Instead, manual or automatic control of the stern fins, or both stern and bow fins, may be required so that the resultant angle of attack can be varied to maintain zero, or a small downward, force on the stern.

If a set of automatically controlled active fins is properly designed, then such a system might also enable a contouring mode of operation to be maintained in State 7 or worse head seas. This should be possible because at 20 knots the period of encounter with respect to 1000-ft waves, about where the maximum spectral energy is concentrated in fully developed extreme conditions, will be close to the heave period (9 to 12 sec) of an oceangoing SWATH ship. The latter fact suggests that a SWATH ship will have time to respond to an upward force from the fins, assisting it to rise up and over the wave crest.

One practical difficulty in achieving this capability involves the selection of a device to sense the approach of a large contourable wave. Further, it must be ascertained whether the foil activation rate required to apply sufficient force at the proper time is reasonably within the capabilities of state-of-the-art shipboard hydraulic systems. If provision of a contouring capability is not feasible solely with stern fins of the assumed size, a decision must be made to design for more cross-structure clearance or else to add active bow fins to increase the control forces generated. (The latter approach will detract somewhat from the performance of hull-mounted sonar.) A good rule of thumb (based on seakeeping tests of several models) is that from the standpoint of an acceptable frequency of impacts, the design should provide a cross-structure clearance that is at least 10 percent higher than the significant wave of the sea state in which it is anticipated the ship will operate.

In the same vain, a pitfall to guard against in evaluating multifaceted control systems for SWATH ships is the tendency for expectations to rise following demonstrated improvements. It is

unrealistic to apply the near-level ride possible in State 5 seas as the standard for State 7. Additionally, a SWATH must be designed to withstand the inevitable impact of waves on its cross structure.

Motion Response in Beam Seas

When SWATH ships are underway in moderately stormy beam seas, their motions are as superior to those of comparable monohulls as in head seas. The typical motion of SWATH ships in most beam seas is heave/ sway rather than roll because their natural roll periods are typically about 60 percent greater than the natural heave period. In pure beam seas, the characteristic periods of "average" ocean storm waves are shorter (and the frequencies higher) than the period for SWATH roll response, resulting in supercritical values for the roll tuning factor. On the other hand, the tuning factor for heave will be near resonance under the same circumstances. In long swells or in State 7 beam seas, or worse, the tuning factor for heave will be subcritical relative to the wave periods of maximum seaway energy, but the tuning factor for roll will be close to resonance.

The roll responses of ship models in regular beam waves are usually presented nondimensionally as roll divided by maximum wave slope. At first glance, this is analogous to presenting ship heave responses in terms of heave divided by wave amplitude. However, there is a crucial difference in the relative linearity of heave and roll responses which makes the presentation of roll responses in this manner far less meaningful than it appears. For a given wave length, the heave response of either a monohull or SWATH ship is approximately proportional to the wave amplitude, which means that the quotient of heave response divided by wave amplitude remains roughly constant. In contrast, it may be seen from Figure 35 that for a given wave length, the unit response of roll angle divided by maximum wave slope varied inversely with wave steepness when the most recent SWATH model was tested at zero speed. This type of behavior is also observed with monohulls.

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Normally, unit response curves such as Figure 35 are multiplied by wave spectral energy distributions to predict statistical ship response in particular seaways. A problem arises in following this procedure to predict roll response, however, because wave steepness is a variable in any irregular seaway. Predictions based on model responses in waves of identical steepness are obviously of questionable validity. A better measure of SWATH ship behavior in beam seas, then, is the statistical roll response when a model is tested in simulated irregular waves. On the other hand, it is difficult to generalize measured roll based on wave spectra from just one seaway.

Nevertheless, completed tests of several SWATH models in regular and irregular beam waves enable some qualitative conclusions to be noted about general trends. First, with regard to unappended SWATH forms, relatively large unit roll responses occur at zero speed in long waves corresponding to resonant frequency (see Figure 36). Clearly, roll damping is insufficient. Although heave/pitch stabilizing fins provide little benefit in this regard at zero speed, the bilge keels tested on the SWATH IV model appeared to augment substantially the zero speed damping of heave as well as roll motions.[23] The chief drawback is that bilge keels would also create substantial drag on the ship when moving and would affect trim changes with speed.

Even with no appendages, an increase in speed to 10 knots full scale decreased the peak roll amplitude of the SWATH IV model by 50 percent, as shown in Figure 36. Undoubtedly there was some increase in viscous roll damping, but the main factor was a decrease in the roll exciting force because the horizontal ship velocity created an effective angle of attack on the vertical (roll-producing) wave velocity component. Moreover, because of damping, any SWATH ship with stabilizing fins will experience still more marked reductions in peak roll responses when underway. As with heave and pitch, the potential for damping roll is greater for a SWATH ship because in the 4000-ton size, for example, the natural roll period of a representative SWATH was 18.2 sec[23]

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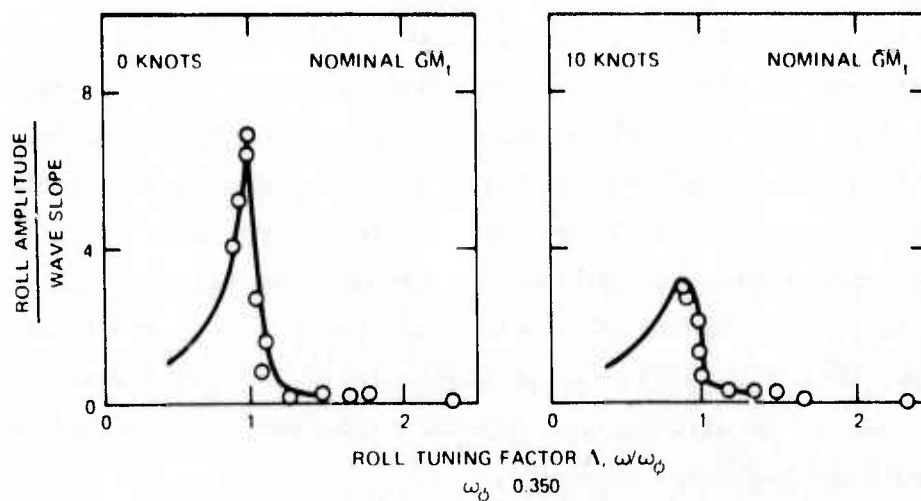
Figure 36 -- Effect of Ship Speed on the Bare-Hull
Roll Response of the SWATH IV Model in
Regular Beam Waves

(at 28-ft draft; from Kallio and Ricci[23])
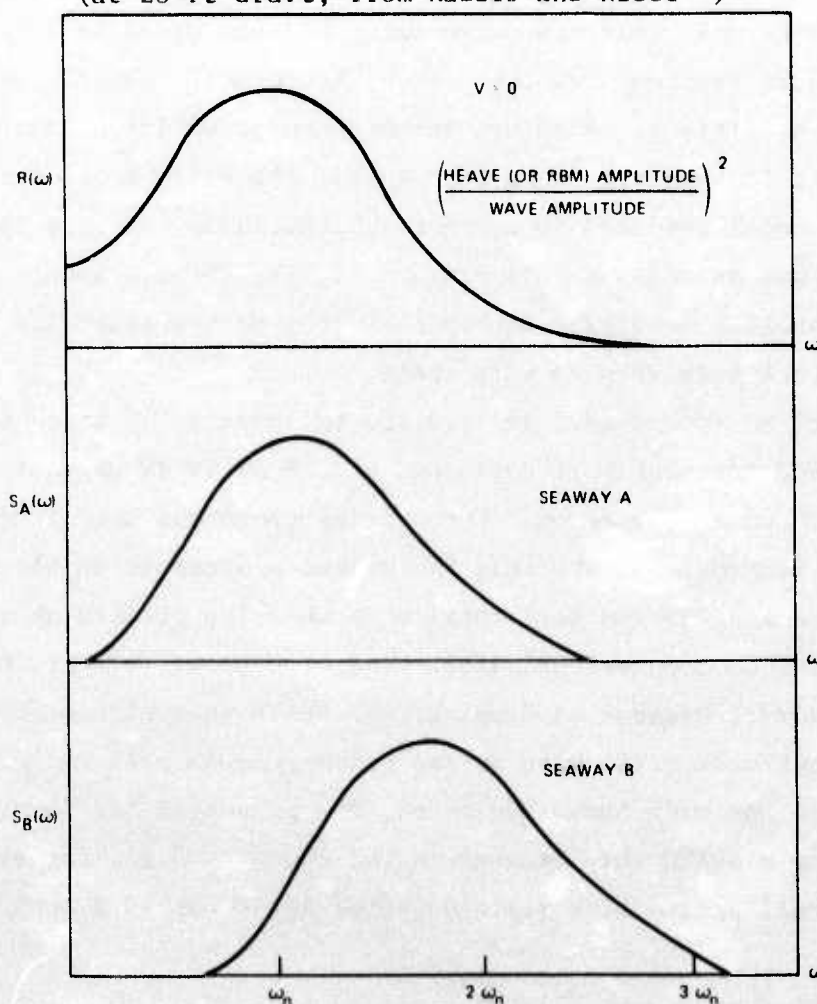
Figure 37 -- Example of the Distribution of Wave Energy
for Two Sea Spectra and the Variation in Motion
Response Amplitude Operator with Wave
Encounter Frequency

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compared to 9.2 sec for one monohull destroyer.* This means that the
roll of a SWATH is much softer and the magnitude of critical damping
about one-half as great. The corresponding wave lengths at which
roll resonance will be excited in beam seas are about 1700 ft for
SWATH IV and 435 ft for a conventional 4000-ton ship. This discrepancy
is significant because the shorter wave will be much steeper,** thereby
exciting larger roll angles.

Tests of the SWATH VI model, representing a 3000-ton ship with a
pair of fixed fins forward and aft, demonstrated roll motions at
20 knots in simulated State 6 beam seas that were better than those
exhibited under the same conditions by a 4000-ton monohull using
active antiroll fins. The heretofore unpublished SWATH model results
are shown in Table 9.

TABLE 9 -- PREDICTED ROLL MOTION IN IRREGULAR BEAM WAVES OF A
3000-TON SWATH SHIP EQUIPPED WITH FIXED FINS FORWARD AND AFT

Displacement, L. tons	3000
Speed, Knots	20
Significant Wave Height, Ft	15.7
Significant Roll, Deg*	7.7
*Peak-to-peak	

To this point, the motions of SWATH ships have been discussed for
principal headings only. The more general situation is one where a
ship encounters oblique seas; this implies that some degree of roll
excitation by the waves will usually exist. Indeed, conventional ships
have visible roll motion even in bow and following seas. Recent tests
of the SWATH VI model, however, revealed very little rolling when

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*Reported informally in NSRDC Technical Note C-011-H-04.

**For equal wave height, a 1700-ft-long wave has about one-fourth the
maximum slope of a 435-ft wave.

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run at 20 knots in bow-quartering seas with a 20-ft significant wave
height. The fact that the lower roll motion and acceleration make it
unnecessary to reduce speed or change heading may well be the single
most beneficial aspect of SWATH ship seakeeping from the viewpoint of
improving combatant operability in adverse conditions.

PREDICTING PERFORMANCE IN THE OCEAN ENVIRONMENT

The objective in designing naval ships is to provide a platform
that can carry out assigned missions regardless of sea conditions. A
common need is a means of maintaining speed to chase or evade an enemy,
to protect a convoy, or to maintain station with larger ships in a task
force. Ability to perform these roles is limited by shipping of water,
bow slamming, propeller racing, and deck accelerations. Air-capable
ships must satisfy additional mission demands. To safely launch and
land planes, a minimum speed must be maintained into the wind and there
is a simultaneous requirement to keep the amplitudes of vertical motion
and acceleration at the catapult, or in the landing area, within accept-
able values.

It is essential, therefore, for the naval architect to predict
the performance of his design in ocean waves. But the outstanding
characteristic of the world's oceans is the irregularity of their
surfaces, both when storm winds are blowing and under relatively calm
conditions. Oceanographers have found that an irregular sea can be
described by statistical mathematics by assuming that a large number
of regular waves having different lengths, directions, and amplitudes
are superimposed. Other researchers have found that the motions of a
ship in all but the most extreme seaways can be described as the
superposition of the responses of the ship to all component waves
of the seaway. The behavior of a ship in simple regular waves is thus
fundamentally important as an intermediate step in predicting behavior
in the real-world irregular wave situation.

The following discussion of considerations in making and interpreting predictions of ship motions in statistical seaway wave spectra is based in large part on an appendix to Reference 23 which bears repeating.

In general, for motion prediction purposes it is not sufficient to represent a seaway by specifying its statistical average wave height alone. Many sea conditions can have the same statistical average wave height and yet quite different spectral density (energy) distributions with respect to wave frequency. Particularly if a ship has small inherent damping, predicted motion amplitudes will be largest when wave spectral energy is concentrated at or near one of the resonant frequencies of the ships.

For example, assume two sea conditions with identical significant wave heights but considerably different spectral density distributions such that seaway A has its peak energy near the ship natural frequency while seaway B has its maximum energy at some higher frequency (see Figure 37). $R(\omega)$ designates the response amplitude operator, which is merely the squared value of one of the unit motion responses, as a function of wave frequency. The ship natural frequency for this type of motion is ω_n. There is the same total spectral energy for A and B

$$\int_0^\infty S_A(\omega) \, d\omega = \int_0^\infty S_B(\omega) \, d\omega$$

But the energy of the ship response (the area under the curve of motion versus wave frequency) will be much greater in seaway A than B

$$E_A = \int_0^\infty R(\omega) \, S_A(\omega) \, d\omega \gg E_B = \int_0^\infty R(\omega) \, S_B(\omega) \, d\omega$$

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Assuming that this energy has a Rayleigh distribution, the comparative significant motion amplitudes $(M_{1/3})$ in seaways A and B are directly proportional to the total ship response energies:

$$(M_{1/3})_A = 2\sqrt{E_A} \gg (M_{1/3})_B = 2\sqrt{E_B}$$

Clearly, the mathematics indicates this ship would experience much larger significant motions in seaway A even though it has no more spectral energy than B.

Since naval ships will be required to operate in a wide range of ocean wave spectra, caution must be exercised in using responses determined from experiments in a few wave spectral formulations (as is the case for random seas generated in a model test tank). To establish the operability of a design, motion responses should be quantified for the various seas which the ship will encounter during her lifetime. Since it is physically impossible to generate all these spectra in a tank, the approach taken is to first establish the response amplitude operators (RAO) either by analytical means or by experiments in regular or random waves and then to predict ship responses in any desired sea spectra. Second, if it is desired to predict statistics such as significant values or most probable maxima, the probability density function governing the phenomena must be decided on.

For a conceptual 4000-ton ship based on SWATH IV, the principle of linear superposition was applied to experimentally obtained RAO's and utilized in conjunction with 305 available ocean spectra measured at Station India in the North Atlantic Ocean. The assumption was made that the probability density function of peak-to-peak excursions followed a Rayleigh probability distribution law. Figure 38 compares these calculated responses with SWATH IV responses in tank-generated spectra. The predictions, designated by cross symbols in the figure, were obtained from the equation:

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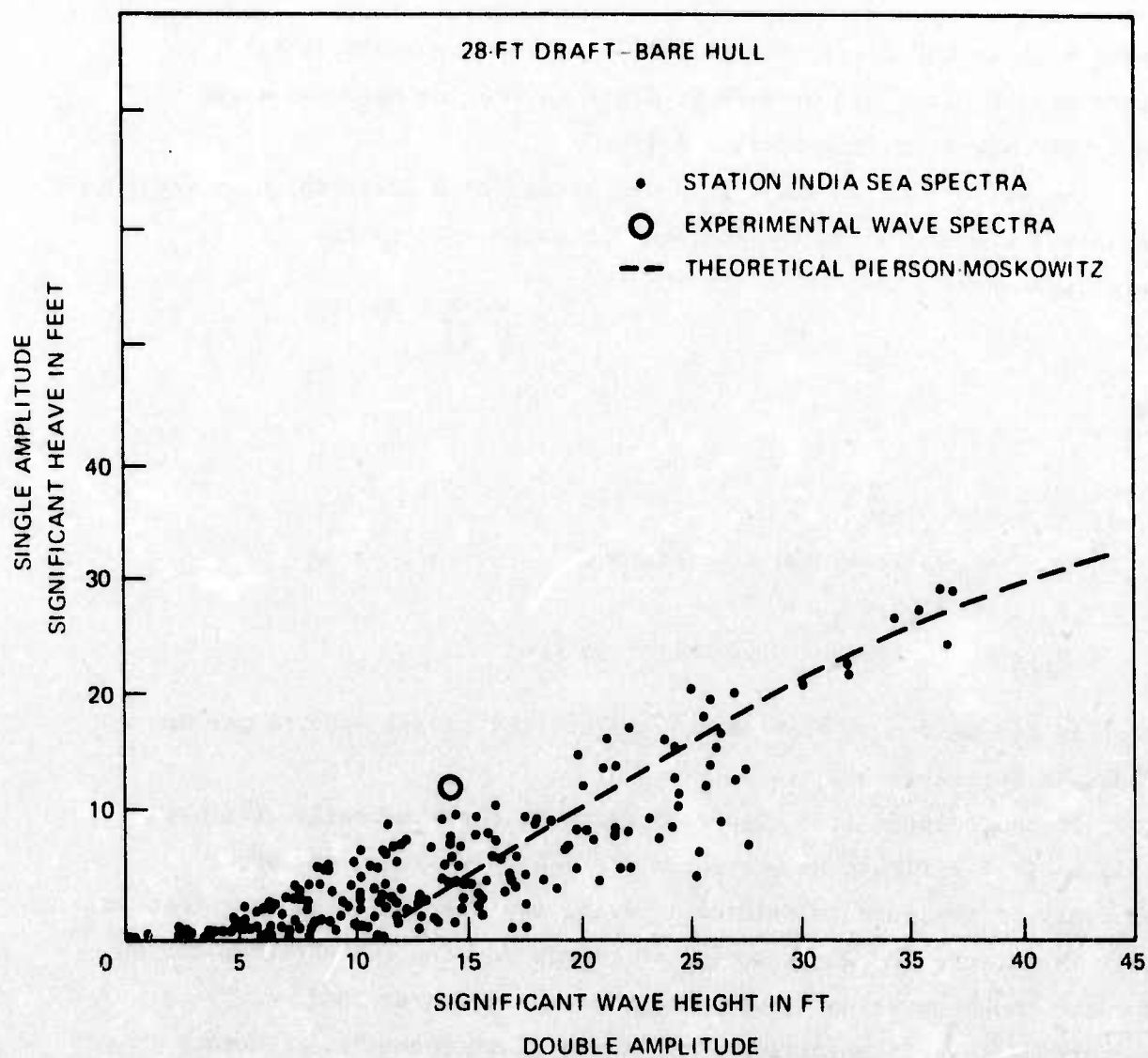
Figure 38 -- Comparison of Measured Heave Motion in Tested
Wave Spectra with Motion Produced in
Station India Spectra

(From Kallio and Ricci[23])

$$\text{Significant heave (or RBM) amplitude} = 2.0 \sqrt{\int_0^\infty R(\omega)\, S(\omega)\, d\omega}$$

where $R(\omega)$ is the response amplitude operator for SWATH IV based on tests of the bare hull at a 28-ft draft in regular head waves and $S(\omega)$ is a wave spectrum from Station India.[32]

The solid line in the figure was obtained by using the same response amplitude operators and the Pierson-Moskowitz spectra for a fully developed sea:

$$S(\omega) = \frac{A}{\omega^5}\, e^{-\left(\frac{B}{\omega^4}\right)}$$

where A = $0.0081g^2$

g = gravitational acceleration

B = $33.65/(h_{1/3})^2$

$h_{1/3}$ = significant wave height in feet

A clear discussion of the meaning and utility of sea spectra may be found in Reference 33.

It can be seen from Figure 38 that the experimentally obtained values of significant heave motion for SWATH IV lie at the upper boundary of the data calculated by using the Station India wave spectra. This is because the distribution of energy for the sea spectrum chosen for the model experiments was such that the spectrum obtained by converting wave frequencies to the appropriate encounter frequency for a ship speed of 20 knots had substantial energy near the heave

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[32]Miles, M., "Wave Spectra Estimated from a Stratified Sample of 323 North Atlantic Wave Records," National Research Council, Division of Mech. Eng. Report LTR-S1-118 (1971).

[33]Michel, W.H., "Sea Spectra Simplified," Marine Technology (Jan 1968).

Figure 39 -- Differences in State 6 Wave Spectra Used in SWATH IV
Tests and the Corresponding Encounter Spectrum for a Ship
Speed of 20 Knots, Head Seas

natural frequency of the SWATH IV model (see Figure 39). Using the term-
inology of the previous example, an A type seaway was used for the SWATH
IV tests; actually a large fraction of the real-world Station India
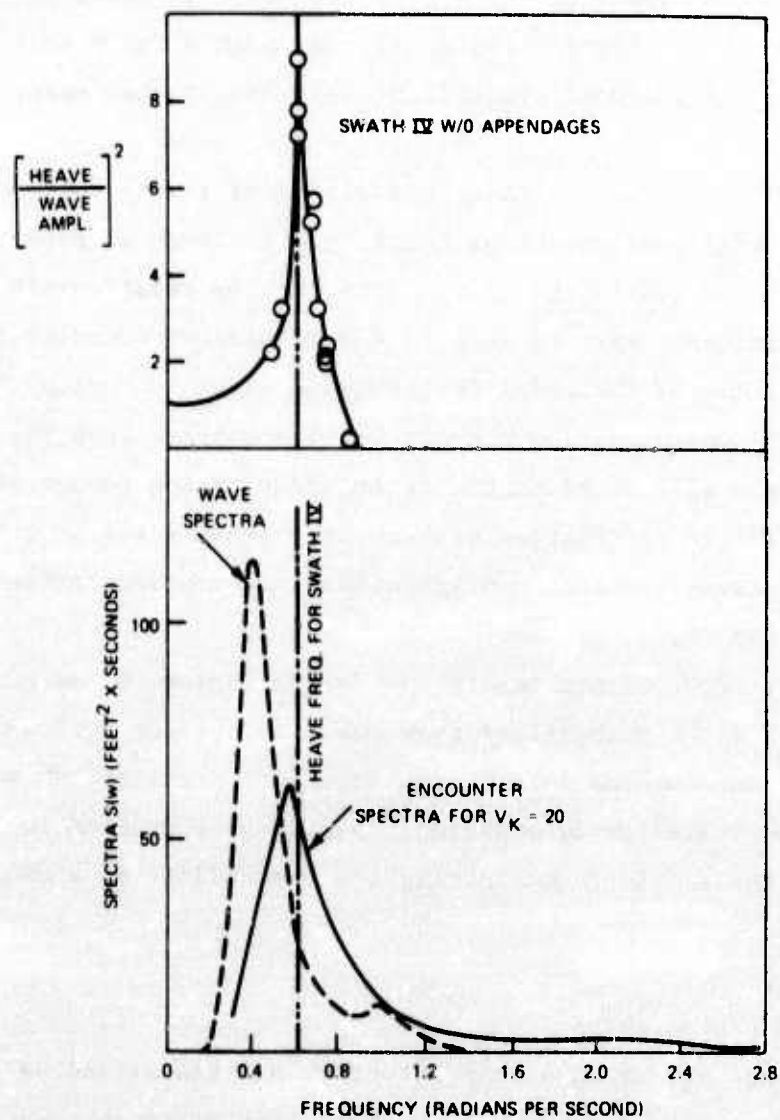spectra are of the B type with respect to the SWATH IV heave period of
10 sec. In many of the Station India spectra, such a SWATH ship would
have less motion for the same significant wave height than reported in
Reference 23.

The lesson to be drawn is that comparisons of seaway motions be-
tween different ship configurations should not be taken at face value
but rather should be considered in the light of the relationship of the
seaway modal* frequency with respect to the natural frequencies for each
ship configuration. If the modal frequency is close to a natural
frequency for one configuration but not for the others, then the sea-
keeping comparison will be distorted in the case of the former ship. A
more accurate picture of relative seakeeping potential can be obtained
by predicting motions for each configuration in a representative sample
of the 305 Station India spectra.

The Society of Naval Architects and Marine Engineers has provided a
concise summary of the probability that waves of various periods and
heights will be encountered in the most important areas of the world's
oceans.[25] This or similar information[33] should be consulted in deciding
which wave spectra to use in evaluating the operability of a SWATH ship
in those areas.

SEA-INDUCED STRUCTURAL LOADS

The sea loads acting on a ship structure are classified as primary,
secondary, or tertiary, depending on whether they affect the whole ship,
its supporting grillage, or merely localized plating. Loads used for
design purposes may be instantaneous values to account for maximum
response or long-term values to allow for fatigue effects. Furthermore,
they can be either dynamic (wave-induced) or quasi-static (hydrostatic
pressure).

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*The wave frequency of greatest energy for a particular spectrum is
termed modal.

Maximum wave-induced primary forces are usually estimated for monohulls by considering the ship as a beam statically balanced on a trochoidal wave of the same length as the ship and with a wave height of 1.1 $\sqrt{L}$. Other designers prefer a wave height of L/20, but the approach is the same. Weight distributions corresponding to "light ship" and "full load" conditions are used in conjunction with the buoyancy distribution resulting from the assumed wave profile to provide the design shear and bending moment distributions. (Studies of the stresses on the structure of two naval ships indicate that these static balance primary sea loads are roughly equal to the statistical maximum lifetime bending moment in a State 7 sea.)[34] Design scantlings are then increased locally, where necessary, in the light of secondary or tertiary load considerations.

However, the resulting stresses are quite small when longitudinal shear and bending moments are applied to SWATH ships in the traditional manner. More critical factors for designing the structure of twin-hull ships are (1) the transverse vertical bending moment from forces tending to separate or push together the two hulls and (2) the torsional moment from differential pitch motions (see Figure 40). Even a more sophisticated static balance approach is unsatisfactory for either of these factors because the sea loads on SWATH ships are largely hydrodynamic. Motions such as heave and roll must be included in order to obtain valid analyses of certain primary wave loads on SWATH designs. Beam and quartering headings are the "worst case" conditions for predicting design primary loads of a SWATH.

Investigations to date have sought to meet the immediate need for a definition of maximum expected sea loads on SWATH ships of various sizes. As yet no attempt has been made to determine the average long-term wave loading spectra necessary for designers to evaluate fatigue stresses on important structural members.

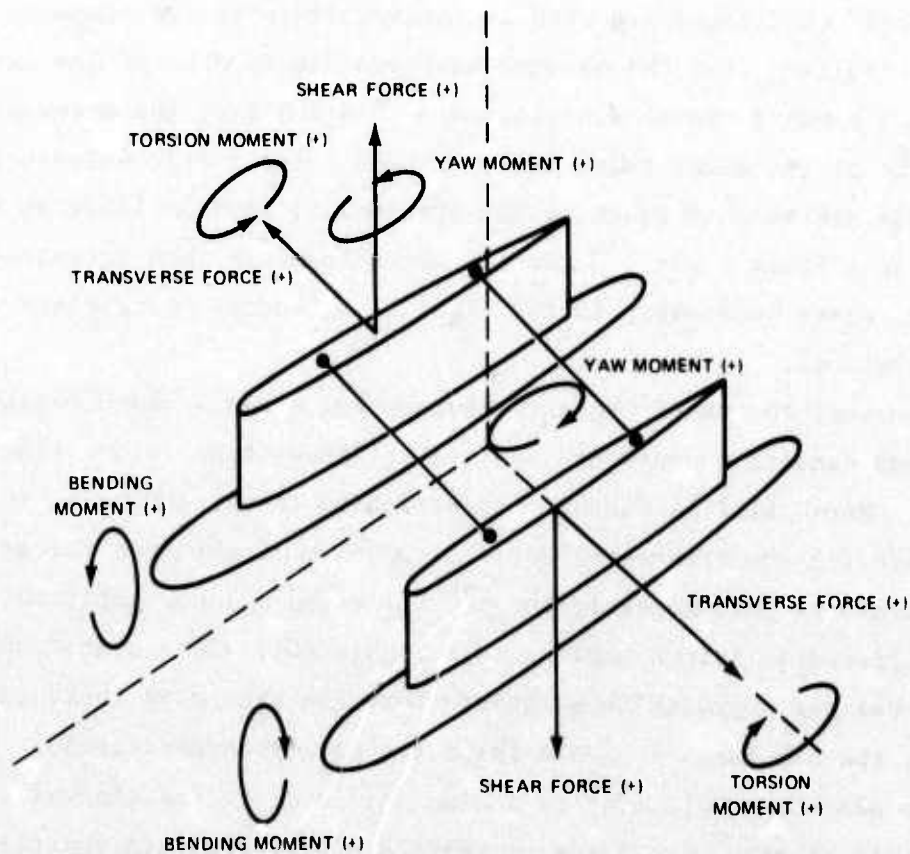[34]Andrews, J.N., "Model and Prototype Responses for a DL Class Destroyer," NSRDC Report 3325 (Mar 1970).

Figure 40 -- Sign Convention Used for Structural Loads
in Presentation of Experimental Results

(From Jones and Gerzina[12])

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Some tentative conclusions from the few completed empirical and analytical studies of wave-induced loads will be discussed first, followed by a description of guidelines for determining the maximum hydrostatic and hydrodynamic (slamming) pressures.

Tentative Conclusions Related to
Primary Loads

• The DTNSRDC close-fit SWATH ship motion computer program predicts that incident and diffracted wave forces (calculated by assuming no ship motion) govern some primary loads on a SWATH ship in beam seas.[13] Roll has essentially no effect and heave only slight effect on the transverse vertical bending moment or horizontal shear force, but both roll and heave influence the vertical shear force.

• Load measurements from tests of two different single strut-per-hull SWATH models demonstrate that the maximum transverse vertical bending moment at the longitudinal centerline of the cross structure is experienced at zero speed with the ship in beam waves.[23,12] Data for the first of these tests showed that the transverse bending moment is reduced somewhat in bow-quartering seas and is still smaller in stern-quartering seas.[12] What seems surprising is that neither the peak bending moment magnitude nor the wave length at which it occurred was affected by hull spacing over the range tested with the SWATH II model of an 850-ft CVA; see Figure 41. The main impact of a change in hull spacing is the effect on roll motion, but the theoretical predictions presented in Lee et al.[13] indicate that roll will not affect the peak magnitude of the centerline transverse bending moment of SWATH ships (see Figure 42). The peak bending moment occurs at a far different wave length than for roll resonance. Figure 43 shows that the bending moment on a SWATH ship at zero speed in beam waves can be predicted analytically by assuming that the ship is restrained. In the light of this finding, one may infer that the magnitude of the transverse bending moment acting on a SWATH ship will be influenced by the draft and projected area of the ship and by the length and

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0.0 F_n 0.153   0.306

X = 90°

BENDING MOMENT AMPLITUDE / DISPLACEMENT X WAVE AMPLITUDE

HULL SEPARATION OF 207 FEET

X = 90°

λ/L

HULL SEPARATION OF 157 FEET
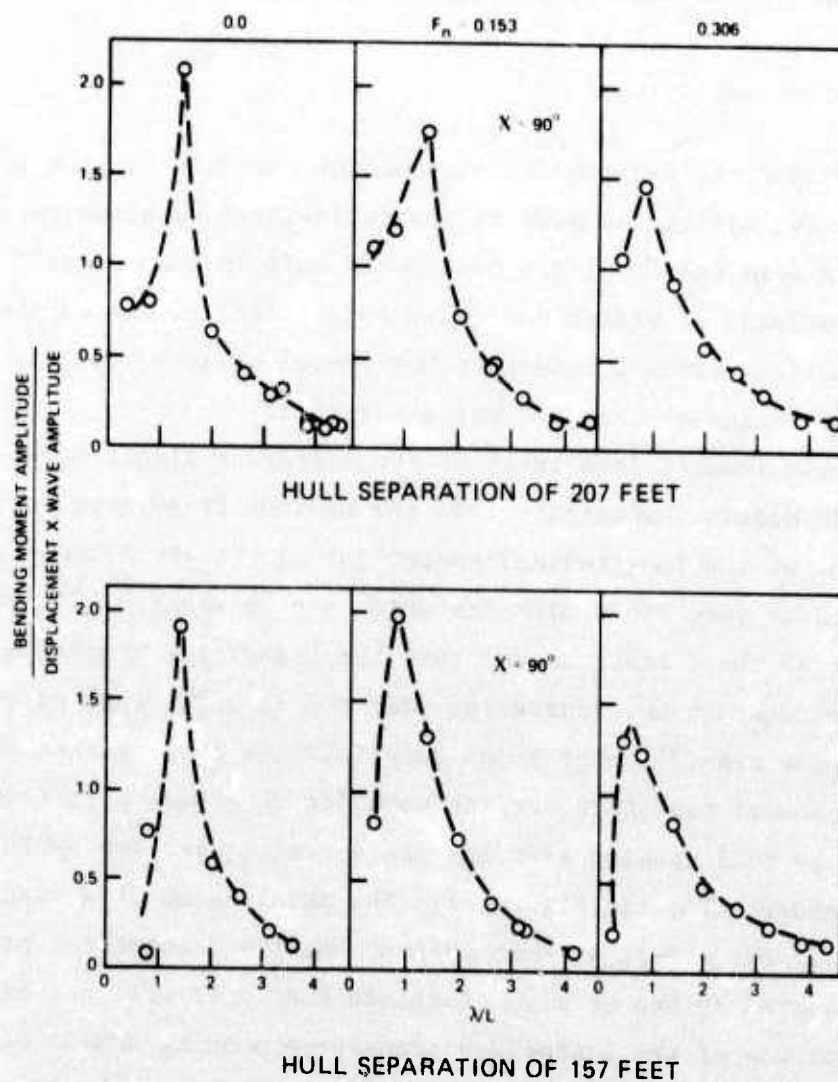
Figure 41 -- Effect of a Change in Hull Spacing on the
Transverse Bending Moment of the SWATH II Model
in Beam Waves

(From Jones and Gerzina[12])
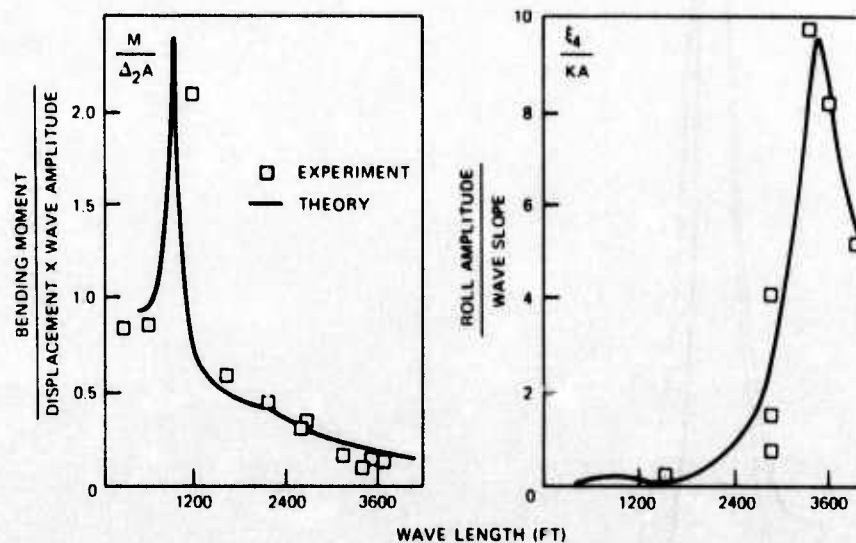
Figure 42 -- Comparison of Wave Lengths at Which Peak
Roll and Transverse Bending Moment Occur for
SWATH II at Zero Speed in Beam Seas

(From Lee et al.[13])
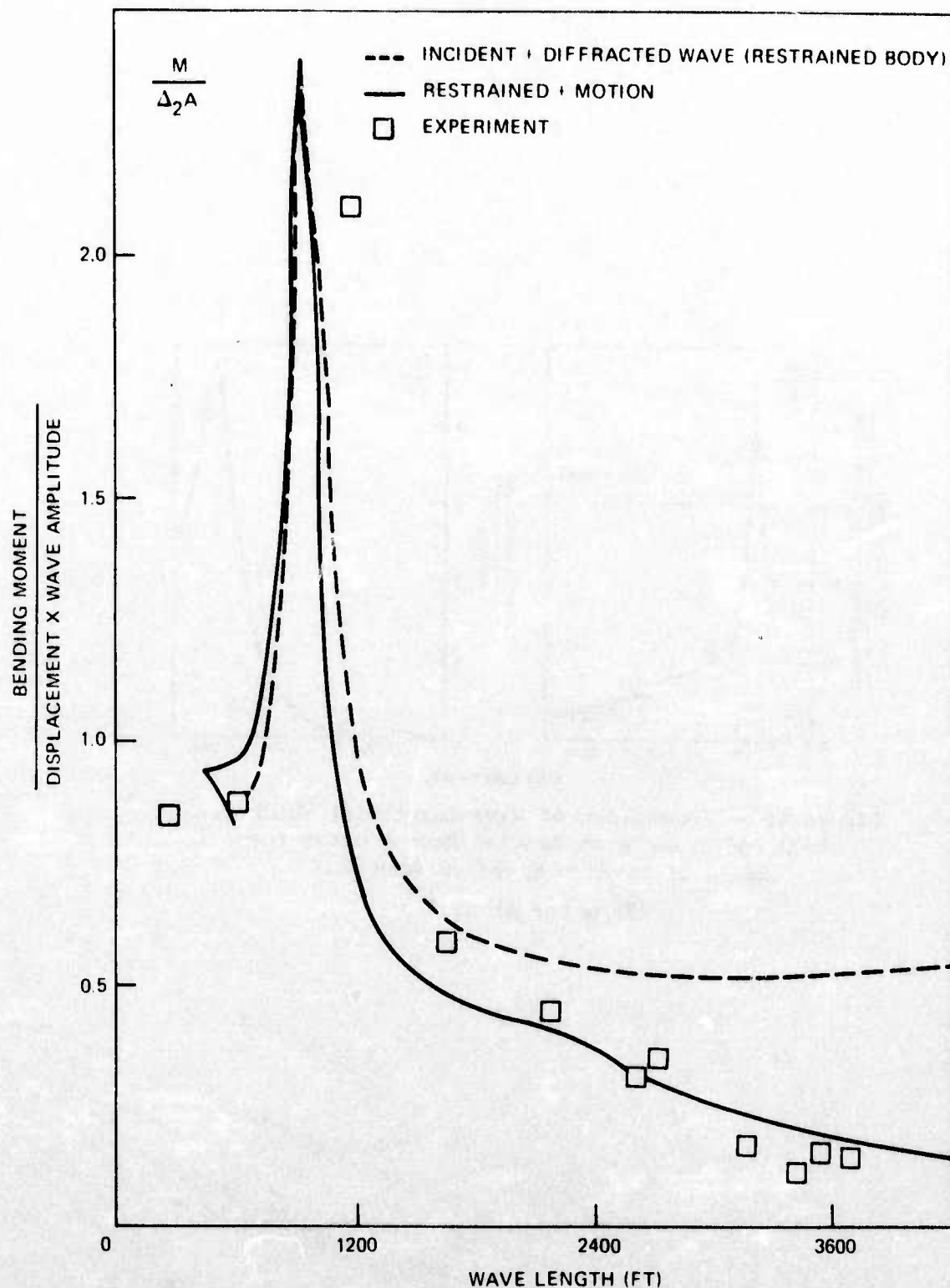
Figure 43 -- Curves of Predicted Transverse Bending Moment
as a Function of Wave Length for Alternative
Theories as Compared with Experimental Data
for SWATH II

(From Lee et al.[13])

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height of the incident wave. Thus one implication is that use of
tandem struts or of lower hulls with elliptical rather than circular
cross sections should decrease the transverse vertical bending moment
acting on a SWATH ship of a given size. However, tandem struts will
generally also have a smaller total section modulus, so stresses may not
be smaller.

• Other experimental load measurements on SWATH II indicate that
the largest horizontal and vertical shear forces occur in beam seas but
that the magnitudes for both are also appreciable in bow-quartering and
stern-quartering seas.[12] The horizontal shear force clearly decreases
with increased forward speed in beam seas. Measurements of vertical
shear force on SWATH II showed no consistent speed effects. Large roll
motion was accompanied by large vertical shear forces, but there were
other wave conditions that also caused this.

• Available test results confirm that the peak torsional and yaw
moments occur in bow-quartering and stern-quartering waves.[12] The
torsion moment magnitude appears to increase slightly at higher speeds
whereas the reverse is true for the yaw moment. Another difference in
their behavior is that the torsional moment increases noticeably with
greater hull spacing, but this effect on the yaw moment is barely dis-
cernible. For the structural configurations that have been designed
so far, both the torsional and yaw moments were relatively small.

• For structural design purposes, it is essential to know the
maximum lifetime primary wave-induced loads; these are generally taken
as State 7 conditions. With respect to the transverse vertical
bending moment, the recommended magnitude for preliminary design is
that moment corresponding to a wave force of one-half the ship displace-
ment acting at middraft, a distance d from the neutral axis of the
cross structure. Recent tests on a segmented load-measuring model of
a single-strut proposed SWATH developmental ship of 3050-ton dis-
placement served to corroborate the validity of this design criterion.

A significant single-amplitude transverse bending moment corresponding to a side force of 0.217 Δ (Δ = ship displacement) was measured[35] in simulated high State 7 seas with a significant wave height of 44 ft. Statistics predict that the maximum lifetime bending moment in State 7 seas would be about twice the significant value, or 0.434 Δ. A somewhat smaller equivalent side force can safely be assumed for tandem-strut SWATH structural designs. With regard to a design value for the peak torsion moment, the largest value measured in regular wave tests of the SWATH II model amounted to 60 percent of the peak transverse bending moment expressed nondimensionally in terms of displacement times wave amplitude.[12] In contrast, however, the greatest torsion occured at 30 knots in bow-quartering seas rather than at zero speed in beam waves.

Guidelines for Determining Hydrostatic
Pressures

A successful ship structural design must be capable of withstanding local maximum wave-induced pressures as well as the primary forces and moments. These pressures arise from quasi-static and dynamic effects, the latter being more difficult to predict.

The hydrostatic pressures which act at any point on the ship outer shell depend solely on the depth of submergence, or hydrostatic head, at each point. The hydrostatic pressures on a ship moving through waves are constantly changing since the submergence depth is a function of both wave height and ship motion amplitudes. Consequently, the maximum hydrostatic head for design of shell plating and supporting structure must be based on an understanding of the ship motion response characteristics in the most severe sea states likely to be encountered.

The controlling hydrostatic pressures on the shell are due to the maximum lifetime operating head of water above (below) the weather deck,

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[35]Andrews, J.N., "Determination of Wave-Induced Loads on a 3000-Ton Proposed Developmental SWATH Ship from Test Results of a Segmented Model," (in preparation by Structures Dept).
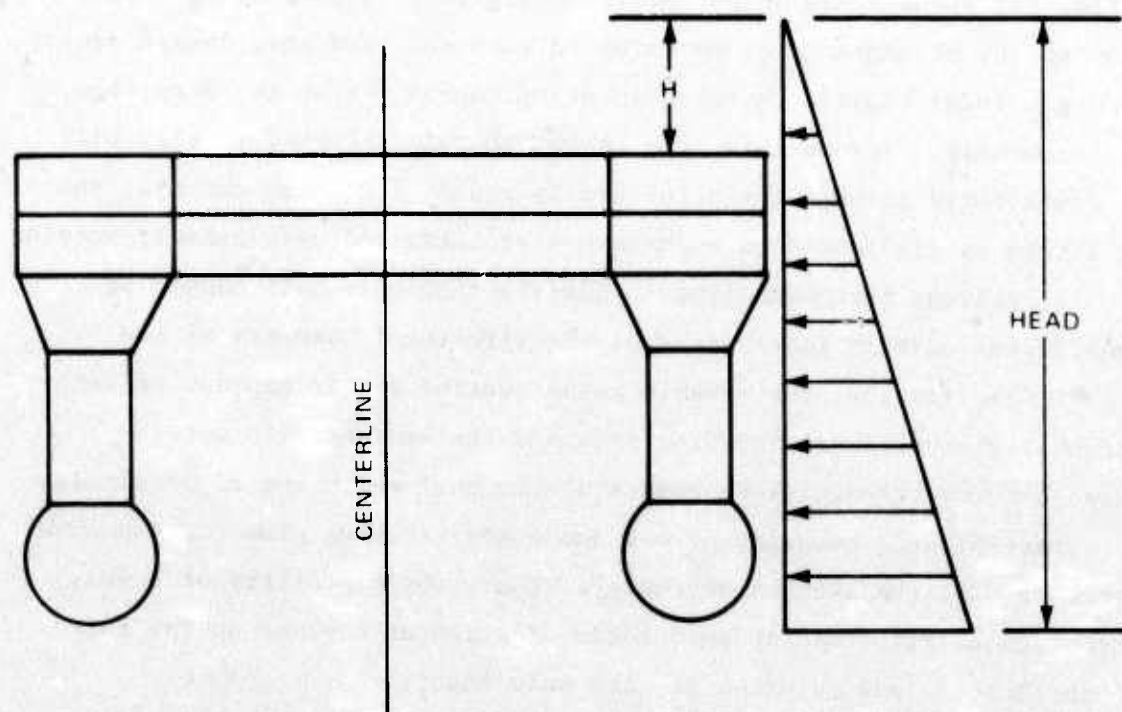
Figure 44 -- Design Lifetime Operating Hydrostatic Head

Figure 44. The scantlings of interior decks and bulkheads must also be sized to withstand existing Navy criteria for damaged hydrostatic heads in normal and vital spaces.

Considerations for Determining Hydrodynamic (Impact) Pressures

As yet there are few established design criteria for the transient loadings which arise from impacts of the sea on the structure of monohulls, let alone SWATH ships. In general, these impact loads result from an abrupt exchange of momentum between ship and sea; damage occurs when the local elastic energy absorption capability of the structure is inadequate. Beyond this, the energy that is absorbed locally will be distributed through the structure by means of dynamic response and will then be dissipated through both structural and hydrodynamic damping.

It follows that hydrodynamic loads acting on a hull cannot be considered entirely independent of the structural response of the hull. Specifically, the dynamic magnification factor depends on both the hull-structure natural frequency and the hydrodynamic terms. Those extreme structural responses of the hull which are of particular interest--plastic buckling or permanent set--require time for the absorption of large amounts of energy. Thus, the capability of a ship structure to withstand dynamic loads or stresses depends on the rate of application and duration of each wave impact.

Transient loads expected to be experienced by SWATH ships in extreme seas include slamming on the undersides of the cross structure and forward portion of each lower hull, strut bow flare immersion, and frontal wave impacts of green water on the upper box in very rough seas. Impact loadings for monohulls are generally most severe in the forward portion of the hull structure because that is where relative velocities between ship and sea are highest. However, the duration of monohull bottom slam loads is usually too brief to cause buckling of local structure. Slamming on the underside cross structure of a SWATH ship is probably similar to that on the bottom of a monohull. Since a

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SWATH ship has greater freeboard than a comparable monohull, the shipping of green water over the weather deck of a SWATH ship should be much less likely. If this were to occur, however, the large frontal area of a SWATH ship suggests that substantial hull loading could result from taking green seas aboard at the bow. Structural considerations, then, militate in favor of as much cross-structure clearance as feasible in a balanced SWATH ship design.

Preliminary estimates of slamming pressures on the cross structure of a 5000-ton SWATH design with 15 ft of clearance have been made analytically.[36] The accuracy of these estimates is both questionable and largely academic because model seakeeping tests have shown that a clearance of 15 ft is insufficient for State 6 seas. Use of model pressure measurements correlated with full-scale pressure and wave data appear to be the only valid recourse. Trials of the 190-ton SSP KAIMALINO will generate the essential full-scale impact data for verifying pressure predictions based on already completed tests of an SSP model. However, even the full-scale SSP data will be difficult to generalize. The relative velocity between ship and sea varies with speed and heading, with wave height and steepness, with cross-structure clearance height, with ship trim angle, and--most important--with the degree of motion control insofar as it affects heave/pitch response and phasing. Moreover, the resultant impact pressures depend on the shape of the underbody.

HULL STRUCTURAL DESIGN AND WEIGHT

Perspective

Twin-hull ships designed for a particular mission usually have greater enclosed volume and deck area than an equivalent monohull and, as a result, they tend to have a greater percentage of their displacement taken up by structural weight. This trend is accentuated in

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[36]Gianotti, J.G., "Estimate of Wave Impact Loads and Pressures for the Cross-Structure of a SWATH Ship," NAVSEC Report 6136-74-22 (Nov 1974).

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SWATH ships because of their deeper draft and the need for comparatively wide hull spacing to ensure adequate transverse stability.

Because the struts of a SWATH ship provide relatively little reserve buoyancy, the ship becomes weight-limited once the lower hull dimensions of a particular design are fixed. Therefore, the ultimate payload capabilities of the ship as eventually built will depend primarily on the structural weight, assuming that other ship weight groups will be similar in magnitude to those for a comparable monohull. When the time comes to select final hull dimensions, it is highly advantageous to be able to accurately predict the hull structural weight of a SWATH ship. The penalty for uncertainty will mean larger weight growth margins, resulting in a larger lower hull with increased wetted surface area, i.e., degraded powering performance. This effect is pronounced for SWATH ships because, typically, they have about twice as much wetted area per ton of displacement as a monohull.

Depending on the structural material employed and on the stress levels and configuration, from 2.0 to 8.0 lb of structure are required to enclose each cubic foot of ship volume. Whereas steel ships generally have structural densities of at least 5 pcf, aluminum ship structures achieve densities of 3 pcf or less. Intermediate densities result when steel and aluminum structural components are combined in a single structure. Despite its greater weight, steel continues to be the prime structural material for naval displacement ships because of its strength, lower cost, ease of fabrication, and toughness. Alternative lightweight materials such as aluminum result in higher ship acquisition cost and uncertain reliability, as evidenced by low permissible stress levels and the need for fire protection.

Consequently, the designer of a SWATH ship will use aluminum only if the steel-hull version has unacceptable payload and/or performance capabilities for the intended mission. Before this decision is made, he needs to determine the minimum-weight, economic steel structure for the SWATH configuration in question. It is therefore essential for the

designer to understand not only sea-induced loading but also how the ship transmits these loads to the various structural elements; the transitions and intersections are particularly important.

The tentative conclusions summarized below cannot be divorced from the design criteria and loads on which they were based. There are many subtle and unreconciled differences in the design assumptions used in the past by individuals, both inside and outside the Navy community, who have examined SWATH ship structures. This situation developed principally because (1) the sea loads (transverse vertical bending and cross-structure slamming) on SWATH ships were not understood fully and (2) the behavior and design stresses for aluminum in a marine environment are still the subject of much debate. Every effort is being made within the Navy to ensure that future SWATH structural designs have a common basis, but past results have to be taken "as is."

Therefore, it is not for parochial reasons but rather because of the author's knowledge of the design assumptions used in the analyses that most of the findings presented herein are based on DTNSRDC computer studies.[15,37] These tentative findings may or may not remain valid for SWATH ships larger than the size range of 2000 to 5500 tons within which these Navy studies were confined.

Tentative Conclusions on Effect
of Material

• With existing assumptions and Navy-established criteria, potential reductions in primary structural weight of 40 percent compared with steel can be predicted for aluminum plate-and-girder construction. However, this figure does not reflect the usual need to "beef up" aluminum structures for greater rigidity or to withstand fatigue stresses. When the need for additional insulation or other fire protection measures are also taken into account, the weight savings shrink to 20 percent.

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[37]Lev, Frank M. et al., "Structural Weight Determination for SWATH Ships," NSRDC Report 4335 (in preparation).

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• In general, HTS (high tensile steel) appears to be a good choice of material for constructing SWATH ships. With existing design criteria, HY-80 is marginally advantageous even for the submerged lower hulls, which are mainly subject to compressive stress. Use of mild steel, on the other hand, will increase total primary structural weight by about 10 percent.

• Various types of hybrid construction have become a more practical option for SWATH ship structures with the advent of the exploded bimetalic joint method of connecting welded aluminum to welded steel. The principal caveat is that these joints must not be immersed in salt water where electrolysis would destroy them. This objection can be met by confining hybrid construction to the above-water upper hull of SWATH ships. In the limiting case with steel struts and lower hull coupled with an entirely aluminum upper hull, the potential weight savings are about 20 percent. Indeed, the first Navy SWATH-type craft (the 190-ton SSP KAIMALINO) has precisely this type of hybrid steel-aluminum structure. Less extensive use of aluminum can result in smaller but also significant weight reductions.

Tentative Conclusions for
Design/Configuration

• Probably the single most important determinant of structural weight for SWATH ships is the amount of enclosed volume in the upper hull. Beyond this, the upper hull proportions in terms of length, width, and depth are significant factors. Typically, if the same material is used throughout, the upper hull compromises about 50 percent of the total weight of primary structure in a SWATH ship.

• Even without an inner bottom, a one-level upper hull is structurally adequate to resist maximum wave-induced loads in SWATH ships as large as 5500 tons; on the other hand, two levels are far superior from the standpoint of damage stability and watertight integrity.

• Doubling the depth of a one-level SWATH upper hull from 9 to 18 ft (while maintaining the same length and width) increases the weight

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of the bridging structure by about 6 percent while decreasing the structural density by over 40 percent. The subsequent addition of a middle deck to divide the 18-ft-deep upper hull into two levels increases the weight of the bridging structure by 15 percent. Thus, it is possible to double the upper hull volume while increasing the primary structural weight of the upper hull by only 20 percent and the total weight of primary structure by only 10 percent.[37]

• Two generic cross-structure arrangements are capable of with- standing primary wave-induced forces and bending moments, regardless of whether the SWATH configuration has one or two struts per hull. The superior arrangement from the standpoint of damage subdivision is basically a grillage. Transverse bulkheads act together with the effective deck and/or shell plating to form box girders which resist both normal and axial transverse loads from whatever cause. Similarly, longitudinal bulkheads act with deck and shell plating to resist normal and axial loads in the longitudinal direction. The entire structure combins to resist torsional loads.

An alternative cross-structure arrangement is to use a combination of relatively few transverse stiffeners and stanchions to transmit deck loads into a deep double-bottom structure. This has been the preferred approach for Navy designs because the double bottom is considered to act as a shock absorber when wave impacts occur.

Tentative Conclusions on Effect of
Design Loads

• With existing assumptions and Navy criteria, the scantlings for most structural members on SWATH ships under 5000 tons appear to be governed by secondary and tertiary design hydrostatic heads, slamming pressures, and/or local deck loads. One computer study[15] indicated only a 10-percent increase in the estimated structural weight of a 4000-ton SWATH ship following a threefold increase in the magnitude of the wave- induced bending moment over that obtained with a total side force of one-half the displacement (the standard design load). Because the

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imposed transverse vertical bending moment is assumed to vary linearly from the ship keel to the neutral axis of the bridging structure, the weight of structure for the upper hull increased by 12 percent compared to only 6.5 percent for the lower hull.

• A second computer study of the same 4000-ton SWATH ship predicted that structural weight could be reduced about 10 percent if the design hydrostatic head could be decreased from 66 ft (main deck) to 33 ft (5 ft above design waterline). As before, the weight decrease was not distributed uniformly, ranging from a savings of 5.5 percent in the upper hull to almost 20 percent in the lower hulls.

• To investigate the significance of the slamming criterion on structural weight, the local design slamming pressures on the cross structure and struts were arbitrarily reduced from 100 psi at the quarter length and 45 psi amidships to zero throughout. The resulting weight of the hypothetical SWATH structure was 9 percent less for the lower strut and about 7 percent less for the upper hull. Actually, slamming may have an even greater effect on structural weight because the original design was based on a uniform pressure of 1500 psf acting over the entire slam-prone area whereas at-sea measurements on the AGOR-16 conventional catamaran indicate that 30 psi (4320 psf) may be more realistic.[38] Valuable pressure data were obtained recently with the SWATH VI model in State 7 seas but these have not yet been analyzed.

FEASIBILITY/CONCEPTUAL DESIGN

Feasibility exploration and conceptual design are concerned with the preliminary determination of major ship characteristics which affect performance and cost. The design process is iterative in nature. It is necessary to start with a "reasonable" hull form and general arrangement as the basis for estimating weights, displacement, resistance and powering, endurance, stability, and so forth. These initial, first-cut numbers then serve as a point of departure for subsequent steps in the

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[38] Hadler, J.B. et al., "Ocean Catamaran Seakeeping Design Based on the Experiences of USNS Hayes," Paper No. 2, Presented at the 1974 Annual Meeting, Society of Naval Architects and Marine Engineers, New York, N.Y. (1974).

design process; refinement through successively more detailed analyses until a consistent and satisfactory design is obtained. Since a SWATH ship is weight-sensitive, the choice of reasonable hull dimensions must be based on a quite accurate estimate of full-load displacement. The initial hull form should also reflect the known sensitivity of various aspects of SWATH performance to small changes in hull dimensions and proportions.

Governing Considerations

Five key technical areas contribute factors that are important for a successful, balanced SWATH ship design: (1) speed-power in calm water, (2) sizing of pitch-stabilizing motion-damping appendages (3) seakeeping with active rather than passive controls, (4) sea-induced structural loads, and (5) hull structural design and weight. Now that these technologies have been discussed in some detail, a methodology for designing a SWATH ship will be set forth. First, the controlling considerations and parameters must be identified.

To the extent that emphasis can be placed on any single category of technology needed to design SWATH ships with greater operability than conventional ships, hydrodynamics in all of its facets should be given precedence when selecting principal dimensions and hull shape. Simplicity of hull structure and propulsion machinery are subordinate considerations for high performance naval combatants.

An essential step in conceptual design is to determine the hydrodynamic performance that can be expected from alternative configurations of hydrostatically balanced SWATH ships. Calm-water powering requirements are strongly influenced by the wavemaking resistance characteristics which, aside from operating speed, are affected by ship length and slenderness, number of struts per hull, size of control surfaces, and depth of submergence. Improved seakeeping must be designed into SWATH ships by minimizing the likelihood that resonant wave frequencies will be encountered at intended operating speeds and by ensuring that, once excited, undesired motions are dampened to the greatest extent

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possible without incurring unacceptable drag penalties. In particular, the heave, pitch, and roll natural periods determine the threshold sea conditions in which SWATH ship motions will start to deteriorate at various headings relative to the waves. The designer should strive for SWATH configurations with all natural periods, at least 9 sec, but well separated, and with no natural period that is an integer multiple of the period for another motion mode. Damping of vertical motions can be increased by adding horizontal control surfaces and incorporating strut flare above the design waterline or an elliptical cross section for the lower hulls.

The multitude of design factors and innumerable combinations thereof constitute both a difficult problem in synthesis and an unprecedented opportunity. Because there are more degrees of freedom in SWATH design, there is a greater probability that ship characteristics can be tailored to specific mission requirements. It is possible to approximately rank controlling dimensions according to their usual impact on a SWATH ship design:

1. Displacement:

    • A major influence on the selection of lower hull and strut proportions because of the need to satisfy both buoyancy and stability requirements.

    • Affects powering requirements as a result of its direct impact on the amount of wetted surface area.

    • Influences SWATH motion characteristics and seakeeping since it is one of the factors which determine the natural heave and pitch periods.

2. Upper hull beam/Beam overall/hull spacing:

    • Together with upper hull length, this determines the amount of area available on the main deck for mission equipment and operations. It affects intact transverse stability and roll motion characteristics.

    • Affects powering requirements because of its impact on the amount of interference drag resulting from the proximity of the two demihulls.

• In combination with the cross-structure clearance height it establishes the maximum damage heel angle.

• Determines accessibility to the Panama Canal and limits the number of suitable building ways and drydocks.

3. Cross-structure clearance height:

• Affects both seakindliness and seaworthiness by controlling the frequency and severity of wave impacts on the upper structure.

• Affects static stability by influencing the height of the center of gravity as well as the total structural weight.

• In combination with the upper hull beam, it determines the maximum damage heel angle.

4. Lower hull diameter:

• Maximum value is often constrained by requirements of propulsion machinery arrangement, whether the prime mover is located in the upper box or lower hull.

• Effectively limits the selection of power plants suitable for location in the lower hull of small, high-performance SWATH ships to the few marinized aircraft gas turbines.

• Limits the maximum hull spacing of beam-constrained ships, whether for the Panama Canal or other requirements.

• Determines the minimum hull submergence for acceptable wavemaking resistance characteristics, thereby influencing the minimum operating draft.

• One of the major influences on length selection, and therefore on displacement, because of the sensitivity of wavemaking resistance to length-to-diameter ratio for certain Froude number regimes.

• Affects powering as well as structural weight requirements because of its impact on the surface area of the lower hulls.

5. Waterplane area/strut thickness:

• Minimum area is determined by intact stability requirements; the minimum strut thickness is often governed by needs related to removal of propulsion machinery from the lower hull.

• The amount and longitudinal distribution of strut waterplane area affects the magnitude and occurrence of ship motions as well as the powering penalty due to wavemaking resistance.

6. Lower hull length/slenderness:

• Minimization of high-speed powering requirements depends on a tradeoff between design speed-length ratio, wetted surface area, and the lower hull and/or strut slenderness.

• The degree of slenderness is limited by propulsion machinery size requirements and, ultimately, by structural considerations.

• Increasing the lower hull length tends to increase structural weight and ship displacement because of the accompanying increase in upper box length and volume.

7. Lower hull submergence/draft:

• Minimum acceptable submergence of the lower hull is usually governed by the onset of "air drawing" into the propeller; together with the hull diameter, this submergence requirement determines the minimum operating draft.

• Further increases in draft may improve motions in severe seas but will have no appreciable affect on powering requirements.

• Lower hulls with elliptical cross sections can be used to decrease operating draft without major effect on speed-power performance.

Bounding the Design Problem

To facilitate the initial selection of a reasonable SWATH form, it is desirable to narrow the choice of values for the key dimensions to more manageable proportions by a process of exclusion, successively applying "filters" of decreasing mesh width. An obvious starting point in determining first-order design limits on these controlling dimensions is to take operational as well as practical engineering and/or hardware considerations into account.

One should keep in mind that the contour of feasible design solutions for SWATH ships is discontinuous, with several well-defined boundaries

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and therefore that relatively small changes in one factor may make it necessary to revamp the whole design. A displacement increase of 15 percent, for example, would turn the typical SWATH ship design into a barge, floating on its boxy upper hull structure. In this event, the initial design would probably not be suitable as the starting point for the next iteration. It is precisely because of the weight-sensitive nature of this configuration that initial weight estimates used in arriving at the total displacement must be made thoroughly and carefully.

Probably the three most stringent design constraints are those for the maximum upper hull and underwater beam, cross-structure clearance height, and minimum lower hull diameter. Considerable flexibility remains in the selection of values for other key hull dimensions. A criterion for excluding many combinations of principal dimensions which provide adequate volume and displacement is the need to satisfy requirements for intact static stability. With monohull ships, transverse stability is usually an important consideration but adequate longitudinal stability can be taken for granted. But in the design of SWATH ships, equal care is required to ensure that longitudinal as well as transverse stability are acceptable. For purposes of completed feasibility design studies, acceptable stability was defined as a transverse metacentric height (GM_T) of at least 3.5 ft and a minimum longitudinal GM_L of 5 percent of the ship length.*

Principal design factors which affect the value of the transverse and/or longitudinal metacentric height include: (1) full load displacement, (2) centerline hull spacing, (3) amount and distribution of strut waterplane area, (4) vertical center of buoyancy above the keel (KB), and (5) vertical center of gravity above the keel (KG). The vertical center of buoyancy is of secondary importance because it is a dependent function of the design draft. Similarly, the vertical center of gravity depends on the general ship configuration, i.e., the vertical distribution of fixed and variable weights. Numerous conceptual designs based on aluminum as well as on steel construction

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*Subsequent analyses and model seakeeping tests indicate that a minimum GM_L of 10 percent of ship length would be more realistic.

have demonstrated that the KG location above baseline for a SWATH
ship in the full-load condition can be approximated by the following
equation:

$$KG \approx 29.0 \text{ ft} + (0.001 \text{ ft/ton}) \times (\text{full-load displacement})$$

A particular steel SWATH design may have a vertical center of gravity
located from 1 to 2 ft higher than the value given by this equation
whereas an aluminum SWATH design may have a KG that is 1 to 2 ft lower.

The stability-limited values of displacement, hull spacing, and
strut dimensions were calculated by using the criteria for minimum
GM_T and GM_L and the appropriate equation for KG. These parametric
results for single-strut SWATH ships whose beams will be constrained by
the width of the Panama Canal are given in Figures 45 and 46; they
correspond to the approximate minimum and maximum practical values of
strut fullness (waterplane area coefficient). For purposes of evaluating
transverse stability, the maximum submerged beam was taken as 106 ft
(the width of the Panama Canal is 108 ft), to allow clearance for small
projections.

For this analysis, the strut waterplane area was broken into its
three component factors: strut length, maximum thickness, and water-
plane area coefficient. Strut length was assumed to be a constant
85 percent of the lower hull length. Maximum strut thickness was ex-
pressed as a fraction of the lower hull diameter; four values were
considered (0.30, 0.40, 0.50, and 0.60). Waterplane coefficient values
smaller than 0.70 did not provide sufficient longitudinal inertia, and
values larger than 0.90 were considered undesirable from the standpoint
of wavemaking resistance.

The lower hulls were assumed to be slightly elliptical in cross
section (major axis 1.25 x minor axis) with dimensions chosen to provide
the same area as circular hulls with diameters ranging from 14 to
22 ft. For each nominal diameter, the hull spacing was assumed to be
the maximum possible with an equivalent elliptical lower hull, as
summarized in Table 10. The draft used in this analysis for the

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SWATH represented by each combination of parameters was the minimum
value considered permissible for avoidance of propeller air drawing in
calm water, approximated as 1.67 x the nominal hull diameter. For
purposes of computing displacements, each lower hull was assumed to have
the buoyant volume provided by a prismatic coefficient of 0.80.

TABLE 10 -- HULL DIMENSIONS AND MAXIMUM HULL SPACING FOR
WHICH STATIC STABILITY-LIMITED DISPLACEMENTS
WERE COMPUTED

Nominal Lower Hull Diameter ft	Equivalent Elliptical Lower Hull ft	Maximum Hull Spacing ft	Assumed Design Draft ft
14.0	15.65 x 12.52	90.35	23.48
16.0	17.89 x 14.3	88.11	26.83
18.0	20.12 x 16.1	85.88	30.18
20.0	22.36 x 17.89	83.64	33.54
22.0	24.6 x 19.68	81.40	36.89

From consideration of Figures 45 and 46, the following points can be
drawn:

  • For a particular lower hull diameter and strut thickness, the
maximum feasible displacement tonnage can be increased merely by in-
creasing the lengths of the struts and lower hulls by the same proportion,
thereby ensuring adequate transverse and longitudinal stability.

  • The minimum length-to-diameter ratio is governed by longitudinal
stability requirements, varying with hull diameter as well as the strut
W/D ratio and waterplane area coefficient. Combinations of parameters
to the left of the end points marked on the lines of constant W/D ratio
are unstable.

  • The effect of increased strut fullness (waterplane area coefficient)
is to provide more choice in the selection of feasible combinations of
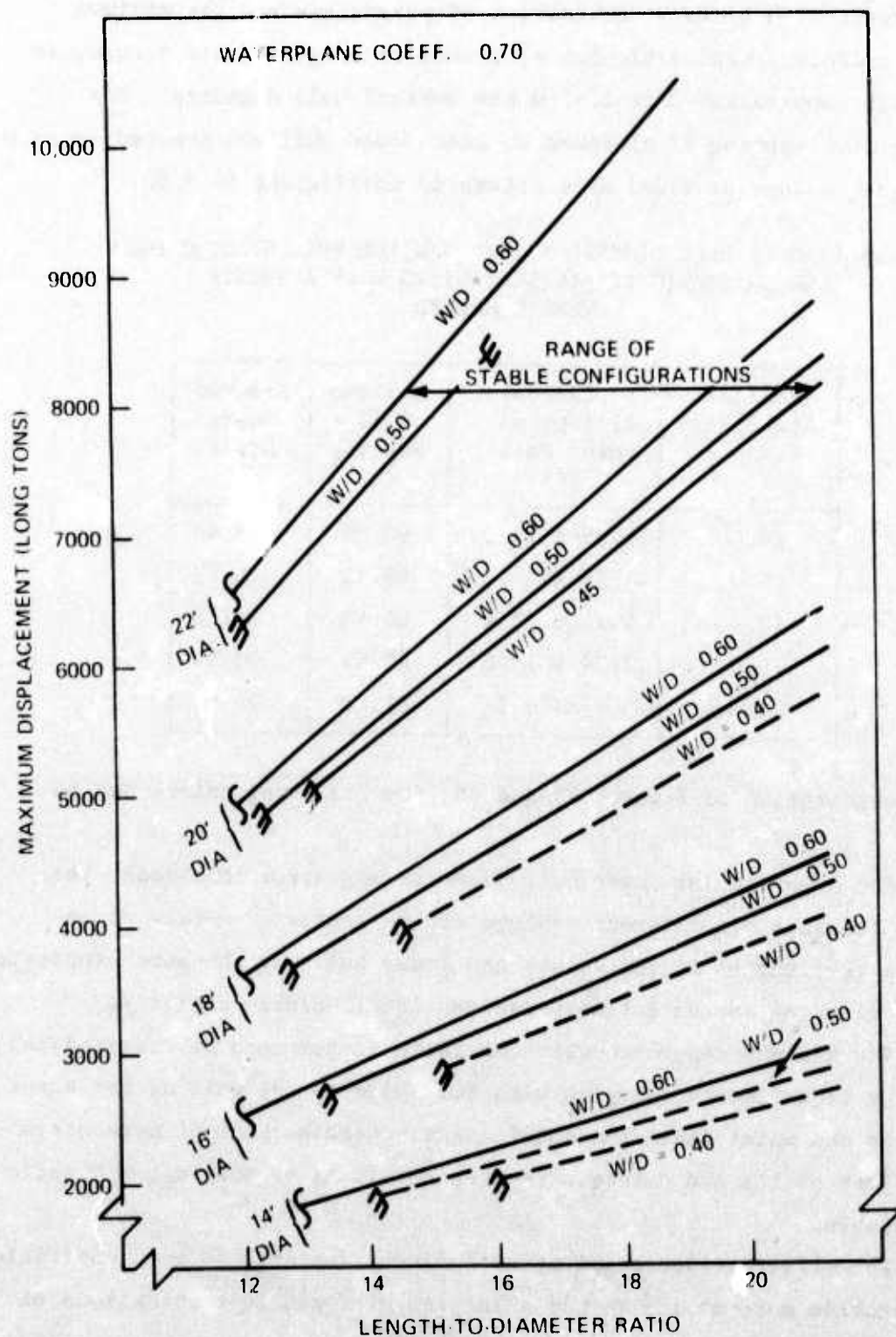hull dimensions.

Figure 45 -- Boundaries of the Maximum Statically Stable Displacement
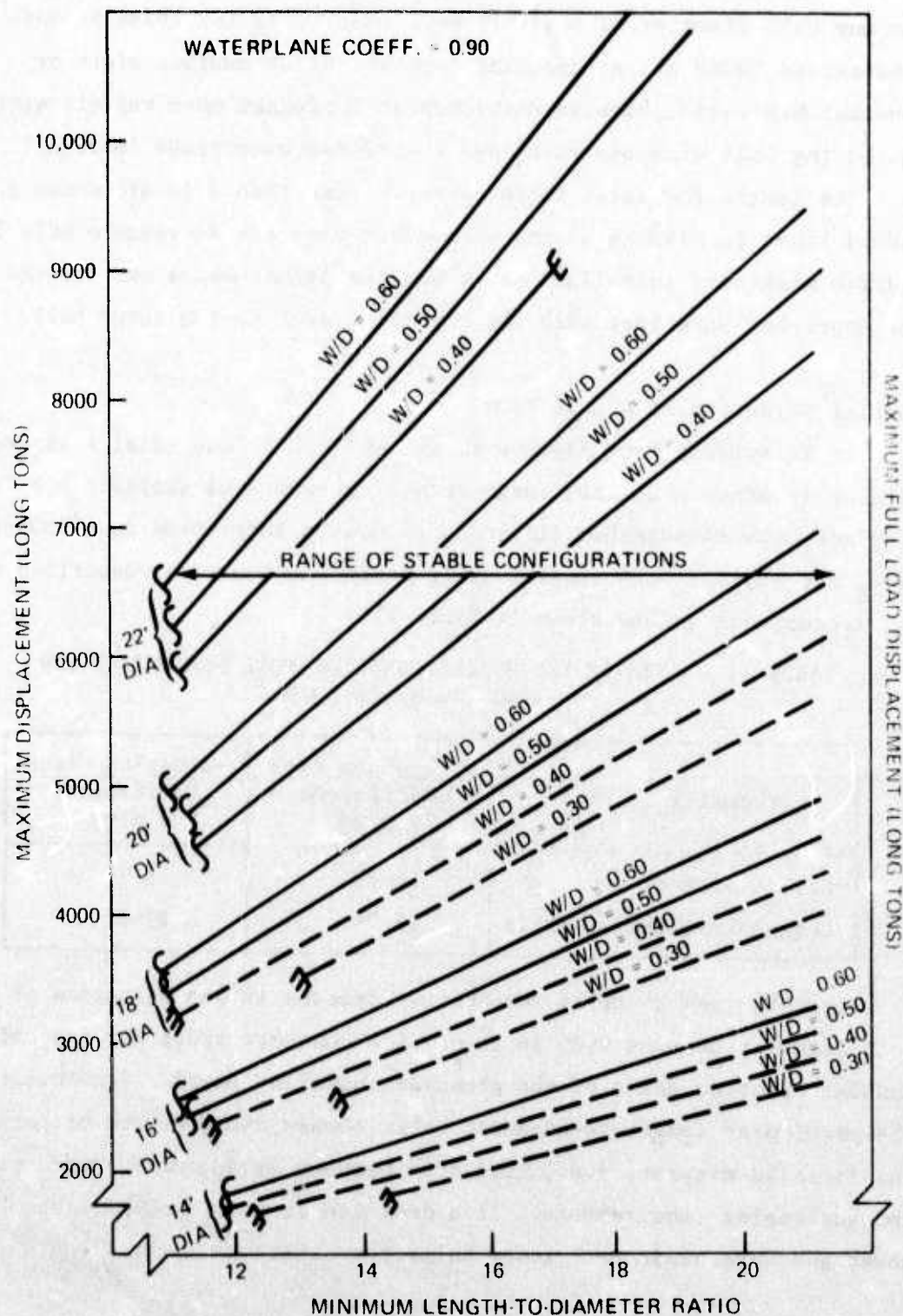for Selected Hull Parameters and Waterplane Coefficient of 0.70

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Figure 46 -- Boundaries of the Maximum Statically Stable Displacement
for Selected Hull Parameters and Waterplane Coefficient of 0.90

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• Although not shown specifically, there is a well-defined absolute
maximum hull diameter of a little more than 22 ft for these PAUMAX-
constrained SWATH ships, assuming constant strut maximum width or
constant W/D ratio, because displacement increases more rapidly with
increasing hull diameter than does transverse waterplane inertia.

The limits for strut thicknesses of less than 8 ft are shown as
dashed lines in Figures 45 and 46 because they are acceptable only for
Z-drive machinery installations, where the prime movers are located in
the upper box structure with the reduction gear in the lower hull.

Initial Selection of a Hull Form

It is evident from Figures 45 and 46 that if the canal beam con-
straint is adhered to, the range of hull proportions suitable for large
displacements is somewhat limited. If one is interested in a 4000-ton
ship, for example, the feasible hull proportions are circumscribed by
the approximate values shown in Table 11.

TABLE 11 -- STATICALLY STABLE RANGE OF HULL PARAMETERS FOR
A 4000-TON SWATH SHIP

Parameter	Waterplane Area Coefficient = 0.70	Waterplane Area Coefficient = 0.90
Hull Diameter, ft	16-18	16-19
Length-to-Diameter Ratio	13-21	11-21

In this case there is comparative freedom in the selection of a
hull diameter because even 16 ft provide adequate space for conventional
double-reduction gears of the probable installed power. Consequently,
the particular length-to-diameter ratio chosen would depend primarily on
the intended mission, i.e., tradeoffs between arrangement, speed-power,
and seakeeping requirements. If a decision is made to locate one high-
power gas turbine in each lower hull, then the 7-ft clear width

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needed for engine removal will define the minimum acceptable strut thickness-to-diameter ratio as 0.44 for a 16-ft-diameter and 0.37 for a 19-ft diameter hull. The total amount of strut waterplane area will generally be the minimum consistent with transverse stability requirements and will vary with the hull spacing.

Provision of additional waterplane area should be avoided because it will degrade seakeeping performance by decreasing the heave natural period and increasing the heave response stiffness. The extent of hull and strut slenderness is constrained first by geometry, i.e., the need to provide adequate buoyancy and strut waterplane area. Beyond this, speed-power performance becomes the dominant consideration, but the impact on arrangements must also be investigated. The combination of length, strut thickness, and hull diameter that is finally selected is usually not simply the optimum for minimum high-speed drag but a compromise, involving good powering characteristics at cruise speed as well.

SUMMARY

The preceding discussion of different aspects of SWATH ship technology is representative of current prediction tools and techniques. No valid generalization can be made about the comparative merits of SWATH and conventional ships for the Navy; it is beyond the scope of this report to present the requisite in-depth comparisons. The size of functionally equivalent SWATH and monohull ships should be based on a matching of payload as well as arrangement area and volume. In most cases, alternative designs will be predicated on the basis of equal cruising range and either the same installed horsepower or equal speed capability in calm water. Weights can be estimated by traditional means except that the weight of the primary hull structure for SWATH designs (and possibly monohulls too) will be obtained from a structural design synthesis computer program. Some of the design seaway loads will be analytical predictions from a partially verified computer program similar to that used for estimating motion response. Design

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wave impact pressures must be based on limited model test measurements
that have been compared with data for conventional catamarans already
validated by at-sea measurements.

A performance evaluation of the resulting conceptual SWATH ship
of particular displacement, dimensions, and hull form will utilize a
variety of techniques. SWATH frictional and wavemaking bare-hull drag
in calm water can be predicted analytically with considerable confidence.
Propulsive efficiency can be assumed to fall within known bounds, and
a generous allowance can be made for the additional drag of control
surfaces. But model tests are necessary to define precisely what
improvements in seakeeping can be expected for particular SWATH ships.
It is ironic that the facet of performance in which SWATH ships differ
most from conventional ships is difficult to quantify. For monohulls,
computerized strip theory can predict pitch, heave, and--in some
cases--roll characteristics at three principal headings. Although it is
not yet possible to predict SWATH ship freebody heave and pitch responses
accurately in head seas, the addition of fixed control surfaces
makes the motion prediction problem manageable because it becomes more
nearly linear.

Notwithstanding the inherent difficulties, hydrodynamic efforts
are focused on developing and verifying computerized methodologies for
predicting SWATH controlled responses in five degrees of freedom. Why?
Because these numbers are essential inputs to an evaluation of the
operational advantages of a SWATH ship, particularly for helicopter/
aircraft landings and sonar performance. So far, tests to quantify
SWATH seakeeping characteristics have focused on displacements of
2000 to 4000 tons because this size range promises the greatest improve-
ment over monohull performance and also constitutes the most taxing
seakeeping problem. In March and April of 1975 it was demonstrated with
the SWATH VI model that a 2900-ton SWATH ship will be capable of main-
taining speeds of 30 knots in high State 6 seas and that it could
withstand high State 7 seas at lower speeds without incurring damage.
Thus, larger SWATH ships have become a matter of course. With larger

SWATH ships, resonant wave condition will be encountered less often and their responses will be reduced because of their greater mass; further, it will be easier to design into them sufficient cross-structure clearance to minimize the frequency and severity of wave impacts at high speed.

Generally, the design technology for SWATH combatants has progressed to the point where there is a fairly sound understanding of the tradeoffs necessary to achieve balanced SWATH ship designs, with reasonable payloads and operational characteristics. Comparative studies of both single and two strut-per-hull configurations will continue, with emphasis on their relative performance in a seaway. Nevertheless, SWATH feasibility designs already developed appear to be capable of approximating conventional surface ship payload and speed-power in calm water as well as achieving superiority in most other measures of performance.

CONCLUSION

In ship design as in other fields, innovative approaches are greeted with a healthy skepticism by knowledgeable technical specialists. This reaction is only proper because a radically different hull form must satisfy numerous stringent and unyielding requirements for successful adaptation to the environment of the sea. In the early stages there is a substantial probability that something has been overlooked by proponents of the new hull form, i.e., that there is a fatal flaw in the concept.

It is therefore understandable that the majority of technical people involved in the Navy SWATH ship development program were initially doubtful regarding concept viability. But as minor problems have been overcome, as no major problems have been encountered, and as the claimed advantages have been demonstrated by model tests and operation of the SSP, a consensus was reached that the SWATH concept has genuine potential.

On balance, the concept is judged to be applicable to a wide variety of naval combatant and support missions, but it is especially attractive for ships of up to 15,000 tons. Aside from increased mobility as a byproduct of less motion in waves, the principal advantages of SWATH ships will be their substantially greater compatibility with hull-mounted sonars and helicopter or aircraft operations. These attributes appear to be well suited to the operational requirements for future naval combatants which, it is important to keep in mind, must be relatively small ships to keep costs in bounds. From a technical vantage point, this author believes that there is ample justification for the Navy to proceed with an intensified advanced development effort on SWATH ships.

ACKNOWLEDGMENTS

REFERENCES

1. Motora, A. and T. Koyamo, "On Wave Excitationless Ship Forms," Sixth Naval Hydrodynamics Symposium, Washington, D.C. (1966).

2. Hadler, J.B. and T.H. Sarchin, "Seakeeping Criteria and Specifications," SNAME Seakeeping Symposium, Webb Institute (Oct 1973).

3. Kehoe, J.W., "Destroyer Seakeeping, U.S. and U.S.S.R.," Naval Engineers Journal, Vol. 85, No. 6 (Dec 1973).

4. Oakley, O.H., "Size Determinants in Destroyer Design," Marine Technology (Oct 1968).

5. Sarchin, T. et al., "Technical Report: Small Waterplane-Area Twin-Hull (SWATH) Combatant Ships Feasibility Design Studies," NAVSEC Report 6114-74-8 (Jan 1974).

6. "SWATH Ship Sonar System Description (U)," Naval Undersea Center Document 356-00100-73 (Jun 1973) SECRET.

7. Avery, J.T., "ASW Mission Performance of Alternative SWATH Configurations and Competitive Platforms, Vol. 1: Background Development (U)." NUC Report TN 1341 (Apr 1974) SECRET.

8. Setterstrom, D. and P. Cojeen, "SWATH Design Synthesis Model Documentation and User's Manual," NAVSEC Report 6114-74-3 (Nov 1973).

9. Chapman, R. and R. Wernli, "Operating Instructions for 'Drag' Computer Program," NUC Report TN 1385 (Jul 1974).

10. Chen, R., "The Pien Wavemaking Resistance Computer Program, Part II: User's Manual," NSRDC Report 4371 (Apr 1975).

11. Lin, W.C. and W. Day, "The Still-Water Resistance and Propulsion Characteristics of Small-Waterplane-Area Twin-Hull (SWATH) Ships," AIAA/SNAME Advanced Marine Vehicles Conference, Paper 74-325, San Diego, California (Feb 1974).

12. Jones, H. and D. Gerzina, "Motion and Wave Induced Bridging-Structure Load Characteristics for a Large Modified Catamaran CVA in Waves," NSRDC Report 3819 (Jun 1973).

13. Lee, C.M. et al., "Prediction of Motions and Hydrodynamic Loads of Catamarans," Marine Technology, Vol. 10, No. 4 (Oct 1973).

14. Aronne, E.L. et al., "Structural Weight Determination for SWATH Ships," AIAA/SNAME Advanced Marine Vehicles Conference, Paper 74-326, San Diego, California (Feb 1974).

15. Nappi, N.S., "Structural Design of a 4000-Ton Steel Small-Waterplane-Area Twin-Hull (SWATH) Ship," NSRDC Report 3886 (Nov 1972).

16. Holmboe, E.L. and A.D. Evans, "A Guide to Assess the Operational Implications of New Ship Design Concepts, Part II," Operations Research Inc. (Mar 1973).

17. Carpenter, J.C., "USS Dealey (DE-1066) - Analysis of Standardization Trials and Comparison with Model Test Results," NSRDC Report C-911 (Feb 1958) CONFIDENTIAL.

18. Hawkins, S. and T. Sarchin, "The Small-Waterplane-Area Twin-Hull (SWATH) Program - A Status Report," Paper 74-324, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, California (Feb 1974).

19. Chapman, R.B., "Drag Measurements on Models of SWATH Ships and Basic SWATH Components," Naval Undersea Center Report TN 984 (Apr 1973).

20. Ochi, M.K. and L.E. Motter, "Prediction of Slamming Characteristics and Hull Responses for Ship Design," Trans. SNAME, Vol. 81 (1973).

21. Baitis, E. et al., "A Seakeeping Comparison between Three Monohulls, Two SWATHs, and a Column-Stabilized Catamaran Designed for the Same Mission," NSRDC Evaluation Report SPD-622-01 (Apr 1975).

22. Lee, C. and M. Martin, "Determination of Size of Stabilizing Fins for Small Waterplane Area, Twin-Hull Ships," NSRDC Report 4495 (Nov 1974).

23. Kallio, J. and J. Ricci, "Seaworthiness Characteristics of a Small Waterplane-Area, Twin-Hull Ship (SWATH IV), Part I," NSRDC Evaluation Report SPD-620-01 (Mar 1975).

24. Munk, M.M., "Aerodynamic Theory of Airships," W.F. Durand, Berlin (1934).

25. "Principles of Naval Architecture," SNAME, New York, N.Y. (1967).

26. Kallio, J. and J. Ricci, "Seaworthiness Characteristics of a Small Waterplane-Area Twin-Hull Ship (SWATH IV), Part II," DTNSRDC Evaluation Report SPD-620-02 (Mar 1975).

27. Den Hartog, J.P., "Mechanical Vibrations," McGraw-Hill, Inc., New York, N.Y. (1947).

28. Salvesen, N. et al., "Ship Motions and Sea Loads," Trans. SNAME, Vol. 78, pp. 250-287 (1970).

29. Frank, W. and N. Salvesen, "The Frank Close-Fit Ship Motion Computer Program," NSRDC Report 3289 (Jun 1970).

30. Kim, K.H., "Determination of Damping Coefficients of SWATH Catamaran Using Thin Ship Theory," MIT Report 75-4 (Jan 1975).

31. Kinsman, Blair, "Wind Waves," p. 10, Prentice-Hall, Englewood Cliffs, N.J. (1965).

32. Miles, M., "Wave Spectra Estimated from a Stratified Sample of 323 North Atlantic Wave Records," National Research Council, Division of Mech. Eng. Report LTR-S1-118 (1971).

33. Michel, W.H., "Sea Spectra Simplified," Marine Technology (Jan 1968).

34. Andrews, J.N., "Model and Prototype Responses for a DL Class Destroyer," NSRDC Report 3325 (Mar 1970).

35. Andrews, J.N., "Determination of Wave-Induced Loads on a 3000-Ton Proposed Developmental SWATH Ship from Test Results of a Segmented Model," (in preparation by Structures Dept).

36. Gianotti, J.G., "Estimate of Wave Impact Loads and Pressures for the Cross-Structure of a SWATH Ship," NAVSEC Report 6136-74-22 (Nov 1974).

37. Lev, Frank M. et al., "Structural Weight Determination for SWATH Ships," NSRDC Report 4335 (in preparation).

38. Hadler, J.B. et al., "Ocean Catamaran Seakeeping Design Based on the Experiences of USNS Hayes," Paper No. 2, Presented at the 1974 Annual Meeting, Society of Naval Architects and Marine Engineers, New York, N.Y. (1974).

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