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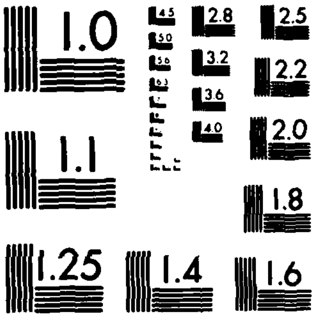

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

SHIP PITCH STABILIZATION – PROGRESS AND PROGNOSIS

by

A. Erich Baitis
Paul Kaplan
Andrew Clark
and
George Gaudin

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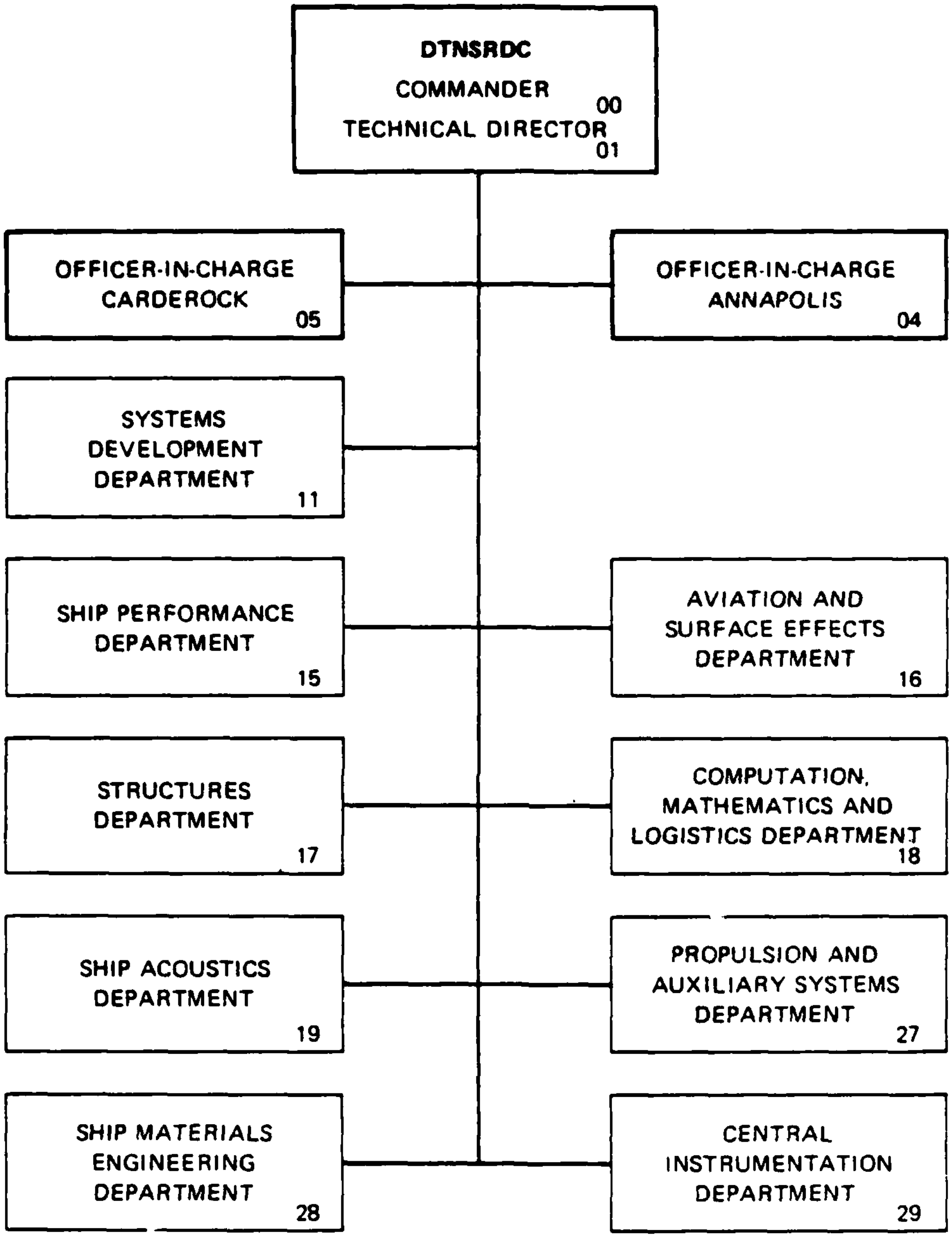

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Efforts to overcome some of these limiting features involve approaches using hydrodynamic lifting surfaces in a different manner. These approaches consider fin location in the stern region; the effect of the propeller race; specific types of control system command rules; and the use of special high lift hydrofoils dependent on flow control.

Results of the program to date are presented, based upon theoretical analysis and actual demonstration on a small vessel at sea. The beneficial results obtained on a 12.80 m (42 ft) cabin cruiser when equipped with controlled fins in at-sea tests in the Pacific Ocean support the basic concept of achieving useful pitch stabilization of ships in a seaway. The application and extension of these results toward larger commercial and naval vessels is considered and discussed further in the report.

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ADMINISTRATIVE INFORMATION

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Ship Stabilization - Progress and Prognosis* No. II-A-4

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ABSTRACT

The problem of pitch stabilization of ships is considered for different vessels of varying size, with application to both commercial and military craft. The various operational benefits of pitch stabilization are described, together with the history of prior efforts applied to this problem area by use of hydrodynamic force elements (i.e., fins or other lifting surfaces), including a discussion of the limiting hydrodynamic phenomena and vessel behavior that have inhibited the use of pitch stabilization with fins.

Efforts to overcome some of these limiting features involve approaches using hydrodynamic lifting surfaces in a different manner. These approaches consider fin location in the stern region; the effect of the propeller race; specific types of control system command rules; and the use of special high lift hydrofoils dependent on flow control.

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INTRODUCTION

At the present time naval vessels such as destroyers and similar size vessels make use of active fin stabilization systems for achieving roll reduction when operating in a seaway. Similar installations are present on commercial vessels and pleasure boats of varying size. The operating regime in which these fins function most effectively involve the ship moving at a sufficiently large forward speed to develop substantial lift forces. These lift forces provide a roll moment as a function of the fin orientation relative to the local water flow. The roll moment is applied via a proper control law to counteract the wave induced roll motion. This roll reduction can also be achieved by means of canted rudders as well as with the use of fins, and extensive efforts have been developed toward establishing the proper system design, from both the hydrodynamic and control points of view, to achieve satisfactory roll motion stabilization (e.g., see (1)).

While the occurrence of roll motion and its subsequent reduction has an important influence on many aspects of performance of ships, there are other motions such as those in the vertical plane (e.g., pitch and heave) which also act to limit the performance of different vessels in a seaway. These particular motions influence the occurrence of slamming, the magnitude of vertical accelerations, the added resistance in a seaway, etc. as direct measures of influence on the ship performance per se, while also having a significant influence on the ability to launch and retrieve aircraft that operate from the decks of different naval vessels, and also on the different motion-induced effects on crew members (i.e., human factor influences of sickness, fatigue, stability, etc.). In view of the significance of these motions, an effort has been directed toward determining feasible types of ship motion reduction systems using possible different arrangements of fins and similar appendages such as canted rudders. The present investigation is directed toward that basic objective, subject to different constraints on the size of the fin appendages as well as other related hydrodynamic and operational constraints.

A number of previous investigations have been carried out in order to determine the effectiveness of fin

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stabilizers as a means of reducing pitch motion of ships in waves. These investigations have involved both experimental and computational studies, as represented by (2) - (4). In these prior studies the effect of fins at the the bow and (in some cases) also at the stern were investigated for both passive fins installed at stabilizers directly, as well as considering the fins to be actively controlled under the action of a specific control rule. The results of these studies have shown that an appreciable degree of pitch reduction can be attained, but that other deleterious effects are associated with the benefit of pitch reduction.

The most significant degrading effect associated with the use of bow fin stabilizers was the occurrence of ventilation (which may be associated with cavitation susceptibility also) that led to the collapse of the ventilated air bubble during the course of the pitch oscillation. This bubble collapse, which often occurred asymmetrically on both sides (i.e., port and starboard) of the fin during the course of the downward motion of the ship bow, produced significant impact forces and resulting vibration of the ship hull structure. Since this impulsive load and resultant vibratory response occurred for a large portion of the total time extent of the oscillation experienced by the ship during its motions in a wave system, this associated degrading event led to the discontinuance of any possible installation of pitch-reducing fins on naval ships at that time.

In view of the continued importance of pitch motion influence on ship performance, further efforts are considered necessary in order to determine whether there are any feasible means of achieving a useful pitch motion reduction within the bounds of any constraints associated with the limits due to flow and cavitation problems such as those described above. It is recognized that the forces (and associated moments) that have to be generated by various fin systems for pitch reduction have to be quite large, especially in contrast with the case for roll stabilization, due to the large inertia of a ship in pitch as well as the significantly larger wave-induced excitation moments. It is this difficulty (which is also affected by cavitation and ventilation limits) that restricts the capability of achieving pitch stabilization, and various means have to be considered in order to provide a successful motion reduction system.

The present paper describes the methods used and the results that have been recently achieved in the development of such a pitch motion reduction system. The development effort, involving many different technical specialties, includes contributions from the U.S. Navy and associated contractors as well as foreign and domestic commercial organizations who have been joined together in this cooperative program.

ANALYSIS AND CONCEPTUAL DEVELOPMENT OF PITCH STABILIZATION SYSTEMS

The U.S. Navy has been involved in a series of studies devoted to the development and/or improvement of different types of motion stabilization systems for various naval combatant vessels. This program is an element of an overall development program known as the CONFORM program. Among the different elements considered for control of ship motions in waves within this program are the use of rudder roll stabilization (5), as well as attempts to establish systems that will be useful for pitch reduction. Although the previous studies cited above (e.g., (2), (3)) have illustrated some of the problems associated with the use of bow-mounted fins for pitch stabilization purposes, another investigation was considered in order to determine the effectiveness of different relative sizes (and areas) of fins as well as variations in their specific location along the hull.

A theoretical analysis of the performance of such fin systems was carried out under contract with the David W. Taylor Naval Ship Research and Development Center by Hydromechanics, Inc., with the results obtained described in (6). The particular vessels considered in this analytical study were the FFG-7 frigate and the CG-47 cruiser, which are considered representative of modern naval combatant ships where reductions in pitch motion would be expected to provide improvements in seakeeping performance. The fin appendages used for providing pitch stabilization in that study had an area of 9.29 m^2 (100 ft^2) with a pair of these fins located at various forward locations on each vessel in order to minimize effects of cavitation and/or ventilation as well as the possible occurrence of the foils emerging from the water surface during the course of the ship motion oscillations. The fins were placed at a significant depth below the baseline, and it was assumed they are attached by a vertical strut with the resulting total fin area of 18.58 m^2 (200 ft^2). The longitudinal locations of the fins and the vertical positions were varied for each of these vessels (between stations 1 and 3 for the CG-47, and somewhat further aft for the FFG-7).

The selection of the location of forward anti-pitch fins is constrained on a navy combatant ship (such as FFG-7 and CG-47) by structural considerations such as the need for a sufficiently strong attachment to the main hull girder, and by the requirement that fin emergence in even the most severe seas must be a very rare event. The structural consequences of fin emergence and possible slamming, as well as hull vibrations induced by excessive ventilation and cavitation due to large induced angles of attack require that the designer seek to minimize the occurrence of fin emergence and the consequences associated with ventilation when the fin approaches the water surface.

In addition, the primary U.S. Navy ships which could benefit from pitch stabilization all employ active hull-mounted sonars. It therefore follows that the integration of a forward anti-pitch fin into a combatant hull requires that the fin neither cavitate, ventilate, or otherwise interfere with the sonar performance.

In order to assure that neither ventilation nor fin emergence has a high probability of occurrence, it was decided to apply criteria regarding the level of the frequency of occurrence of potentially damaging hull emergence at the location of the forward fin. This criterion was applied in severe seas where the benefits of pitch stabilization as well as its drawbacks would be pronounced.

In order to provide increased stabilization capability, other appendage modifications were considered for these vessels so that they would also have effective lifting surface areas in the aft region. This was achieved by means of canted rudders, with each vessel assumed to have equal area rudders with a cant angle of 45° (outward) with respect to the vertical. In order to maintain the basic rudder effectiveness, the area of each of the canted rudders is increased by $\sqrt{2}$ relative to the existing rudder areas.

The operating conditions for each of these vessels considered speeds in the range of 5-25 knots, in 5-knot increments. The headings considered range from 0° (corresponding to a following sea) up to 180° (head sea) in 30° increments, which allows a sufficient gradation of coverage of all possible headings for these vessels (assuming long-crested seas). The sea conditions in which they operate have been specified in the form of two-parameter wave spectral representations, for three different sea conditions. They are designated in terms of the significant height and the associated modal period, as illustrated below.

Sea Conditions	1	2	3
Significant Height,			
ft	13	20	30
m	3.96	6.10	9.14
Modal Period, sec	11	11	23

Theoretical Analysis of Proposed Systems and Results

The method of analysis used to study the effect of additional appendages as a means of reducing vertical plane motions is by use of linearized equations of ship motion in waves. The vertical force and pitch moment due to the different appendages are added to the basic ship forces and moments expressed in an analysis such as the SCORES program (7). This procedure is used for both the case of passive stabilization due to the fins in a fixed orientation, as well as for the case where the fin angles were actively controlled.

The vertical force and pitch moment acting on a ship due to the forward fins, in accordance with the notation, axis system, etc. used in the analysis in (7), are given by

$$Z_f = -C_{L_{\alpha_f}} \rho S_f V(\dot{z}+V\theta-x_f\dot{\theta}+w_{o_f}) \qquad (1)$$

$$M_f = -x_f Z_f \qquad (2)$$

with Z (vertical force) positive down and M (pitch moment) positive bow-up. In these equations the following definitions apply:

$C_{L_{\alpha_f}}$ = lift rate of fin

ρ = water density

S_f = area of one (1) fin

x_f = location of forward fin quarter-chord relative to ship CG (positive forward)

V = forward speed

z = heave displacement, positive down

θ = pitch angle, positive bow-up

w_{o_f} = wave vertical orbital velocity at the fin

For the case of the canted rudders, or for any other type of fin appendage in the aft region, the vertical force and pitch moment are represented by

$$Z_r = -C_{L_{\alpha_r}} \rho S_r V(\dot{z}+V\theta-x_r\dot{\theta}+w_{o_r}) \quad (3)$$

$$M_r = -x_r z_r \quad (4)$$

where

$C_{L_{\alpha_r}}$ = lift rate of aft appendage

S_r = area (projected) of one (1) aft appendage

x_r = location of quarter-chord point of aft appendage from ship CG (negative for location aft of CG)

w_{o_r} = wave vertical orbital velocity at aft appendage

The effect of these force and moment representations is to alter the basic stiffness and damping of the pitch mode of motion, as well as providing some additional damping in heave. In addition there is also an increment in the total wave excitation force and moment. Solution of these linear equations follows the standard procedures described in (7) in order to obtain basic transfer functions of pitch and heave motions in the frequency domain. Similarly, measures of other responses that are represented as the sum of different linear responses arising from heave and pitch, etc. are found. This information is then combined with that of the sea conditions, which are represented in the form of power spectra for the waves, in order to determine statistical measures of response such as rpm value and other related quantities (such as extreme values for a particular time of operation) by means of spectral analysis techniques.

Calculations of heave and pitch motions were made for the two naval ships of interest, covering the speed, heading and sea conditions described previously, for both the stabilized and the unstabilized case (without the presence of the added appendages) in order to determine the relative improvement in performance. Other ancillary information obtained in the course of the computations was the relative vertical motion of the fin and the canted rudders with respect to the local sea surface elevation (to determine fin emergence) as well as the effective "angle of attack" induced at each appendage due to the ship motion in waves. The degree of pitch motion reduction indicated by these results is not that significant, perhaps ranging up to barely 20% at the most, with the largest effect for the FFG-7 (the smaller ship). A further examination of the results showed that the vertical motion of the forward fin location was such that the forward fin often came out of the water, i.e., broached the free surface, a large percentage of the time, especially for the larger sea conditions. Another deleterious aspect indicated by the calculated results was the value of the effective angle of attack at the appendages, especially for the case of the forward fin. A larger angle of attack was experienced at the forward fin, with those values ranging up to 3 times larger than the angle at the aft canted rudders. With rms attack angles in head and bow quartering seas extending up to 20° at the higher speeds and sea states, with even larger angles for the lower speeds, it is obvious that the forward foil will experience almost continuous cavitation and/or ventilation during the course of its motion. All of these deleterious effects that influence the flow conditions around the forward fins certainly indicate that pitch reductions shown by the calculations would not be achieved due to such flow breakdown, and in addition to the prospect of significant vibratory impacts due to the air bubble collapse also mitigates against the utility of this type of stabilizer for practical applications.

In view of the results obtained for the case of passive stabilizers, wherein the forward stabilizing fin had a high level of emergence and also experienced angles of attack that would lead to cavitation and/or ventilation, another approach was considered as a means to obtain possible increased pitch reduction. That approach used actively controlled canted rudders since the angle of attack variation at the aft location was found to be significantly less than for the forward fin. In that case the control signal involved an additional term that was added to the expression for the angle due to motions, with this additional commanded angle represented by

$$\Delta\delta_r = a_1\theta + a_2\frac{|x_r|\dot{\theta}}{V} \quad (5)$$

where the quantities a_1 and a_2 are the appropriate control gains. This concept of considering the control action to be supplied by the aft stabilizers was also considered in (4).

A series of computations were carried out for one of the ships under consideration, viz. the CG-47, assuming that it was operating in head seas for two speeds of interest (15 knot and 25 knot) for the three sea conditions considered. The results obtained with a control of this type included produced a pitch motion reduction of at most 18%, with large angles of attack still occurring at the forward fin.

The results illustrated by the preceding calculations, as well as earlier studies of pitch motion reduction referenced herein, have illustrated some possible (small) reduction of pitch motion while also having other detrimental effects associated with their operation. These deleterious effects are in a large part due to the occurrence of cavitation and/or ventilation on the fins as a result of their large force generation and their proximity to the free surface. In view of the difficulties associated with the operation of conventional fin systems for use as pitch stabilizers, the possibility of using specialized high lift foils was evaluated. These high lift foils develop large forces by means of induced circulatory flows associated with emission of fluid at their trailing edge region, with that fluid passing internally within the foil due to pressures supplied by an external source (e.g., pumps). Thus there is need for additional power and/or machinery associated with such foil systems.

A particular type of high lift foil is the jet flap foil, which can generate large lift forces with reduced cavitation and separation susceptibility (and the expectation of a reduced prospect of ventilation as a result), with an analysis of the flow characteristics of that type of foil given in (8). While only a simple illustration was given in (8) regarding the prospective utility of that type of foil system as a means of stabilizing pitch motion for a particular vessel (i.e., an aircraft carrier), more detailed studies devoted to the analysis of jet flap foils for reducing pitch motion have been carried out in a study of SES craft control (9).

In the course of the work in (9) it was found possible to achieve effective pitch reduction with the use of controlled jet flap foils located in the stern region of the vessel. The action of the control, when combined with the force due to angle of attack variation at the stern foil, was established via control system design in such a manner as to achieve a more effective means of pitch reduction for that type of vessel. The location of the foils in the stern region allows a number of benefits due to the larger space availability; greater local structural strength; greater availability of water source and pumps; no localized influence on bow-mounted sonar due to the flow about the foils in the stern region; greater space available for possible retraction systems; etc.

Aside from the pure jet flap system per se, another possible type of foil employing lift control concepts which can develop large lift coefficients without any significant cavitation occurrence, as well as small power requirements, is the circulation control foil. In this concept, just as in the case of the jet flap, the use of controlled fluid emission (viz. water in the present application) results in a flow modification about the foil which produces large circulatory lift forces.

In view of all the features described above, it appeared possible that a properly located and controlled high lift foil system could provide a potential means of achieving significant pitch motion reduction. Analytical studies to determine the degree of pitch motion reduction and its feasibility by means of different stabilizers using hydrodynamic lift generation were then carried out.

A series of calculations were carried out for the case of controlled jet flap foils in the stern region of the ships, with passive forward fins also present at their same basic location as previously. It was found that the forces generated by the aft jet flap foils were not that large (even with increased areas) to produce an adequate stabilizing moment, so that the degree of pitch reduction achieved was not that much increased relative to earlier results (even for the case of 25 knot forward speed in head seas). In addition, the angle of attack at the forward foils was still very large, which would lead to the same ventilation and/or cavitation problems that were experienced previously.

Another type of high lift device that was investigated was the circulation control foil. The circulation control foil concept involves the ejection of a thin jet of fluid over the rounded trailing edge of an otherwise conventional foil. The jet sheet adheres to the trailing edge region by means of the so-called Coanda effect, and moves the stagnation point to the foil lower surface which thereby controls the circulation (and resulting lift). High values of lift coefficient are generated by this means, with the value of the lift having a relatively small effect due to the angular orientation of the foil relative to the oncoming fluid stream.

The circulation control concept, when applied to control action in the present case, requires a continuous variation of lift force in both directions (i.e., up and down) and the most direct way to vary the lift is by means of varying the jet momentum. Some indication of appropriate procedures that could be applied to the case of a circulation control foil that has these properties is discussed in (10), where mechanical and engineering aspects of different jet emission foil systems are considered.

The lift coefficient for a three-dimensional circulation control foil is expressed in terms of the non-dimensional jet momentum coefficient C_j (defined in (8), for example) and the angle of attack (α) by the relation

$$C_L = F\left[11.5\sqrt{C_j} + 6.9\alpha\right] \qquad (6)$$

where F is an aspect ratio factor.

In this present case, calculations were carried out with the circulation control foils assumed to be located aft at station 16 for each of the ships. The control rule used was

$$\sqrt{C_j} = A_1\theta + A_2\,\frac{|x_c|\dot{\theta}}{V} \qquad (7)$$

where x_c is the location of the circulation control foil relative to the ship G. This control rule is similar to that used for controlled aft conventional foils (see equation (5)). In the present case the jet momentum coefficient is a function of the pitch angle and pitch rate, with a change in sign of the commanded signal indicating a change in the lift force direction.

Calculations were carried out for some representative cases which included the circulation control foils acting as control elements as well as experiencing the effects due to the changing angle of attack at their location, together with the same passive forward fins considered in all of the prior analyses. The foil area considered for each of the individual circulation control foils were 9.29 m^2 (100 ft^2), 18.58 m^2 (200 ft^2), and 27.88 m^2 (300 ft^2).

The results obtained for this case indicated a significant reduction of pitch motion, but with the associated problem of still having large attack angles at the forward fin which would result in cavitation and/or ventilation for those fins. Further examination of the results obtained in these calculations showed that the major stabilizing moment was contributed by the aft located circulation control foils, with only a small portion contributed by the forward fins. As a consequence, further calculations were then carried out without including any effects due to the forward fins (effectively removing them from the ship).

For head sea operation, at various forward speeds in different sea states, the results show that this method of control is very effective in reducing pitch motion. The pitch reduction (relative to the unstabilized basic ship response) extended to 55%, with the largest motion reduction obtained for the highest forward speed and largest foil area (27.88 m^2 (300 ft^2) for each aft foil). However, the emitted jet fluid flows required to achieve such a motion reduction were not considered as physically realistic, since the foils might stall and there would be too large an instantaneous pump power required. A more realistic condition which required physically realizable flows, powers, etc. was found by altering the control gains in equation (7). This led to a somewhat reduced pitch reduction which could be reasonably acceptable when also considering the pump power requirements. A listing of the stabilizer performance using this control concept for an aft location is shown in Table I for the FFG vessel.

Table I

Pitch Stabilization Results, FFG in Head Seas Using Controlled Aft Fins (Circulation Control Foils)

$H_{1/3}$ ft (m)	Speed, knot	Pitch Angle rms, deg	Reduction (%)
20 (6.10)	10	1.64	13.5
	15	1.53	24.3
	20	1.40	33.0
	25	1.27	40.0
30 (9.14)	10	2.66	12.0
	15	2.46	22.5
	20	2.28	31.4
	25	2.08	38.6

The cavitation and/or ventilation limits of circulation control foils must be determined from calculations involving the pressure distribution over such foils. The state of the art of calculating such pressure distributions for these jobs is relatively complex, and only some limited guidance from the analogous jet flap foil analysis (8) was available. Thus, no definite answer was available, although the general principles of the nature of the pressure distribution shape for this class of foils would generally be beneficial as a means of resisting such flow breakdown problems.

The major problem associated with circulation control foils is the power requirement due to the jet emission required for such foils. Power is also required to overcome the additional induced drag due to the large life forces acting on these foils. Aside from the power penalties for these foils, there are also some compensating benefits which include the thrust recovery of the emitted jet (see (8)) as well as the reduced added resistance due to ship motions due to the reduced heave and pitch of the ship in waves.

A typical illustration is given for the FFG vessel at a 15 knot speed in head seas with $H_{1/3}$ = 30 ft (9.14 m). The time histories of the controlled vessel pitch motion, foil induced drag and pump power when operating with aft controlled circulation control foils are shown in Figures 1-3. The peak pump power requirement of 12,000 HP is extremely large, which will limit the effective utilization of this type of foil control system in practical installations.

Since larger foil areas were considered when using high lift stabilizing fins, further consideration was then given to the case of larger foil areas for conventional fins. In particular the application to larger forward fin areas is a prospective method for possible pitch motion reduction. Previous analyses have indicated that the presence of the aft fins, in the form of canted rudders with conventional type foil surfaces, did not provide a significant contribution to the motion reduction when combined with the effects of passive forward fins, so that the calculations were carried out without any aft stabilizing surfaces at all.

The calculations were carried out for both ships in head seas, covering the speed and sea conditions considered previously. The results show that the increased foil area (up to 27.88 m^2 (300 ft^2) for each foil) provides a larger reduction of pitch motion than the earlier smaller foil cases. However, although the fin angles of attack are also reduced somewhat, their magnitudes are such that the problems of cavitation and/or ventilation will still be present. Although the relative vertical motion is also reduced, there is still a significant portion of time in which the forward fins will broach the surface. Considering all of these features, it still does not appear that the use of large passive bow fin will reduce the ship pitch motion without the associated penalty of flow breakdown, emergence, etc. which will limit its practical application. On this basis it is also obvious that any additional angle due to control action would only aggravate this situation and not provide any benefit toward pitch stabilization.

Evolution of U.S. Navy Conceptual Approaches

As mentioned previously, the U.S. Navy has been considering the development of various types of advanced hydrodynamic control devices for application to combatant ships. Although major efforts have been devoted to roll stabilization, some of the ideas have also been considered with regard to their possible application toward problems of pitch stabilization as well. A study of novel high lift devices for

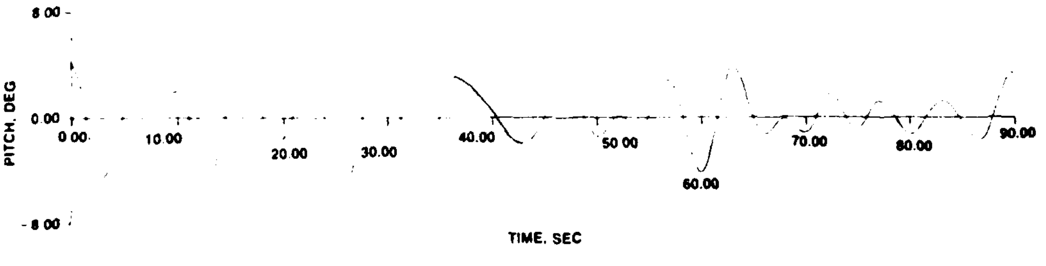


Figure 1 - Time History of Pitch Angle, Using Circulation Control Foil System, FFG-7, Head Seas, $H_{1/3}$ = 30 ft (9.14 m)

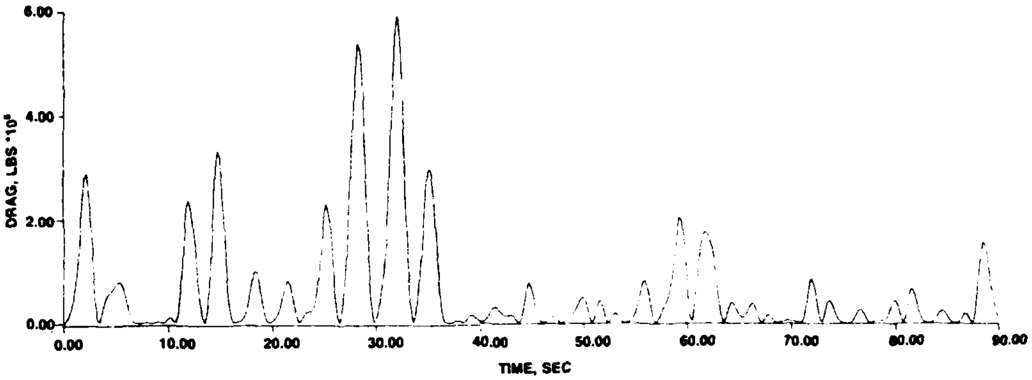


Figure 2 - Time History of Foil Induced Drag, Using Circulation Control Foil System, FFG-7, Head Seas, $H_{1/3}$ = 30 ft (9.14 m)

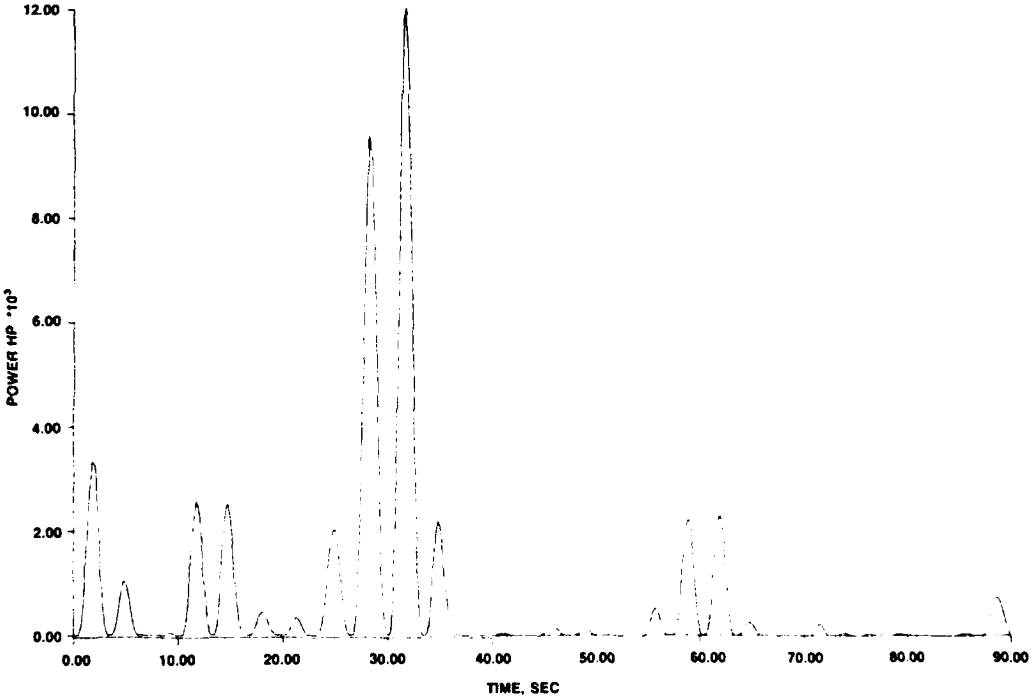


Figure 3 - Time History of Pump Power, Using Circulation Control Foil System, FFG-7, Head Seas, $H_{1/3}$ = 30 ft (9.14 m)

possible application to roll stabilization (10) also pointed out some of the benefits of large lift force development associated with reduced cavitation and/or ventilation susceptibility. This was also consistent with earlier studies in (8) for possible use of such systems for pitch stabilization.

One of the obvious results indicated by the theoretical analyses described earlier is the utility of applying large lift forces for control purposes in the aft region of a ship, especially when recognizing the problems that have been exhibited by various fin systems that have been mounted in the bow region. As a consequence, it was then necessary to consider systems that would lead to large lift force development (with resulting large stabilizing pitch moments) without any of the deleterious effects associated with flow breakdown, etc. Although it was seen that such a system would require additional power, that may not be an important consideration when viewed in an overall sense. The limiting aspects of ship behavior in a seaway are not necessarily those due to the increased power requirements for ship operation, but are due to the imposed accelerations and motions due to the seaway which affect the ship structural loads, impacts, and influence on human operators (i.e., crew members). The usual reason for a ship slowing down and/or altering course when operating in severe seas is due to those associated aspects of motion per se, rather than any problem of excessive power demand. There is often sufficient power available on a ship that can be diverted to some control system if it results in a reduction of the severe motions induced by the seaway.

A particular concept that the U.S. Navy has evolved makes use of a large high aspect ratio horizontal foil in the stern area which can be used for pitch control. The particular system has this large foil supported at the bottom of twin rudders, and it is designated as the inverted Pi rudder system, as illustrated in Figure 4. The rudders have a fixed butt attachment to the hull to which the large horizontal foil is also attached. The large movable portion of the rudders is then available for purposes of coursekeeping and maneuvering control in the horizontal plane, with the large horizontal fin used for pitch control purposes. This large fin is attached in such a manner that it can be rotated in its own angular orientation so that lift forces are generated as a result of changing the incidence angle. Possible arrangements that only involve movable flap portions of such a foil are also conceivable, subject to various aspects of mechanical linkage constraints, etc.

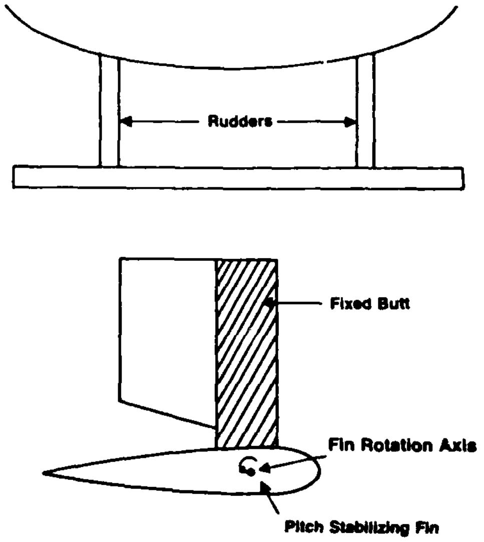


Figure 4 - Pictorial Representation of Pi-Rudder Concept

This system also allows possible use for rudder roll stabilization, and in addition has a possibility of being applied for roll control by the horizontal foil if it is "split" and a differential incidence angle is applied to each of the separate split foils. Although there are a number of possible arrangements of the particular elements associated with this Pi rudder, its main utility from the present point of view is only being considered for pitch stabilization purposes, and any other prospective applications remain as ideas for future consideration.

The Pi rudder system is established in such a manner that the horizontal foil is definitely located in the propeller race, thereby obtaining an augmented incident velocity field which acts to increase the lift force developed by such a foil system. In this case, the forces are increased as a result of absorbing a byproduct of the power of the main engine, without the necessity of any auxiliary power devices as a means of obtaining increased lift effectiveness. This Pi rudder concept was conceived in 1980 by U.S. Navy personnel at DTNSRDC and the Naval Sea Systems Command as a logical extension of the successful twin rudder roll stabilization system installed (see (5)) on the U.S. Coast Guard cutters of the HAMILTON class. Furthermore, this concept was proposed as a development effort to the Office of Naval Technology in 1981. While direct support of that project was not obtained at that time, other related development work is continuing in order to further advance concepts of similar nature for propsective use on naval ships.

Parallel System Development

At about the same time that the recent U.S. Navy developments aimed at pitch control development were being carried out, a separate effort was being carried out by a small commercial products company that was involved in the ship stabilization field for small boats. That work was being carried out by Gaudin Products Co., of Newport Beach, California. Gaudin Products is a U.S. west coast distributor for Vosper ship stabilizers that were primarily used for roll stabilization on small boats and yachts.

In late 1979, Gaudin Products initiated a project to develop a pitch stabilizer for small boats. This effort concentrated on a practical demonstration of the pitch moment capacity of the stabilizer, with the first installation on a 5.18 m (17 ft) single screw motor boat. The initial development of Gaudin Products was aimed at providing a dynamic trim tab for such vessels, with further developments stimulated as a result of discussion with DTNSRDC personnel who were involved in ship stabilization work. It was suggested to Gaudin Products that the stabilizer should have a dual direction of the stabilizer force, in a continuous manner to provide overall pitch reduction, and that the stabilizing fins should be located in the propeller race in order to increase their force effectiveness. The initial development, representing the incorporation of these concepts into a total system, evolved into a final configuration which was a three fin system. The three fins were made up of a separate center fin with two outboard fins (port and starboard) located at a somewhat lesser immersion depth. This system received a patent (U.S. Patent No. 4,261,278) on April 14, 1981.

As a follow-up development, a similar three fin system was subsequently designed, built, and installed during the period 1980-1981 on a 12.80 m (42 ft) cabin cruiser (M. V. ENTERPRISE). This latter installation again placed the central pitch fin well below the hull into the race of the twin propellers on that vessel.

A group of consulting and design engineers were engaged by Gaudin Products to design the fins, their attachment to the boat, the actuating hydraulic system, and also an electrical controller unit. After a series of modifications the resulting fin system was taken out to sea for trials. A repeated series of sea trials without any precise measurement instrumentation, both in calm water and offshore in wave systems, again demonstrated the substantial pitch inducing capability of this fin system. Finally, in March 1982, a more useful demonstration was attended by personnel from DTNSRDC and also Vosper Thornycroft (of Great Britain). Those tests were carried out in both calm water and rough water offshore, and the results of that test and subsequent tests are described in the following section.

JOINT DEMONSTRATION TRIALS AND RESULTS

The availability of a vessel that can be used to demonstrate the effectiveness of pitch stabilization allowed an opportunity for different organizations involved in pitch stabilization work to provide at-sea demonstrations of such a capability. In addition to the vessel and the stabilizer system, (developed by Gaudin Products Co.), the efforts of Vosper Thornycroft in the development of a hydraulic system for such a stabilizing system also provided established technical support in that specific area. The interest of DTNSRDC in advancing the development of such stabilizer systems then led to a cooperative data sharing and working arrangement between the three parties concerned with this subject. The contribution of DTNSRDC was primarily in the area of planning and conduct of the trials, installation of measurement and control instrumentation including the computer systems as well as the analysis of the data from such trials.

The intent of the trials was to establish a practical full-scale demonstration that pitch stabilization is a hydrodynamically and mechanically feasible process, in contrast to much of the existing literature (e.g., (2)-(4)) which suggests that pitch stabilization of surface ships is not practical. Thus the joint demonstration trials that have been carried out on the M. V. ENTERPRISE provide an unusual and unique opportunity for purposes of demonstrating that specific capability on an actual vessel, with the experience obtained providing the base for further development of systems for other (larger) vessels as well.

The different trials of this vessel, when fitted with pitch stabilizing fins, were carried out in March, June, and August 1982 as well as in August 1983. Each set of trials has led to a better understanding of the practical problems associated with pitch stabilization, as well as an improvement in the response of the overall system. A description of the characteristics of the M. V. ENTERPRISE is given below in Table II, followed by a description of the characteristics of the fin system.

Table II

Characteristics of the M. V. ENTERPRISE

LOA	12.80 m (42 ft)
LBP	11.58 m (38 ft)
Beam	3.96 m (13 ft)
Displacement	39,000 lb
GM	1.05 m (3.45 ft)

The fin system was made up of three separate flat plate fins, which were intended to provide stabilization in both pitch and roll, and they were mounted at the transom of the vessel. A photographic illustration of these fins in place on the vessel is shown in Figure 5. The central fin is mounted between the two propellers at a submergence of about 0.91 m (3 ft) below the water surface, thus lying within the propeller race. The two outer fins lie outboard of the propeller at about 0.61 m (2 ft) submergence, and they obtain no significant flow influence from the propeller. Each of the fins has a chord dimension made up of a 12.70 cm (5 in.) fixed leading edge, with 38.10 cm (15 in.) of movable flap behind. All of the fins are made of aluminum plate, and the flap angle of incidence that can be achieved extends ±18°. The center fin has an area of 0.79 m^2 (8.47 ft^2) while the outer fins have an area of 0.44 m^2 (4.72 ft^2) for each fin. Since the objective of these trials was to establish the feasibility of pitch stabilization, the performance of the two outboard fins in roll stabilization was not investigated until the August 1983 trials. At this time the

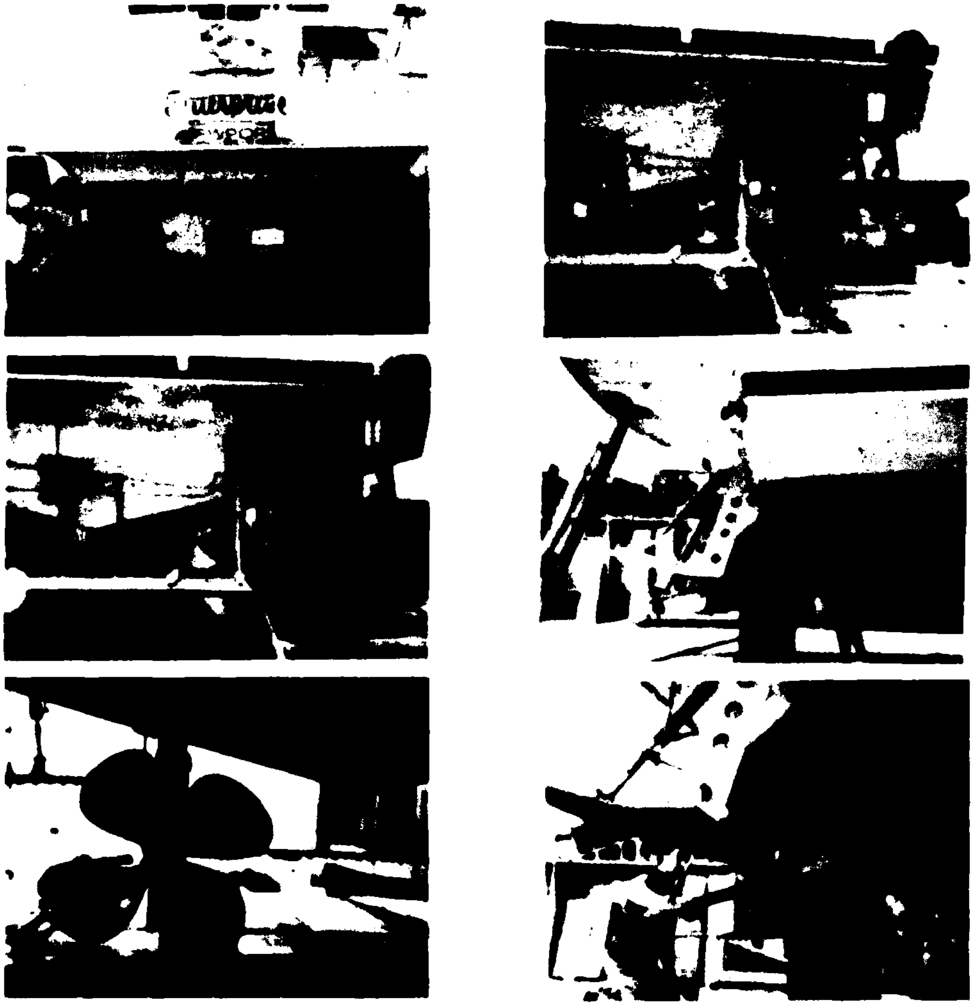


Figure 5 - Photographs of Fin System Installation, M. V. ENTERPRISE

roll stabilization of the outboard fins was demonstrated.

The March 1982 trials were of limited scope and were performed primarily to demonstrate the practical feasibility of pitch stabilization with transom mounted fins. Neither the control, actuation nor measurement equipment were of a quality achieved during subsequent trials. Nevertheless the forced calm water pitch test results repeatedly demonstrated a large nearly instantaneous pitch response to an imposed fin angle. Similarly open ocean results suggested at times pitch stabilization values up to 38%. Pitch stabilization feasibility was therefore demonstrated. In addition deficiencies in the fin hydraulic system and controller were identified.

For the June 1982 trials a new hydraulic system was constructed which allowed the speed of each fin to be accurately set in both directions. The fins were controlled using the ship-based fin control system, which led to the flaps being restricted to a maximum rate of 25 deg/sec in order to allow adequate flap positioning accuracy. This severely limited the effectiveness of the stabilizers at higher frequencies of actuation.

The tests were carried out covering different aspects of fin actuation in calm water. At different boat speeds the fins were sinusoidally oscillated through their maximum (and half maximum) amplitudes at periods between 2 and 10 seconds. Some tests were run using just the center fin, and others using only the two outer fins. Other tests were run to determine the boat response to step inputs, and the steady state fin angles were also measured. Similar type tests were also carried out in August 1982.

The results obtained from these tests are demonstrated by the pitch amplitude obtained from the maximum fin motion, which represents the maximum forced pitch angles developed by the system moving through the maximum fin angular excursion. This is shown in Figure 6 for a nominal ship speed of 10 knots. The March 1982 data represent the forced pitch angle developed using all three stabilizer fins simultaneously, while the June and August 1982 data represent the forced pitch using either the roll (outboard) fins only or the pitch (center) fin only.

The improvements obtained are obvious, since the roll flaps in June produced as much pitch as did all three fins in March. Furthermore, the pitch fin in June 1982 clearly provided more pitch than the larger area roll fins, which is a measure of the influence of the propeller race in increasing the incident velocity at that fin. The August 1982 trial results using only the pitch fin illustrates a definite improvement over earlier results in pitch generation capacity at shorter pitch periods. This is important since most of the vessel pitch motions in head and bow seas would occur at such smaller periods. Similar type results were obtained at other (higher) ship speeds, with the later data extending the range of pitch response to the important lower periods.

The magnitude of the pitch angle generated by a stabilizer system is interpreted as a simple direct measure of the capacity of the system to reduce pitch motion in waves. The degree to which this pitch reduction capacity is attained in the practical case is affected by the effectiveness of the fin control law, the hydraulic system, and the machinery capacity to follow the commanded fin position.

In the basic system developed by Gaudin Products Co., which was installed on this trial vessel, a deadboard was present in the fin position control circuit which acted to restrict the fin angular velocity. For the August 1982 trials it was decided to use DTNSRDC's digital computer system to simultaneously collect fin and ship data, calculate fin position error, fin position command, and directly control the fin positioning valves. In addition the hydraulic system was also modified to allow higher fin angular actuation velocities by changing the diameters of the pitch cylinder, increasing the hydraulic system pressures, and changing the diameters of the pipes supplying the cylinders. A diagram of the hydraulic system used in the August 1982 trials is given in Figure 7.

The HP 9845 digital computer system was used to control the fin position by opening and closing on-off valves in the hydraulic system. Opening the flow valves allowed the fins to move at a rate of about 60 deg/sec. With a maximum fin deflection of the order of $\pm 18^{\circ}$, which is desired for a motion period extending down to 1 sec, the maximum computer sample rate of 15-18 samples/sec allowed the fin to move about 3.33-4.00 deg between the successive computer commands. Thus there was about a 4 deg uncertainty (or deadband) in the command position out of a total fin travel of 18 deg in any direction. Such a level of uncertainty and lack of accurate fin positioning was considered to be unsatisfactory for smooth control of the fin position throughout its range of operation.

The inadequate rate of command signal sample generation by this computer system prevented its use as a

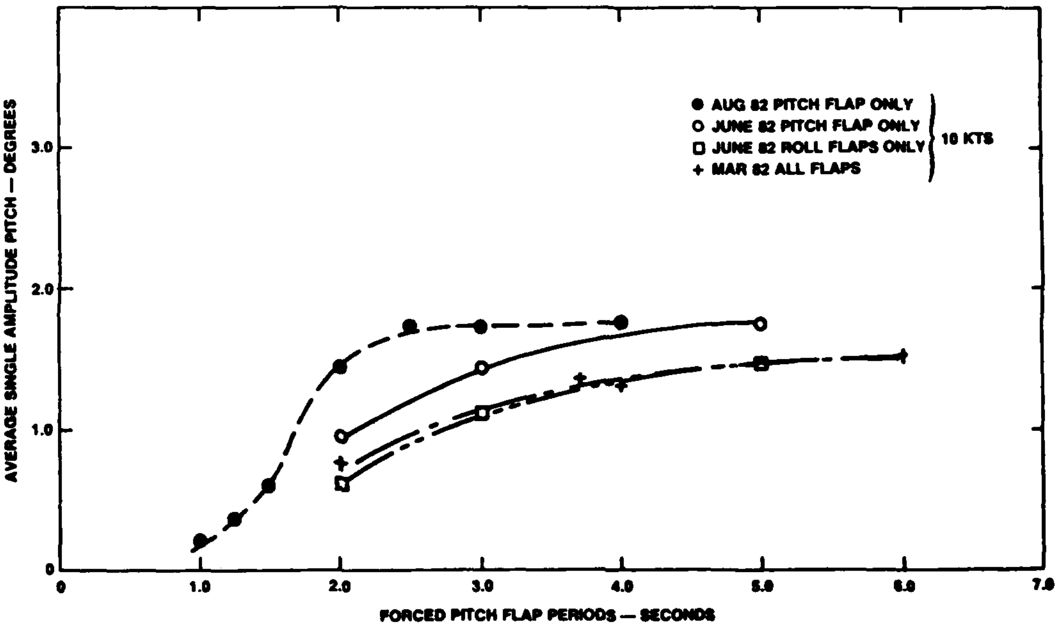


Figure 6 - Comparison of Maximum Forced Pitch Response at 10 Knots for the Antipitch Fin Combinations during the March, June, August 1982 Trials

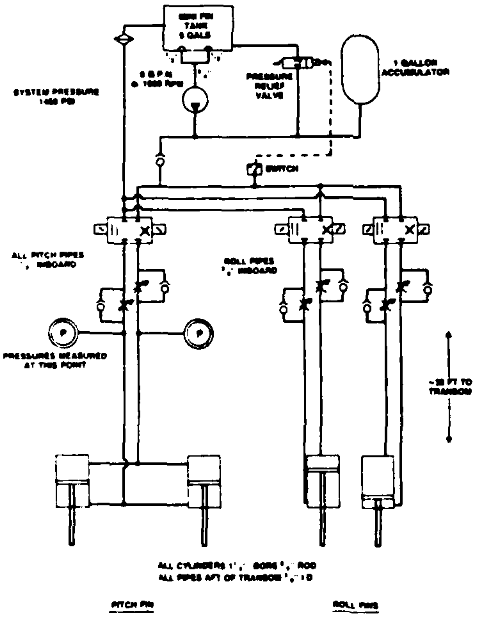


Figure 7 - Hydraulic System Used in August 1982 Trials

satisfactory controller for the fins. It would be necessary to have a computer with a sample rate of about 35-50 samples/sec in order to perform the desired control tasks. This is certainly a significant requirement for using a general purpose digital computer as the major element of a fin machinery controller.

The development of a successful control law for the fin pitch stabilization involves different combinations of control signals that are dependent on the ship motion. The control law must generate a signal as rapidly and inexpensively as possible within present developmental constraints on funding and time. It is expected that a controller for pitch stabilization will represent greater design difficulty than the case of a controller for roll stabilization since pitch motion contains a very wide range of periods. As a consequence, a pitch controller will have to cope with a wider range of motion frequencies and amplitudes than a roll controller, which is usually concerned with a more limited frequency range near the roll natural frequency. When considering the design and construction of a satisfactory adaptive pitch controller, the nature of this problem is such that it is best solved by using as flexible and fast a computer/controller as possible.

As part of the preparation for further trials, as well as have use in the development of on-board digital computer controllers, a number of different types of computers were tested at DTNSRDC by means of timing runs made with special benchmark programs. The objective was to obtain the fastest and most effective computer for the basic use as a dedicated multi-task point processor, which could be applied for sampling, recording, and processing a large number of signals while also generating appropriate control signals. The particular computer selected for this basic purpose at DTNSRDC was the HP 1000 series, model A 700, with associated disc system for enhanced memory capacity, etc.

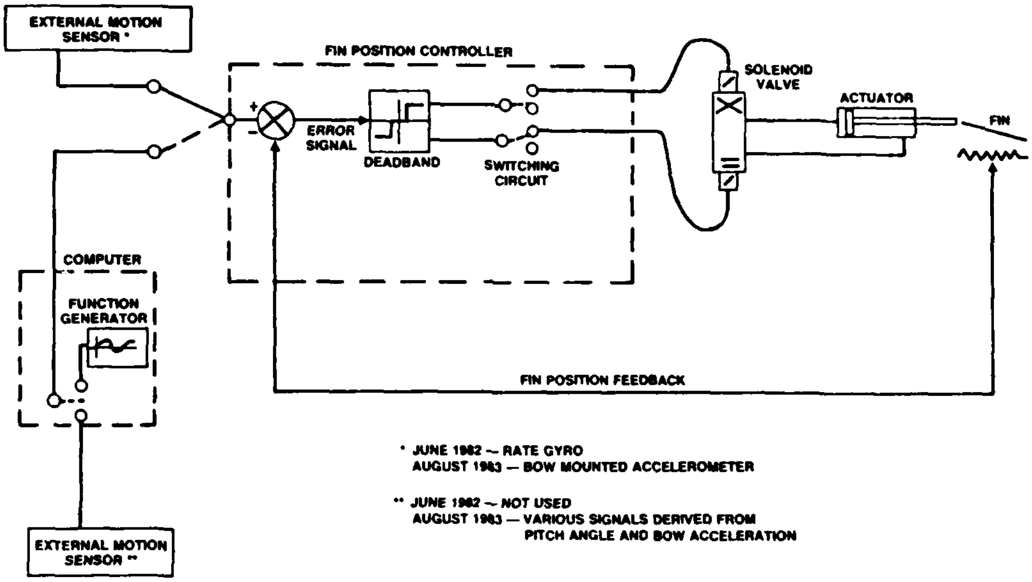
Since this particular computer was relatively new, its utility for the latest test series (August 1983) on the M. V. ENTERPRISE would be somewhat limited due to software limitations, lack of complete familiarity, etc. As a result, the operational plan was to also use the HP 9845, an older machine with more fully developed software systems and a greater degree of familiarity by DTNSRDC personnel, as an adjunct system together with the A 700 computer on board the test ship during the August trials. The A 700 computer would be used to sample and record all measured variables of interest, operating at a rate of 50 samples/sec in the present application, while also generating the required fin command control signal. The HP 9845 was linked to the A 700 and the disc memory, so that the data was transferred to the HP 9845 for post processing and data analysis, together with print-out of tabulated statistically analyzed data, plotted graphs, time history presentations, etc.

The above computer system was installed aboard the M. V. ENTERPRISE and used in the August 1983 tests. The hydraulic system in those tests remained the same as in the August 1982 tests, and it was decided to use the existing ship fin control system to perform the fin positioning function. The A 700 computer, however, was used to supply the basic fin command control signal. A schematic diagram of the control and actuation system used in both the June 1982 and the August 1983 trials is given in Figure 8. In addition to these basic elements there were different types of low pass analog filters present between the computer output and the fin position controller, as well as associated with some of the measurement instrumentation.

For the August 1983 tests some changes were also made in component values in the fin controller so that the deadband was matched to the set maximum fin velocity of 80 deg/sec. This produced the fastest acting and best positioning control of the entire test series since its inception. The motion sensor used for the ship fin controller was also changed from the rate gyro used previously to a vertical accelerometer mounted at the bow. In addition to using this accelerometer, the computer was also used to establish stabilizing control signals from different sources which included a pitch angle gyro and also another bow vertical accelerometer. The signals from these sensors were operated upon by means of integration and differentiation operations in order to provide a number of different possible control signals. These different control signals were applied in the course of the at-sea tests in August 1983, when operating offshore in different ambient sea conditons.

The number of test conditions in rough water was limited due to the seasonal limits of storm systems off the coast of Southern California. The maximum observed wave heights ranged from 0.91-1.52 m (3-5 ft) (visually estimated) and various test runs were made to obtain data under both unstabilized and stabilized conditions when operating with different types of command control signals. The recorded data were analyzed on the computer with information such as mean values, standard deviation (rms relative to the mean), minimum and maximum values, etc. determined for the different measured variables of interest.

An illustration of some of the results obtained is given in Figure 9, which shows a 70 sec portion of the bow vertical acceleration and the pitch angle for two successive runs (stabilized and unstabilized). These data represent motions at a (nominal) forward speed of 10 knots in waves of about 0.91 m (3 ft) height, until heading angle in the head-bow seas orientation. The pitch angle standard deviation (unstabilized) was 1.24 deg, while stabilized it was 0.86 deg., corresponding to a 30.6% reduction. The bow acceleration was reduced from 0.195g to 0.096g, a reduction of 50.8%. Aside from the magnitude reduction itself, the time histories in Figure 9 show that the number of oscillations are reduced and that higher frequencies in the responses are thereby significantly reduced. Since acceleration effects



* JUNE 1982 — RATE GYRO
AUGUST 1983 — BOW MOUNTED ACCELEROMETER

** JUNE 1982 — NOT USED
AUGUST 1983 — VARIOUS SIGNALS DERIVED FROM PITCH ANGLE AND BOW ACCELERATION

Figure 8 - Schematic of Control and Actuation System for Both the June 1982 and August 1983 Trials

are the important influences on ship dynamics and the human operator responses (fatigue, motion interruption such as stumbling, etc.), this aspect is certainly demonstrated as beneficial.

In addition to the tests in rough water, which were limited to the relatively small wave systems encountered, other tests were run in calm water with forced periodic oscillations of the fins. The results were obtained at nominal speeds of 10 knots and 14 knots, with data analysis on the computer used to obtain transfer function information, etc. that would be useful in understanding the nature of the ship and control element response characteristics. A typical illustration of the forced pitch motion obtained from some of these tests is given in Figure 10, for a period of 2.5 sec. In addition to information on the pitch angle obtained, the final portion of that record shows the natural decaying response after the pitch fin command signal is removed. This decay record shows the generally heavy damping associated with the natural ship response, indicating that this vessel is typical of many conventional ships with relatively high damping in the pitch mode.

The frequency response information on the actual pitch fin angle and the ship pitch angle, relative to the command signal entering the fin

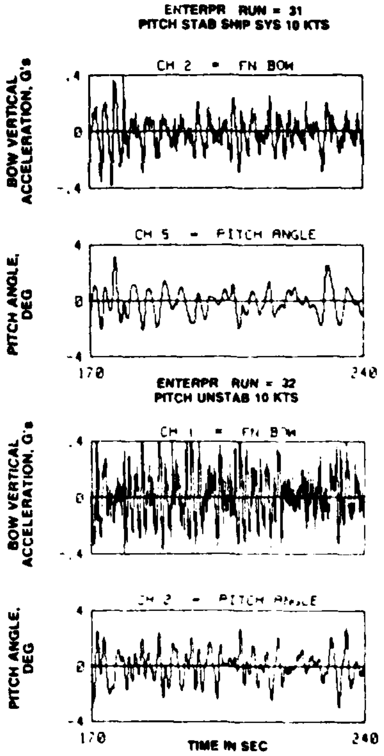


Figure 9 - Time Histories of Pitch Angle and Bow Vertical Acceleration, Stabilized and Unstabilized, at 10 Knots in Rough Water

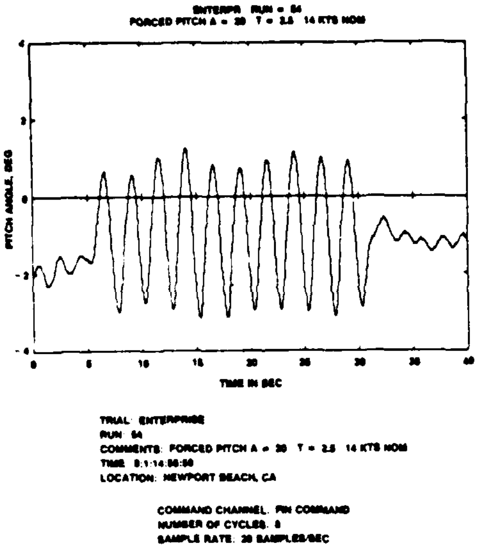


Figure 10 - Forced Pitch Oscillation Test Time History, M. V. ENTERPRISE, 2.5 Second Period

controller, is shown in Figure 11 for both amplitude and phase. These results show that the fin controller and actuation system have small phase lags at the longer periods, and that the fin angle magnitude is almost the same as the commanded angle, except at the lower periods. The ship pitch angle response also reduces significantly at the short periods, with the phase lag also larger at these short periods. An examination of the phase lag shows that it can also be interpreted as equivalent to a time lag of 0.6-0.7 sec over the entire measured frequency range. All of this information is of great use for establishing an effective control system design for this vessel, as well as indicating procedures for application to other ships that may have similar dynamic response properties but with different parameter values in general.

ACHIEVEMENTS AND FUTURE DIRECTION

The results of this development program are primarily illustrated and reported by the full-scale experimental data obtained in recent tests during 1982-1983. A coordinated program which started with basic analytical studies under U.S. Navy support, extended into development of concepts for effective fin control devices, and then made use of the opportunity to demonstrate effectiveness on an operating vessel has brought the problem of pitch motion stabilization to a point where there is a high degree of confidence that such systems are practical. While the basic demonstrations have been somewhat limited due to the nature of various support constraints, as well as the lack of significant environmental conditions during the tests wherein larger motion responses would be experienced, the results obtained so far support the concept of feasibility for pitch stabilization.

As far as the applicability of this concept is concerned, there are at least three distinct areas. These include pleasure boats; small military offshore patrol boats (e.g., U.S. Coast Guard and U.S. Navy vessels); and large surface ship combatants. These areas of applicability are listed in the order of their estimated technical difficulty in providing large pitch stabilization capability. At the same time this listing also demonstrates the procedural approach for development, application, and demonstration of pitch stabilization for these different classes of vessels.

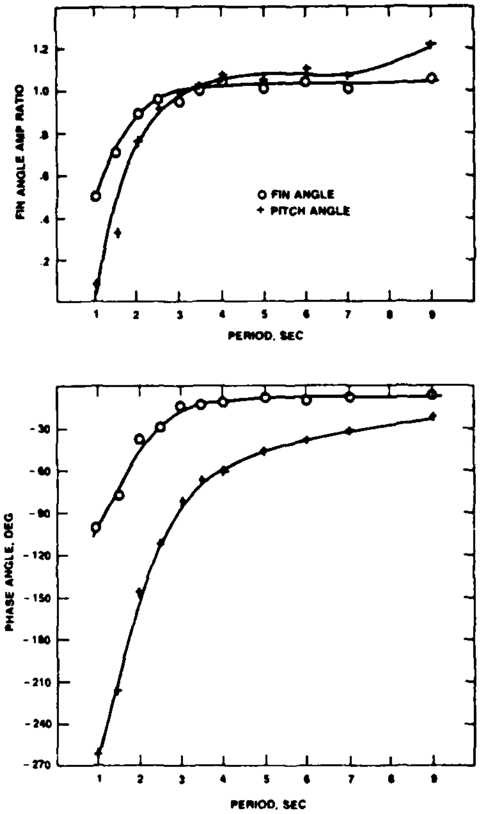


Figure 11 - Frequency Responses (Amplitude and Phase) of Fin Angle and Ship Pitch Angle Relative to Filtered Control Command Signal, 10 Knot Speed

There are a number of technical improvements that can be made with the basic system, as illustrated by the configurations that have been tested as well as different designs that can evolve from them. It is possible to have two sets of control surfaces so that both roll and pitch stabilization can be achieved from one installation on a ship. These control surfaces can also be used to provide control of the heel and trim angles of the vessel during their operation. As a result, the degree of deck wetness, pounding, slamming, etc. can be adjusted to some extent by virtue of the controls that are used in this manner, with both the dual motion control capability as well as influencing the average operation orientation conditions.

Another area for required improvement is in the area of the control system used for pitch stabilization. The major problem will be the development of appropriate control algorithms that can properly compensate for the increasing phase difference between the fin movement and the ship pitch response, especially at the higher frequencies. This control algorithm would be able to provide an effective phase lead which can be obtained by proper combination of gains of various signal rates (e.g., pitch angular velocity and acceleration) within the control rule. The control rule should employ active filtering as an integral part of its operation, which is possible to achieve with the use of a fast digital computer. The development of an adaptive capability for the control, which would involve active adjustments of the various gains associated with different signals used in the control rule, would also be a useful development since adaptative controls can provide the most effective means of control throughout the various types of motions that are experienced in the pitch mode of ships.

A program to allow more effective designs of such control systems will require the establishment of proper hydrodynamic ship motion mathematical models that can be combined with control system and control force models in computer simulation studies. This allows for an effective method of designing such systems and predicting their expected behavior. Further demonstration studies with installations on different vessels will then illustrate the benefits obtained, with the objective of establishing such control systems and/or devices on board these vessels to provide improved motion responses at sea. The present limited demonstrations support the basic concept, and future installations will provide further opportunities for additional demonstrations of the benefits of pitch stabilization for many seagoing vessels.

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