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A SEAKEEPING COMPARISON BETWEEN THREE MONOHULLS, TWO SWATHS, AND A COLUMN-STABILIZED CATAMARAN DESIGNED FOR THE SAME MISSION

David W. Taylor Naval Ship
Research and Development Center
Bethesda, Maryland

July 1975

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NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

A SEAKEEPING COMPARISON BETWEEN THREE MONOHULLS, TWO SWATHS, AND A COLUMN-STABILIZED CATAMARAN DESIGNED FOR THE SAME MISSION

by

A. E. Baitis
W. G. Meyers
D. A. Woolaver
and
C. M. Lee

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SHIP PERFORMANCE DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

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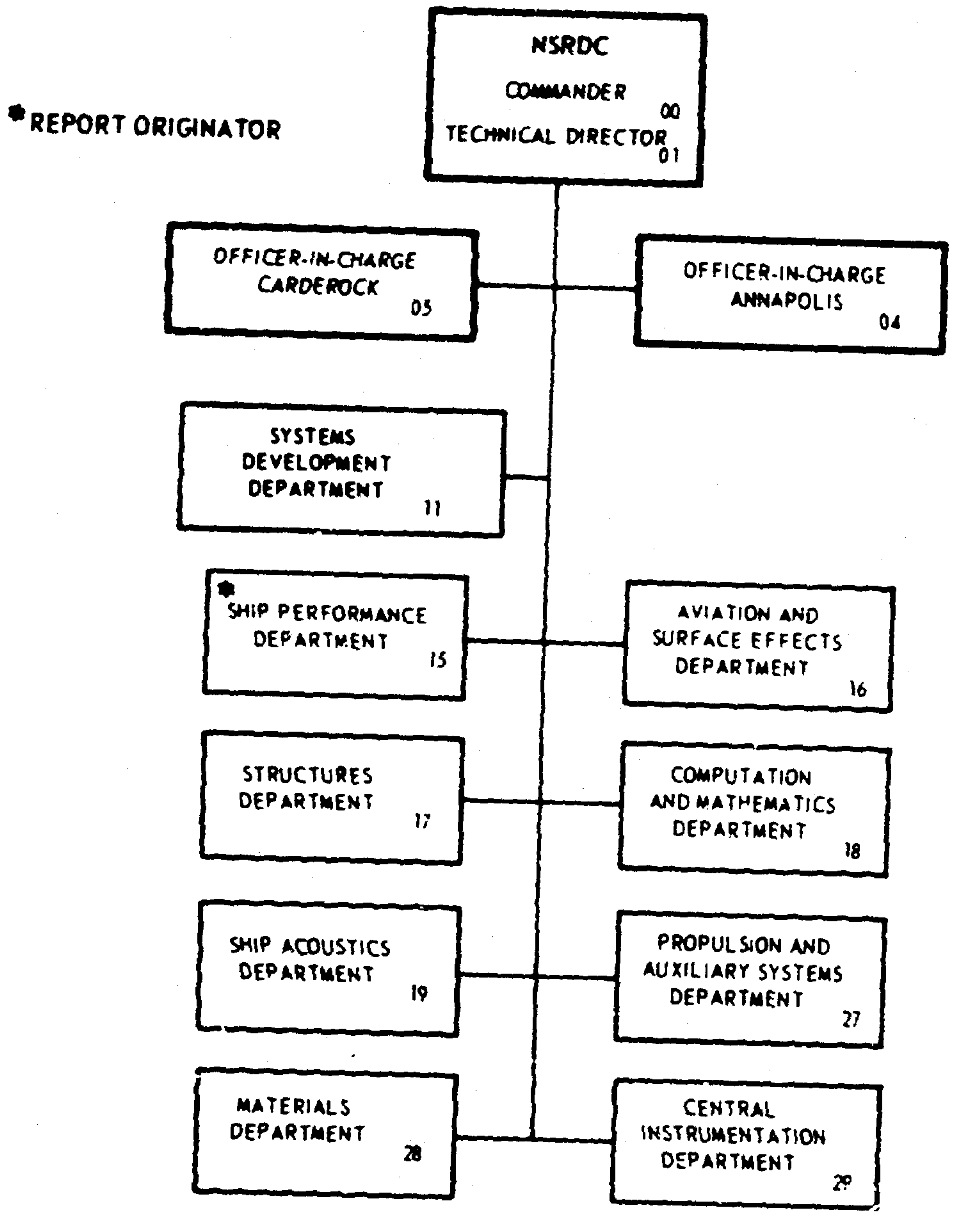

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The seakeeping characteristics of six basically different ship designs were evaluated to determine their comparative effectiveness as a U.S. Navy workboat.
Three of the designs represent conventional monohulls with different size and speed capabilities. Ship A represents the currently employed torpedo retriever boat, and Ships B and C represent larger versions of A with expanded capabilities. Two designs (Ships D and E) represent small waterplane vehicles which have the same mission capabilities as B and C.

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Again, Ships D and E differ primarily in their speed capabilities. The remaining candidate design represents a vehicle which has two distinct operating characteristics. In the transiting condition, this ship is essentially an oceangoing catamaran and is denoted as Ship F. Once the working station is reached, this ship floods down and becomes a very small waterplane area vehicle. The submerged catamaran hulls are connected to the superstructure by four slender elliptical vertical struts. In this configuration, the ship is designated as Ship G. Based on the weighed characteristics of all ship candidates in transit as well as in the stationkeeping mode, it was established that Ship E (a 20-knot, small waterplane area twin hull–SWATH–design) is the most suitable for the defined mission of a Navy workboat. This conclusion is based entirely on the seakeeping responses of the candidate designs without reference to construction or operating costs.

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NOTATION

C	Clearance between the calm water surface and the ship cross structure or freeboard at longitudinal location L_C.
D	Draft at L_C
GM_L	Longitudinal metacentric height
GM_T	Transverse metacentric height
$H_{1/3}, (\tilde{\zeta}_w)_{1/3}$	Significant wave height, average of the 1/3 highest waves
$L_{\ddot{A}}$	Lateral acceleration in g
L_C	Longitudinal location for which relative motion between ship and water surface was predicted
L_{PP}	Length between perpendiculars
$L_{\ddot{V}}$	Vertical acceleration in g
RAO	Response amplitude of operator
RBM	Relative bow motion at L_C
RMS	Root mean square, square root of variance
T_Z	Natural heave period, period corresponding to maximum value of beam-sea, zero-speed heave RAO
T_ϕ	Natural roll period, period corresponding to maximum value of beam-sea, zero-speed roll RAO
T_θ	Natural pitch period, period corresponding to maximum value of head-sea, zero-speed pitch RAO

ABSTRACT

The seakeeping characteristics of six basically different ship designs were evaluated to determine their comparative effectiveness as a U.S. Navy workboat. Three of the designs represent conventional monohulls with different size and speed capabilities. Ship A represents the currently employed torpedo retriever boat, and Ships B and C represent larger versions of A with expanded capabilities. Two designs (Ships D and E) represent small waterplane vehicles which have the same mission capabilities as B and C. Again, Ships D and E differ primarily in their speed capabilities. The remaining candidate design, a column-stabilized catamaran, represents a vehicle which has two distinct operating characteristics. In the transiting condition, this ship is essentially an oceangoing catamaran and is denoted as Ship F. Once the working station is reached, this ship floods down and becomes a very small waterplane area vehicle. The submerged catamaran hulls are connected to the superstructure by four slender elliptical vertical struts. In this configuration, the ship is designated as Ship G.

Based on the weighed characteristics of all ship candidates in transit as well as in the station-keeping mode, it was established that Ship E (a 20-knot, small waterplane area twin hull (SWATH) design) is the most suitable ship for the defined mission of a Navy workboat. This conclusion is based entirely on the seakeeping responses of the candidate designs without reference to construction or operating costs.

ADMINISTRATIVE INFORMATION

This work was conducted at the Naval Ship Research and Development Center (NSRDC) by Ship Performance Department Code 1568 at the request of NSRDC's Systems Development Department. The work reported herein was funded under Work Unit 1-1170-083.

INTRODUCTION

The U.S. Navy has been employing a small 85-Foot hardchine boat in its Hawaiian operations. This boat has been found to be far from ideal as a workboat in its present role because of its limited size and the associated seakeeping characteristics. NSRDC was requested to perform a feasibility design for a workboat that is more suitable for present and projected tasks in the Hawaiian area. The seakeeping analysis undertaken for this feasibility design is the subject of the present report.

Ship motions, including accelerations, and the relative ship to water motions were predicted in long-crested, irregular seas for a series of six ships of basically different design.

Five represent competing feasibility designs for a workboat to be used by the Navy and the other represents the existing workboat. Since the five competing feasibility designs all have the same mission, motion predictions were made for a series of realistically related ships by using a variety of documented and undocumented ship motion computer programs.

Three aspects of these prediction procedures were somewhat unusual for this type of motion investigation. The first was the use of four distinct wave spectra to represent sea conditions at a specific sea state or wave height level. The second was that ship responses were evaluated for ship mission-oriented conditions, i.e., transiting in head seas to the work site and stationkeeping at the work site. The third aspect was that their effectiveness was evaluated by considering how well the various candidates meet specific ship response criteria for the two operating conditions.

PREDICTION PROCEDURE

OVERVIEW

Four basic computer programs or groups of programs were used to develop ship responses. Two programs developed the responses in the frequency domain, and the other two developed and reduced these responses in the time domain.

The first program developed the response amplitude operators (RAOs) and the second program calculated the responses of the various ships for a series of four distinct sea conditions selected from the intended operating area of the workboat. The third program converted the results of the first program into the time domain, and the fourth program computed the critical wave heights at which ship performance would be degraded by mission-interrupting events such as slamming or deck wetness. It is pointed out that the results of the second program were used primarily to check the time domain ship responses of the third computer program.

Three different computer programs were used to calculate the RAOs which characterize ship responses for particular load, speed, and heading conditions. Monohull RAOs were obtained from the NSRDC Ship Motion and Sea Load Program.[1,2] Both head and beam sea

[1] Meyers, W.G. et al., "Manual NSRDC Ship Motion and Sea Load Computer Program," NSRDC Report 3376 (1975). A complete listing of references is given on page 33.

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

RAOs were obtained for the monohulls from this program. RAOs from SWATH and column-stabilized catamarans in head seas were obtained from an undocumented, modified version of the Frank Close-Fit Ship Motion Computer Program.[3,4] In turn, the beam sea RAOs for these ships were calculated by using an undocumented computer program as well as roll damping coefficients measured during SWATH model experiments.

The RAOs calculated by the various programs were converted to a single consistent coordinate system prior to their use as input to the third or time domain conversion program. The time domain conversion was performed by using the procedures of several investigators.[5-7]

The relative bow motions calculated in the fourth program were developed according to the procedure given in Appendix A. Simple level crossing techniques were employed to establish the number of critical events (slamming, deck wetness or cross-structure impacts) that would interrupt ship mission during 30 minutes of operation in the selected seaways. It should be noted that all ships were subjected to exactly the same seaway time history at a particular modal wave period and speed condition. Thus the responses of the individual candidate vehicles are directly comparable at the various conditions.

SHIP AND PREDICTION PARTICULARS

Figure 1 presents the particulars of the seven configurations for which response predictions were made. Ship A, a small 85-foot hardchine boat, was included because it represents a workboat whose response characteristics as a Navy workboat are already known. The objectionable characteristics of this boat when transiting to the work site (slamming, wetness) as well as during stationkeeping at the site (excessive roll) thus represent response levels against which the new workboat candidates can be compared.

Both the cross sections of the candidate boats at a longitudinal location L_c and the location of L_c on the calm-water waterplane area are shown in Figure 1. L_c was the

---

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

[4] Jones, H.D., "Catamaran Motion Prediction in Regular Waves," NSRDC Report 3700 (1972).

[5] Zarnick, E.E. and J.A. Diskin, "Modeling Techniques for the Evaluation of Anti-Roll Tank Devices," Third Ship Control Symposium, Bath, England (Sep 1972).

[6] Withrington, J.K., "Analytical Methods for Verifying the Structural Integrity of LNG Carriers," Third International Conference on Liquified Natural Gas, Washington, D.C. (Sep 1972).

[7] Baitis, A.E. et al., "LNG Cargo Tanks: A Ship Motions Analysis of Internal Dynamic Loadings," GASTECH 74, International LNG and LPG Congress, Amsterdam (Nov 1974).

location at which relative motions between the ship and the water were computed for all ships in head seas. The reasons for this choice of loca on are discussed later. Both size and arrangement of the waterplane area of the candidate boats are shown in order to demonstrate their significant differences. Two points should be noted in this regard. First, the waterplane areas essentially represent a measure of the static restoring force potential of the different ships, i.e., the tons per inch immersion. The three monohulls (Ships A, B, and C), for example, respectively require 2.72, 8.69, and 10.49 tons to increase draft by 1 inch. On the other hand, the 15- and 20-knot SWATHs (Ships D and E) respectively require only 2.78 and 3.20 tons to increase the draft by 1 inch. The column-stabilized ship requires an increase of 8.96 tons per inch of draft in the surfaced condition (Ship F) even though it has essentially twice the displacement of the monohull with equal 15-knot design speed. Once the hulls of the column-stabilized catamaran are submerged (Ship G), only 1.64 tons are required to increase draft by 1 inch. This, of course, is even less than the very much smaller Ship A although ballast pumping would alleviate this very low extra payload-carrying capacity. The key point to note is that monohulls are much less sensitive to payload increase than are SWATHs. Thus, one of the significant differences between these two types is their sensitivity to payload increases. It is important to recognize this fundamental difference in the payload growth potentials of the two types.

The basic motion behavior in seaways represents a second major difference between the ship types. The small waterplane area SWATH and the column-stabilized catamaran both have very large natural motion periods, particularly for angular ship responses. The natural periods shown in tabular form (Figure 1) were obtained from the zero-speed, beam-sea, roll and heave RAOs and the zero-speed, head-sea pitch RAOs. The importance of the long natural periods is that motion responses due to seas generated by local winds are thus lower for the SWATHs than for the monohulls or the catamaran (Ship F).

The major ship dimensions and particulars are given in Figures 1 and 2. Figure 3 was prepared to demonstrate in detail the specific input to the various computer programs that produced ship motion RAOs. Note that these programs consider only the below-the-waterline hull form. Forward sections are shown on the right-hand side and aft sections on the left-hand side of the figure. The large difference in the beam and drafts of the various ship types is clearly demonstrated. Monohulls (Ships A, B, C) clearly have both the most shallow drafts and the largest waterplane areas whereas the SWATHs (D and E) and Ship F/G have the deepest drafts and the greatest beam and deck area.

Ship responses were calculated for operating conditions which represent two specific elements of the ship mission, namely the in-transit and stationkeeping operating modes. Stationkeeping was considered to consist of head and beam sea responses at 0 and 5 knots. The in-transit operating mode was considered to be represented by head sea responses at speeds up to the design speeds of the candidate ships, i.e., 15 and 20 knots. It should be noted that Ship G, the column-stabilized catamaran in the submerged condition, has a top speed of 5 knots and thus response predictions were made for 0 and 5 knots in head seas.

Figure 4 summarizes the individual responses predicted for the various craft in head and beam seas. Head sea responses were developed for essentially four different locations on the ships and beam sea responses for only two locations. It was considered that head sea or in-transit ship responses could best be represented by vertical accelerations at three longitudinal locations as well as by pitch and the relative motion at a critical longitudinal location L_r (Point 4). Points 1 and 3 represent the furthest practical forward and aft locations at which ship mission-related work might be required during the in-transit operating mode. Point 2 represents the location of the center of gravity (CG) at the main deck level.

Beam sea responses were calculated only to amplify the head sea stationkeeping responses at 0 and 5 knots. Only roll, lateral, and vertical acceleration at the CG (Point 1) were calculated in beam seas at 0 knots. The vertical and lateral accelerations were calculated at the aftmost, outboard location on the decks of the various ships, i.e., Point 2. These acceleration predictions were made on the assumption that Point 2 would be the furthest aft, practical location at which such mission-related work as launch and retrieval of buoys could be made. The transverse distance from the centerline is tabulated as B in Figure 1. The furthest practical forward acceleration responses may be assumed to be essentially identical to the Point 2 predictions.

Figure 5 presents the range of theoretical wave spectra used to represent the range of irregular sea conditions which the workboats are expected to encounter during operation. Figure 6 indicates the various ship and sea conditions for which ship response predictions are made. The sea representation is described in greater detail in the following section.

SEA REPRESENTATION

Realistic seas are composed of a mixture of locally generated wind waves and swell from distant storms. Swell differs from locally generated waves primarily in that waves due to swell are very much longer and somewhat more regular or periodic than short, choppy wind-generated waves. The mixture of such seas can result in waves whose spectra may have two or more distinct modal periods or spectral peaks depending on the differences in the modal periods of the local sea and the swell as well as on their characteristic wave heights. Several authors have noted[8-12] that the variability of realistic sea spectra cannot be adequately accounted for by means of a single-parameter Pierson-Moskowitz wave spectrum formulation.[13]

At present, there are two basic schools of thought as to how the accuracy and realism of the sea description can be improved for purposes of predicting ship response. One[9,11] favors some type of idealized spectral family and the other[8,10] favors use of a weighted set of real, measured spectra. Baitis et al.[7] have demonstrated the equivalence of these two approaches for design purposes.

Simulation techniques, such as those recently employed by Baitis et al.,* can be employed to generate any arbitrary set of realistic waves. Their recent sea simulation considered both swell and wind-driven seas together with their relative directions and their respective characteristic wave heights. However, consideration of all possible combinations of the relevant seaway parameters would result in an extremely large data base, at least as large as that from all previously measured wave spectra. Simplification of such a complex sea model is obviously desirable.

Fortunately, the matching of any particular realistic wave spectrum with an idealized spectrum is of little importance in ship motion-related design because any particular wave spectrum is not likely to be encountered by a ship. It is of the utmost importance, however, to develop sea models which will accurately define the range of ship responses that are likely to be produced by the almost limitless set of real sea conditions (spectra) a ship may encounter. By definition, such a range must include all possible responses that can occur due to widely different, real seas.

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[8] 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).

[9] Baitis, A.E. et al., "Design Acceleration and Ship Motions for LNG Cargo Tanks," Tenth Symposium on Naval Hydrodynamics (Jun 1974).

[10] Cummins, W.E., "Prediction of Seakeeping Performance," 17th American Towing Tank Conference State of the Art Report–Seakeeping (Jun 1974).

[11] Hoffman, D., "Analysis of Measured and Calculated Spectra," International Symposium on the Dynamics of Marine Vehicles and Structures in Waves, University College, London (Apr 1974).

[12] Hoffman, D., "Environmental Condition Representation," 17th American Towing Tank Conference State of the Art Report–Seakeeping (Jun 1974).

[13] Pierson, J.W. and L. Moskowitz, "A Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S.S. Kitaigordskii," J. Geophys. Res., Vol. 69, No. 24 (1964).

*Reported informally by A.E. Baitis et al., in NSRDC Evaluation Report 563-H-01 (May 1974)

This range of ship responses was obtained here by the use of a series of two-parameter wave spectra (significant wave height and modal period) of the form developed by Bretschneider.[14] Table 1 defines sea conditions in terms of significant wave heights and presents the associated modal wave periods of seas generated by purely local winds. Thus, the table gives essentially the normally accepted definition of sea states in terms of wave height as well as the shortest modal period waves associated with a particular wave height. It is to be noted, of course, that when the addition of swell is considered, longer modal wave periods may occur as sea and swell mix.

Table 2 presents the statistical constants by which the RMS wave height or ship responses may be related to statistical levels such as the average, the average of the 1/3 highest amplitudes, etc. It should be noted that this average of the 1/3 highest amplitudes is generally referred to as the *significant response* or wave amplitude. Double amplitudes or wave height statistics are obtained from the RMS values by multiplying the single-amplitude constants by 2.

In the present investigation, the seas were represented by four different modal wave period spectra. Modal periods of 6, 8, 10, and 14 seconds were chosen because they represent the range of sea and swell conditions which typically occur (see Table 3) at the anticipated work site. Typical characteristics of the seas in this locality, taken from recent references, are discussed in somewhat more detail in the following section.

Figure 5 illustrates the Bretschneider wave spectra used to represent the range of local sea conditions. These wave spectra are shown for a 1-foot significant wave height. Table 2 presents the statistical constants as well as the equation for the Bretschneider spectra in terms of the significant wave heights and modal periods which are related to the various sea states defined in Table 1.

Two important results come about because of this choice of sea spectral representation. The first is related to the linearity of the responses and the second to the physical interpretation of the range of responses associated with the four distinct modal periods. Since ship responses are linear for engineering purposes, responses can then be determined for any wave height from the results of the unit or 1-foot significant wave height.

The physical interpretation of the range of responses varies somewhat with wave height. The given modal period wave spectra represent different mixtures of sea and swell at the various wave height levels. When considered for a significant wave height of 2 feet, the

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[14] Bretschneider, C.L., "Wave Variability and Wave Spectra for Wave Generated Gravity Waves," Department of the Army, Corps of Engineers Technical Memorandum 118 (1959).

8-second period spectrum, for example, represents a very gentle, local wind-generated sea with a minor swell at 8 seconds. For these same conditions but a significant wave height of 4 feet, both the wind-generated local sea and the 8-second swell increase in severity, the latter somewhat more than the local sea. As the significant wave height is increased to about 8 feet, this spectrum represents a fully developed wind-generated sea without swell. If the significant wave height is again increased to, say, 12 feet, the 8-second spectrum now represents the steepest, partially developed, hurricane-generated sea commonly found in the open ocean. Further increases in significant wave height at this modal period tend to produce very rare, steep seas which can occur only in land-locked bays or lakes.[15,16] Certainly at steepness ratios (significant wave height/wavelength corresponding to modal wave period) of greater than 1/9 or 1/8, the wave spectrum becomes physically unrealizable.

The most important fact to note in the discussion of sea representation is that this series of different modal period wave spectra establishes the range of the motion responses that can be expected due to the variability of the seas.

SEA CONDITIONS IN OPERATING AREA

Sea conditions in the ocean area (Hawaiian islands) in which the workboat is to operate were recently analyzed both for short-term and long-term characteristics.[17] Based on measured and observed wave data,[18,19] the analysis indicated that seas in the operating area can be grouped into four basic sets according to their independent generation mechanisms: (1) waves generated by northeast trade winds, (2) waves generated by the local Kona storms, (3) swell originating in the North Pacific, and (4) southern swell. The Kona wind waves and the trade wind waves are mutually exclusive; all other combinations of swell and wind waves may or may not occur simultaneously.

For each of the basic wave systems, the analysis[17] presents the frequency of occurrence, the direction from which the waves originated, the average yearly significant wave heights,

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[15] Pore, N.A. et al., "Wave Climatology for the Great Lakes," Nat. Ocean Atmosp. Admin. Technical Memorandum NWS TDL-40 (Feb 1971).

[16] Ploeg, J., "Wave Climate Study Great Lakes and Gulf of St. Lawrence," SNAME T & R Bulletin 2-17 (1971).

[17] St. Denis, M., "The Winds, Currents, and Waves at the Site of the Floating City Off Waikiki," Univ. Hawaii Report 7 (Dec 1974).

[18] Homer, P.S., "Characteristics of Deep Water Waves in Oahu Area for a Typical Year," Report prepared by Marine Advisers, LaJolla, California, for Board of Commissioners, State of Hawaii, under Contract 5772 (1964).

[19] Ho, F.P. and L.A. Sherretz, "A Preliminary Study of Ocean Waves in the Hawaiian Area," Univ. Hawaii, Hawaii Inst. Geophys. Report H 16-69-16 (1969).

and the average significant wave periods. The significant wave periods may be regarded as equivalent to the modal periods of the waves/wave spectra. The results, summarized in Table 3, demonstrate that the modal periods of the local sea conditions range from about 6 to 14 seconds, i.e., the range of periods for which ship motion predictions were made.

It is also of interest to know the relative frequencies at which individual wave systems or combinations thereof occur. These frequency results were therefore prepared from the data of Table 3 and are presented as Figure 7 in the form of a Venn diagram. The frequency of occurrence of individual wave systems is represented by the total area within the circle labeled by the name of the system. For example, northeast trade wind seas are represented by a circle (75.3 percent) composed of four distinct areas of wave system combinations. In turn, each area represents a different combination of wave systems. For example, northeast trade wind seas and calm seas occur together only 9.2 percent of the time, northeast trade wind seas and southern swell occur together only 10.4 percent of the time, the combination of these two with North Pacific swell occurs 29.5 percent of the time, and the combination of northeast trade wind seas and North Pacific swell occur 26.2 percent of the time.

Several important points are demonstrated by these frequency results:

1. The scarcity of single direction or single wave system seas, i.e., pure* wind-generated seas (9.2 + 1.3 = 10.5 percent) and pure swell seas (5.0 + 2.0 = 7.0 percent).
2. The scarcity (5.7 percent) of pure** multidirectional swell in the absence of wind waves.
3. The large percentage (29.5 + 4.0 = 33.5 percent) of wind seas and two-component swell seas of nearly the same period, i.e., about 13 to 14 seconds.
4. The predominance of a mixture of sea and swell (75.1 percent).

This fourth point emphasizes the importance of using a sea representation model of the type selected here for an analysis of comparative seakeeping capability.

Thus the occurrence of pure wind-generated seas is expected to affect the response of monohulls, especially the small one, more severely than the other ship types. Conversely, the occurrence of pure swell seas consisting of either a single swell or two different swells of nearly equal periods is expected to be of greater importance for the seakeeping of the SWATH ships and the column-stabilized catamaran than for the monohulls.

Some comments on the relative importance of various combinations of wave systems are relevant here. St. Denis,[17] calculated that the yearly average significant wave height due to sea and swell from all directions was equal to 6.25 feet and that the average significant

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*Wind seas or calm seas, swell or calm seas.

**Here the term pure implies wind seas without background swell, and, inversely, swells without the presence of local winds and wind seas.

wave period of these seas was equal to 11.45 seconds. He also presented the expected yearly maximum values of significant wave heights: about 5 feet for the southern swell, 12 feet for the Kona storm waves, 15 feet for the trade wind waves, and 19 feet for the North Pacific swell. It is clear from these data that southern swell is not likely to attain heights that will make operation difficult when they augment the heights of waves for other directions. Thus southern swell is not likely to cause difficulties for workboat seakeeping. On the other hand, the combination of extreme Kona winds with North Pacific swell is likely to produce occasional difficulties. Finally, the combination most likely to produce difficulties is the extreme northeast trade wind waves and North Pacific swell.

Based on the above results, it has been concluded that a yearly average wave height of 6.25 feet (due to all waves) will not often be exceeded. More specifically, the wave height due to all seas will be greater than 7 feet only about 13 percent of the time and greater than 10 feet only about 3 percent of the time. Therefore, it has been concluded on the basis of these local sea characteristics that the behavior of the candidate ships in waves up to 6 feet high is of primary importance in establishing their comparative seaway performance. Consequently their survival capabilities have not been examined to any significant extent in comparing the feasibility of designs.

CALCULATION OF ROLL

As mentioned earlier, the monohull responses were calculated in head and beam seas by using the NSRDC Ship Motion and Sea Load Program. The responses were calculated both with and without bilge keels in accordance with standard procedures that are incorporated as part of that program.

The roll motions of the SWATH ships were calculated according to the procedures of Lee and unpublished damping data from recent NSRDC model experiments. The simplified program (unpublished) developed by Lee was used to predict roll/heave motions of the SWATHs in beam seas. This program essentially considers the ship as a constant cross-section body with length and mass equivalent to the actual ship. Experimental roll damping was used to limit the predicted roll response to realistic values.

The experimental roll damping was obtained from a model whose geometric proportions were similar (but not identical) to those of Ships D, E, and F. Model motion decay experiments had been conducted both with the bare hull and with a variety of damping devices such as fixed fins, blisters* near the waterline, and bilge keels; results have not yet been published. Bilge keels resulted in the largest damping increase above the base hull.

*Blisters are appendages added to the hull at/near the waterline to increase the restoring buoyancy forces that result when the hull is depressed below its waterline.

The measured percentage increase in hull damping due to bilge keels was then used to increase the bare hull SWATH hull damping. In determining the motions of a SWATH with bilge keels, this approach considers that the measured damping modifications are applicable to Ships D, E, and F despite differences in geometry, that is, measured damping increases are considered to be physically realizable with reasonable, though unspecified, bilge keels.

The predicted roll RAOs are considered to be inaccurate primarily in the frequency range where resonance occurs, i.e., inaccuracies are associated with the damping. However, since the RAOs are intended for use in predicting roll in seas whose modal periods are far removed from those of resonant roll, the predicted roll is considered adequate for establishing a relative ranking of the various ship candidates.

A similar procedure was employed to predict the effect of bilge keels on the SWATH heave responses in beam seas and the SWATH pitch, heave, and acceleration responses in head seas.

CRITERIA FOR COMPARATIVE PERFORMANCE

The assumption was made that the consequences of excessive relative motions at section L_C would be exactly the same for all ship types, namely, interruption of mission, and therefore that such motions constituted a criterion for comparative performance. More specifically, it was assumed that when a particular statistical level* of relative motions exceeded the clearance or draft of the ship at L_C, the mission would be interrupted by keel emergence or slamming and deck wetness in the case of monohulls and by cross-structure impacts in the case of SWATHs. Figure 2 was prepared to demonstrate the plausibility of this assumption.

All response predictions were made, of course, by assuming linearity, i.e., a 1-foot wave would yield one-third of the response of a 3-foot wave of identical period. The applicability of the linearity assumption to predict the magnitudes of extremes of responses (e.g., occurrence of deck wetness, keel emergence, or slamming) is, of course, highly questionable. However, it was considered that an accurate, relative ranking of the performance of the candidate ships could be established in terms of such mission-interrupting events by extending the relative motion responses linearily to the draft or clearance (freeboard).

The average of the 1/10 highest single amplitudes of relative motion was selected as the criterion for exceeding draft/clearance because this measure ensures that within a practical

*Average of the 1/10 highest single amplitude of relative motion at L_C.

time span of ship operation (e.g., 30 minutes) a motion cycle will be sufficiently severe so that either disruptive mission-interrupting slamming or deck wetness results. The greater precision attainable by specifying extreme response levels inherent in the use of such concepts as threshold velocities for slamming or variations in the statistical motion level (e.g., the average of the 1/3 highest or some other level) is not warranted. Neither the response characteristics at these nonlinear ranges nor the specific consequences of exceeding particular relative motions is known for the different ship types. Moreover, it is emphasized that these specific in-transit ship response criteria were selected in order to achieve a fair, accurate ranking of the candidate ships during this feasibility design stage. However, to resolve the aforementioned limitations of the predictions and to examine ship behavior under survival conditions, it will be necessary to conduct model experiments for two candidates that our predictions indicate are best suited as Navy workboats.

CALCULATION OF RELATIVE BOW MOTIONS IN TIME DOMAIN

The calculation of relative bow motion was based on the difference between the wave at the longitudinal location L_C and the absolute motion of the ship at that location. No correction was included in the calculation for trim or sinkage due to forward speed; these factors have insufficient impact on the accuracy of the calculations to alter the relative ranking of the different ship candidates. A precise definition of the relative bow motion calculation is given in Appendix A.

It should be noted that the prediction for relative bow motion is made in the time domain developed from the spectral representation of the sea. Each relevant sea condition was converted[5,6] from the frequency domain into the time domain for every modal period wave spectrum by decomposing the wave spectrum into about 100 evenly spaced (in frequency) sine waves whose amplitudes are related to the ordinates of the modeled wave spectrum. Random phases were assigned by means of a random number generator to each of the 100 component frequencies. The wave at L_C was obtained from the wave at the origin by shifting the phase of each sine wave by the product of the wave number and the distance $|\ell|$. Figure A.1 of Appendix A illustrates the relative locations of the waves and presents a simple summary of how the various component time histories were combined to yield the relative bow motion.

The pitch and heave RAOs were defined with an interpolation routine for exactly the same frequencies as the components of the wave spectrum. The product of the sine wave components of the wave, the response at the appropriate frequencies, and the appropriate phases were summed for all frequencies to yield the resultant time histories. The appropriate phase at each frequency was defined as the sum of the random phase and the phase associated with the particular response. This procedure of time-history generation which associates the random phases with the wave time history thus made it possible to expose all candidate ships to exactly the same wave time history.

After the component time histories of the absolute motion at L_C had been generated, the absolute motion time history at L_C was obtained simply from the sum of the heave time history and the product of ℓ times the pitch time history; see Figure A.1. Finally, the relative bow motion at L_C was obtained by subtracting the wave at L_C from the absolute motion at L_C. These arithmetic operations were performed for each instant in time.

PRESENTATION OF RESULTS

The various ship and sea conditions for which predictions are made have been summarized in Figure 6.

Tabulated results (Tables 4–11) were utilized to prepare three basic groups of graphs (Figures 8–12).

The first group presents ship responses at various modal period seas for significant wave heights of 1 foot (Figures 8 and 9) and 6 feet (Figure 10).

The second group (Figures 11a and 11b) presents the significant wave height level at which mission-interrupting events are expected from linear ship motion theory (see the discussion of linearity given in the section on criteria for comparative performance). Thus these figures enable a simple ranking of the candidates in terms of the seas which limit their in-transit operating mode. The higher the limiting sea state, the more capable the ship is to fulfill the defined mission.

The third group (Figures 12a and 12b) presents the results of the time domain representation of ship responses. The actual number of times that the relative motions are expected to exceed either the draft at location L_C or the freeboard or cross-structure clearance was calculated by a level crossing subroutine in the time-history-generating computer program. It was considered appropriate to perform these calculations at the average yearly significant wave height that typifies the intended work site area.[17]

The basic graphical format is identical for all three groups of figures and was developed to facilitate a visual comparison of the different ship types. Thus each figure consists of at least three graphical frames, one for each basic ship type (monohull, SWATH, and column-stabilized catamaran). Response magnitudes of each ship are plotted as vertical lines at each of the four modal wave periods. Thus variations in the response of each ship due to the variations in the modal period, or—equivalently—the harmonic content of the sea, are presented as a cluster of four vertical lines representing from left to right the response in the 6-, 8-, 10-, and 14-second modal periods.

Although the tables present the results in RMS form in a sea with a 6-foot significant wave height, the first group of figures presents the results in terms of significant single-amplitude responses. These are equal to twice the RMS values and were selected for presentation because these statistical response levels are generally considered representative of the responses experienced or noted by the crew of Ship A. It has been found that ship operators generally quote angular motions as single amplitudes and translational responses, such as heave, as double amplitudes. The statistical constants which relate the RMS responses to particular statistical response levels such as the average, the average of 1/3 highest or significant, or the highest expected response in N amplitudes are given in Table 2.

RESPONSES PER UNIT SIGNIFICANT WAVE HEIGHT

Figure 8a presents the significant single-amplitude pitch and heave responses for the various candidate ships operating in head seas at 0 knots. It is quite evident that Ship F (the 170-foot, 1032-ton, column stabilized catamaran) generally has the worst pitch motions of any candidate for the new workboat. In fact, its motions are expected to be nearly as bad as those of the presently employed Ship A, which is very much smaller (85-foot, 74-ton hardchine torpedo retriever boat). However, once the column-stabilized catamaran has ballasted down (Ship G) to become essentially transparent to the seas, it will have essentially the lowest pitch responses. This clearly demonstrates the virtue of the dual-operation mode.

Pitch responses for the monohulls (Ships B and C) will not have the undesirably sharp increases in the vicinity of their pitch resonance exhibited by the small or low waterplane candidates (Ships D, E, and G). Such behavior is one of the greatest potential shortcomings of SWATH. However, its practical importance can be negligible provided this pitch resonance condition can be avoided. For example, assuming that operational requirements during the stationkeeping portion of the mission allow such action, the SWATH can avoid pitch resonance by altering its encounter frequency through slight speed or heading changes. Note that Ship E (17.4-second pitch resonance period) is clearly superior to Ship D (comparable period of 12.5 seconds) because it entirely avoids the problem of large responses in swell during stationkeeping. Local sea data for the workboat operating site indicate that 17.4-second swells do not occur with practical frequency. The difference in pitch response levels for these two designs indicate the control that the feasibility ship designer can exert.

Salvesen[20] has given a far more comprehensive discussion of the comparative seakeeping qualities of monohulls and SWATHs; see Sections IVb and c of his paper for an explanation of the differences.

(Because the undesirable nature of such sharply tuned behavior has been amply demonstrated by recent Navy experience with an oceangoing catamaran, the effectiveness of passive damping devices, such as bilge keels, for this mode of operation was included in the present study. This aspect is covered in a later section of the report.)

Heave responses at zero speed are quite good for the various monohulls; only the submerged column-stabilized catamaran (Ship G) can be expected to have lower heave responses. The two SWATH candidates will have the highest heave responses.

At design speeds (Figure 8b), the SWATHs showed the lowest pitch of the candidates and the column-stabilized catamaran (Ship F) the worst pitch. In fact, at design speed, Ship F has the worst pitch and heave of all candidates. Thus if the comparison is strictly on the basis of these motions rather than their consequences, Ship F is clearly the least attractive candidate in its present configuration; even the small current workboat (Ship A) has lower ship responses. These particular points are emphasized with reference to Ship F motion responses because they illustrate the care that the feasibility designer must exercise to ensure that the consequences of such motions do not result in unacceptable mission-limiting events. Weight or displacement allowances and ballast pumping capacity must clearly be tightly controlled in order to avoid a critical loss of clearance between the cross structure and the water surface.

Significant differences in the motion response levels between the 15- and 20-knot SWATHs were again evident at the design speed. These results demonstrate clearly that substantial differences in the responses of different SWATH ships are possible with relatively minor basic alterations. Ship E (the 20-knot SWATH) is considered superior to Ship D (the 15-knot SWATH) so far as heave and pitch responses are concerned, both during the station-keeping and in-transit operating modes.

Other measures of seakeeping performance of the various candidates at zero speed emphasize the consequences of large SWATH heave motions. As shown in Figure 9a, Ships D and E definitely have the largest relative bow motions at section L_C of all the candidates. Monohulls have the lowest relative bow motions, and the smallest monohull (Ship A) has the lowest of all. Thus, the monohulls are superior for such tasks as launching and retrieving buoys and for similar work which requires low relative motions. Using the criterion of relative motions at zero speed, the ranking in order of decreasing effectiveness is Ship A,B, C,E, and D.

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[20] Salvesen, N., "A Note on the Seakeeping Characteristics of Small-Waterplane-Area-Twin-Hull Ships," Advance Marine Vehicles Meeting, Annapolis, Maryland; J. Hydromechanics, Vol. 7, No. 1, pp. 3-10 (Jan 1973).

When the vertical acceleration levels at three typical longitudinal positions on the decks of the various ships are considered (see Figures 4 and 9a), the monohulls are very similar to the SWATHs, except that Ship E is notably better than the others. The ranking is Ship E, C, D, B, A, and F. Vertical accelerations are generally lower over wider or larger deck areas than over the longer but narrow decks of monohulls. However, none of the acceleration levels appears to be objectionably high.

A similar acceleration comparison at design speeds (Figure 9b) however, demonstrates the clear superiority of the SWATHs over the monohulls during the in-transit operation mode. This is particularly noticeable for the column-stabilized catamaran, Ship F. Ranking for the ships is E, D, B, C, A, *and finally* F. The differences between the in-transit acceleration response levels of the SWATHs, monohulls, and the catamaran are on the order of factors of 2 or greater and are important. Significant vertical accelerations which exceed the 0.2- to 0.25-g level tend to become somewhat uncomfortable. Thus, in average 6-foot-high seas, the SWATH acceleration levels would be below these levels, the monohull accelerations would fall at the beginning of the uncomforable range, and the catamaran accelerations would substantially exceed this uncomforable range. Should Ship F avoid these uncomfortable accelerations by ballasting down to become Ship G, the rather low maximum speed of 5 knots would strongly penalize this candidate.

The comparison of relative motions during the in-transit operation mode indicates that Ship F has the largest responses and that the SWATH and monohull candidates have lower but quite similar responses. On the basis of the combined results, it is concluded that in its present form, the column-stabilized catamaran* is the least desirable of the three basic types of ships under consideration.

To provide an additional seakeeping comparison between the different ship candidates, their absolute and relative bow motions are presented for average 6-foot seas at speeds ranging from 0 to design speed (see Figure 10). The absolute bow motions are comparable for the monohulls represented by Ships B and C. It is noteworthy, however, that for these 6-foot significant seas, there is no noticeable reduction in bow motion with increase in monohull size. Thus, even the largest 741-ton, 20-knot monohull experiences essentially the same absolute bow motions as the presently employed 74-ton, 20-knot hard-chine boat.

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*Substantial improvements in the seakeeping performance of the column-stabilized catamaran can be expected if a large damping foil of the type installed on the T-AGOR and the ASR-21 and -22 were to be installed on the present Ship F/G design. There would of course be a drag penalty associated with such a modification, but this should not be serious.

When comparing the absolute bow motions of the monohulls and the SWATH candidates at 0 and 5 knots, it becomes evident that the monohulls are equal to or better than the SWATHs at these low speeds. The column-stabilized catamaran in the submerged condition (Ship G), however, has the lowest absolute bow motion. It is quite evident from these results that the trends of the absolute bow motions with forward speed are substantially different for the ship types. Bow motions of monohulls tend to increase very slightly with increasing forward speed, those for the catamaran in the surfaced condition (Ship F) increase quite strongly with forward speed, and those of the SWATHs actually decrease with increasing forward speed.

The different ship types also have different trends of relative motion with speed. Relative motions of monohulls are quite low at zero speed and increase somewhat more than the absolute motions with increasing speed. Relative bow motions for the catamaran also strongly increase with increasing speed, and those for SWATHs decrease very slightly with forward speed. This behavior of the SWATHs is regarded as quite favorable from the seakeeping point of view. The trend suggests that if a SWATH is satisfactory at zero speed, then it will be satisfactory during the in-transit condition.

Thus a fundamental difference in the seakeeping performance characteristics of SWATHs (Ships D, E, G) on the one hand and monohulls and catamarans (Ships A, B, C, F) on the other hand is their basic response with speed. This trend was also noted by Salvesen.[20] To ease ship responses in severe seas, monohulls and catamarans must slow down but apparently SWATHs must increase speed. (Severe seas are regarded here as seas which produce responses that threaten ship survival.)

It should be noted that even though *absolute* motions and accelerations are important in determining the comfort level on board ship, once *relative* motions exceed specific values, they produce mission-interrupting impacts or deck wetness. This consideration is equally important especially during the in-transit operating mode.

If the mission of these ships is to include extended operations in the open ocean without retreating to a nearby harbor, their survival characteristics must be examined. This would require model experiments to investigate ship responses in severe seas at both zero and design speeds.

If, on the other hand, the ships are to be deployed in the open ocean with the option to retreat from extreme sea conditions, then only zero speed model experiments between the last two basic ship types are indicated.

It is again concluded at this point that in its present configuration, the column-stabilized ship is the worst of the three basic types investigated. It should be noted, however, that this ship apparently has the best survival capabilities of all. For comparative purposes, the results for Ships F and G will continue to be presented, but this ship candidate is considered as essentially eliminated from the competition.

The following section will compare the candidate ships on the basis of their in-transit performance limits.

CRITICAL SIGNIFICANT WAVE HEIGHTS FOR SLAMMING OR DECK WETNESS

The significant wave height at which mission is disrupted by slamming, deck wetness, or cross-structure impacts is considered a fair measure of the seaway performance of the different ship types. This critical wave height thus represents the limits of ship performance in realistic seas. In waves much higher than those predicted by our linear theory, all ships are expected to encounter such severe disruptions that alterations in ship course and/or speed become mandatory. Inherent in our approach is the assumption of accuracy in the relative ranking of ships by means of their critical wave heights. Model experiments in extreme waves are recommended to verify this assumption for the best two candidate ship types.

Figure 11a presents the influence of speed and modal sea period on the actual wave height that cancels operation because of bow emergence, i.e., slamming. The higher this wave height, the better the candidate ship is in both the in-transit and stationkeeping modes.

For the sake of convenience, sea states are indicated on the right-hand side of the graphs. As in the earlier figures, the vertical lines represent the critical significant wave heights. The dashed portion of the vertical lines represent wave height conditions at the particular modal periods that are very steep; these are exceedingly rare and tend to occur only in land-locked bodies of water.[14,15]

These results indicate that in average 6-foot seas, none of the candidate vehicles will encounter mission-limiting keel emergence during stationkeeping. As expected from the relative motion data of the previous figures, the monohulls (Ships B and C) are essentially equal to the SWATHs (Ships D and E) so far as these seaway performance limits are concerned. The small, presently used monohull (Ship A) is essentially the worst from this viewpoint because of its performance in local-wind-generated, 6-second modal period seas.

At design speeds, the SWATH ships are superior to the monohull candidates so far as mission-limiting keel emergence is concerned. The 20-knot SWATH (Ship E) appears to be the best and the column-stabilized catamaran (Ship F) the worst of the candidates unless the large speed loss inherent in its operation as Ship G is accepted without penalty.

This ranking alters somewhat when the ships are compared in terms of when their relative bow motions will exceed freeboard or cross-structural clearance; see Figure 11b. During the stationkeeping and in-transit operating modes, the monohulls are substantially superior to the other candidates. However, none of the ships is really unsatisfactory since all can operate in seas up to State 4, i.e., seas which occur the majority of the time. It must be noted that as far as the wave height indicated for Ship F is concerned, this is the height at which deck wetness of the lower catamaran hulls occurs at section L_C. This is not considered to be a condition which limits the operation of the ship. Ship responses which result in relative motions greater than this lower hull freeboard are inaccurate because the RAO computer programs assume that the basic above-water hull form is wall-sided. Thus relative bow motions are inaccurate, that is, computer predictions are larger than would be expected from model/full-scale experiments.

The ranking established by these performance-limiting wave heights tends to favor the monohulls for most combinations of performance measures and operating mode. The SWATH ships, however, have better in-transit performance both because they have lower in-transit accelerations and higher in-transit sea state capabilities. In other words, they can operate in higher seas for a given motion or acceleration response level. Based on the above considerations, Ship E is considered to be the ship with the best seakeeping characteristics.

Before we proceed to the time domain results, it should be noted that the above ranking of the candidate ships was obtained by equally weighting the responses at each modal wave period. This is not entirely realistic, of course, but ranking made on the basis of responses weighed by the frequency of occurrence of the particular modal period is beyond the scope of this limited project. It is recommended that such ranking be performed once the candidate ship type has been selected.

TIME DOMAIN RESULTS FOR SLAMMING AND DECK WETNESS

The number of times that relative motions can be expected to exceed either the draft at location L_C (see Figures 1, 2) or the available freeboard cross-structure clearance was calculated from the relative motion time histories for all ships. These head sea events were calculated for the yearly average seas with 6-foot significant wave height (see Reference 17).

Figure 12a indicates the likelihood that draft will be exceeded or that slamming will occur. The vertical lines represent the number of times that relative bow motions will exceed the draft at L_C for the various ships. It is evident from these results that only the small, presently employed workboat should experience difficulties in transiting 6-foot seas to the work site. Ship G, of course, also shows some keel emergences in these relatively mild seas.

Similar information on the likelihood of deck wetness is presented in Figure 12b. The extent of such wetness for the individual catamaran hulls is not considered to represent operational difficulties for Ship F. The presently used workboat (Ship A) appears to have some minor deck wetness at the transiting speeds. Again, all other ships are not likely to encounter deck wetness difficulties in these typical seas.

In the absence of reliable information on the levels of ship response that hinder workboat operation while in the stationkeeping mode, it is impossible to establish a comparison of the percentage and number of times that the individual ship candidates will exceed such values. It is recommended that operators of the present Navy workboat be questioned (1) as to what specific levels* of ship responses and (2) what *particular* ship responses most hinder their work while on station. Once such values are given, the productivity of the different workboat candidates can be readily established from the available stored time histories of ship response.

INFLUENCE OF DAMPING DEVICES ON SWATH RESPONSES IN HEAD SEAS

The zero speed pitch response of the SWATHs, especially Ship D, was regarded as potentially unsatisfactory because of the sharp increase in pitch as the modal sea period approached the natural pitch period. This pitch behavior near resonance is of concern not only because the zero speed behavior is potentially unsatisfactory but also because it suggests large pitch responses in sea conditions which contain sufficient energy at low frequencies near pitch resonance. Thus, the SWATH might incur very large pitch responses both in quartering and following seas at speeds which result in low frequencies of encounter as well as in swell. These large motions may unnecessarily limit the operational ship speed/heading.

Active fins would not be expected to provide sufficient pitch moment at zero speed to adequately reduce the potentially unsatisfactory pitch at resonance. At forward speed, of course, active fins can successfully limit the near-resonance motion behavior of SWATHs, as has been demonstrated with the U.S. Navy Semisubmerged Platform (SSP). The pitch and roll excitation moments are presented in Appendix B together with the heave excitation force per unit of wave height to enable estimates of comparative fin sizes.

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*Such as ± 5 degrees of roll, ± 5 feet of relative bow motion, etc.

At any rate, active* fins are obviously a costly last resort and the addition of large bilge keels was considered to be the most practical method of modifying the zero-speed, near-resonance pitch. The effect of the additional damping on both pitch and heave was determined by recalculating the zero-speed pitch and heave in head seas. This recalculation was made by increasing the original bare hull damping coefficients by the same percent (percentage based on bare hull values) obtained from the measured damping increase due to large bilge keels. The damping experiments are briefly outlined in the section on calculation of roll.

The results of the recalculation are indicated in Table 7 which presents results for the 15-knot SWATH (Ship D) with and without bilge keels. In comparing the results with and without bilge keels, it must be recalled that these passive damping modifications are expected to influence responses only in the vicinity of resonance, i.e., in the area where the dynamic behavior of the SWATH is potentially unsatisfactory. A comparison of the pitch, heave, and vertical accelerations at the CG and—equally important—the relative bow motion at section L_C indicates quite clearly that substantial motions occur near resonance, i.e., the 10- and 14-second modal periods. More specifically, compared to base hull values, bilge keels provided a 23–33 percent reduction in pitch, a 5–10 percent reduction in heave, a 12-percent reduction in vertical accelerations at the CG, and a 6–22 percent reduction in relative bow motions. Clearly, the addition of large bilge keels can be expected to substantially improve the near-resonance motion (pitch) of SWATH Ship D. In fact, results suggest that the low-frequency, near-resonance motion responses may be satisfactorily controlled by means of passive damping devices.

INFLUENCE OF BILGE KEELS ON SHIP RESPONSES IN BEAM SEAS

Since Ship A, the presently employed workboat, is known to have less than satisfactory roll motion characteristics at low speeds, it was considered appropriate to evaluate the roll responses of the different candidate ships in beam seas. The monohull candidates were therefore evaluated with and without bilge keels. However, responses of the SWATH ships and the column-stabilized catamaran in the surfaced condition (i.e., as Ship F) were

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*Automatically controlled such as antiroll fins.

calculated only with bilge keels; it was considered that the accuracy with which the effect of bilge keels could be predicted was too low to be of value for these types. The procedures employed have been briefly discussed in the section on calculation of roll. These calculations were not performed for Ship G because roll may be expected to be very small for this ship; moreover, it seems unlikely that it can be considered as a serious candidate for the PMR workboat.

Results of these zero-speed, beam-sea calculations are presented in Table 11 in terms of RMS responses in waves with a 6-foot significant height. Both RMS acceleration and roll values were calculated; these may be converted to significant values by multiplying them by two.

It is emphasized that significant improvements in ship responses can be expected only in seas whose modal periods approach resonance. It is evident that despite the improvement (16 to 17 percent) in monohull roll achieved near resonance, the SWATH roll is still less by an order of magnitude. Their superior behavior in roll and their lower acceleration levels should make the SWATHs better workboat candidates than are monohulls. This conclusion is premised on the belief that the difference in payload growth potential between the SWATHs and monohulls is not very important. In other words, the SWATHs are likely to be better workboats if they are not forced to carry payloads significantly greater than allowed for in the design.

On the basis of the foregoing seakeeping evaluations, the 20-knot SWATH is considered to be the best of the ship candidates. Economic factors, of course, did not enter into the seakeeping evaluation.

CONCLUSIONS AND RECOMMENDATIONS

The behavior of the candidate ships in waves up to 6 feet high is of primary importance in establishing comparative seaway performance. Consequently, their survival capabilities were not examined to any significant extent. The following conclusions are based on considerations of the environment of the intended worksite area.

1. SWATHs are better workboat candidates than monohulls from the seakeeping point of view.

2. In its present stage of development, the column-stabilized catamaran is the worst workboat candidate even though its survival capability appears to be the best of all.

3. The 20-knot SWATH is substantially better than the 15-knot SWATH primarily because of its superior in-transit performance in various sea conditions and its superior roll performance at low speed.

4. Monohulls have substantially better relative motions at low stationkeeping speeds than do SWATHs and thus are better suited for launch/retrieval of floating objects at minimum roll headings.

The following specific recommendations are made:

1. If a preliminary design of the best two candidate workboats is intended, then either Ships E and C or Ships D and E should be examined as the final two candidates.

2. The final two candidates should be evaluated in competitive model experiments.

3. This experimental evaluation should include (a) comparison of the candidates at zero speed in moderate head, bow, and beam seas (stationkeeping); (b) establishment of SWATH behavior in moderate quartering and following seas (low encounter periods); and (c) the survival characteristics of the candidates should be determined if the workboat must accomplish its mission in the open ocean without an option of returning to harbor in severe seas.

4. The load-carrying capacity of the SWATH should be improved by incorporating some of the pumping/ballasting features inherent in Ship F/G.

5. The use of large damping devices, such as bilge keels, is also recommended as an integral initial part of the preliminary SWATH ship design.

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APPENDIX A

DEFINITION OF RELATIVE BOW MOTION

Relative bow motion (RBM) is defined as the difference between the absolute motion V_ℓ and the wave r_ℓ at some point (L_C or X_4) on the ship; see Figure A.1 and Figure 2.

RBM_ℓ is calculated on the centerline of the ship with no allowances for trim and sinkage. Their neglect is not considered significant because both are small (trim less than 1 foot and sinkage less than 1 degree) for the monohulls at the low, stationkeeping speeds considered. Trim and sinkage increase with increasing ship speed and are most severe for the monohulls, particularly Ship A, the smallest. Even though trim and sinkage may exceed their stationkeeping values at design speeds, the values are still considered small enough so that the relative ranking of these ships is not affected. It may be assumed that at 0 and 5 knots, the SWATHs would operate at zero trim and sinkage and that at the higher speeds, the active or semiactive fins would maintain zero trim and only a slight sinkage or rise.

Figure A.1 presents a graphical definition of the relative bow motion and Figure A.2 summarizes the various motion components used to calculate the RBM. It may be seen that RBM is constructed from the wave at the origin r_0. This value and those for heave and pitch motion of the ship at the origin were obtained by summing 100 component sine waves of amplitude r_{0k} and with phase γ_k, that is,

$$r_0(t) = \sum_{k=1}^{100} r_{0k}\, e^{i(\omega_E t + \gamma_k)} \tag{1}$$

where $\omega_E = \omega \quad \frac{\omega^2}{g} V \cos \mu$

ω = circular frequency of the wave

V = ship speed

g = gravity

μ = ship heading relative to wave

The amplitudes of the component waves are modeled in accordance with the Bretschneider wave spectrum $S_\zeta(\omega)$ defined at 100 discrete frequencies, i.e., ω_k's. In other words, r_{0k} is the mean square wave amplitude over the frequency interval $\Delta\omega$ with a center frequency ω_k given by

$$r_{0k} = \left[2 \int_{\omega_k - \Delta\omega/2}^{\omega_k + \Delta\omega/2} S_\zeta(\omega)\, d\omega \right]^{1/2} \tag{2}$$

and the wave spectrum $S(\omega)$ is

$$S_\zeta(\omega) = A\omega^{-5}\, e^{-[B/\omega^4]} \tag{3}$$

where $A = 483.5\,(\widetilde{\zeta}_w)^2_{1/3}/T_0^4$

$B = 1944.5/T_0^4$

$(\widetilde{\zeta}_w)_{1/3}$ = significant wave height

T_0 = modal period of the Bretschneider wave spectrum $S(\omega)$

The random phase γ_k associated with each sine wave of frequency ω_k is obtained by means of a random number generator.

In order to calculate r_ℓ, the wave height at the location L_C or X_4 (see Figures A.1 and 2), the phase of the wave at the origin r_0 is shifted by the product of the distance ℓ from the origin to X_4 and wave number ω^2/g, that is,

$$r_\ell(t) = \sum_{k=1}^{100} r_{0k}\, e^{i(\omega_E t + \omega^2/g\, |\ell| + \gamma_k)} \tag{4}$$

The time history of the response η is obtained from

$$\eta_j(t) = \sum_{k}^{100} \eta_{jk}\, e^{i(\omega_E t - \epsilon_{jk} + \gamma_k)} \tag{5}$$

Here j = 3 represents heave, j = 5 represents pitch, and η_{jk}, ϵ_{jk} represent the amplitude of response j and the associated phase at ω_k taken from the RAOs calculated by the first series of computer programs. The absolute motion at position L_C is

$$V_\ell(t) = \eta_3(t) + |\ell|\, \eta_5(t) \tag{6}$$

Finally at L_C, relative bow motion RBM_ℓ becomes

$$RBM_\ell(t) = V_\ell(t) - r_\ell(t) \tag{7}$$

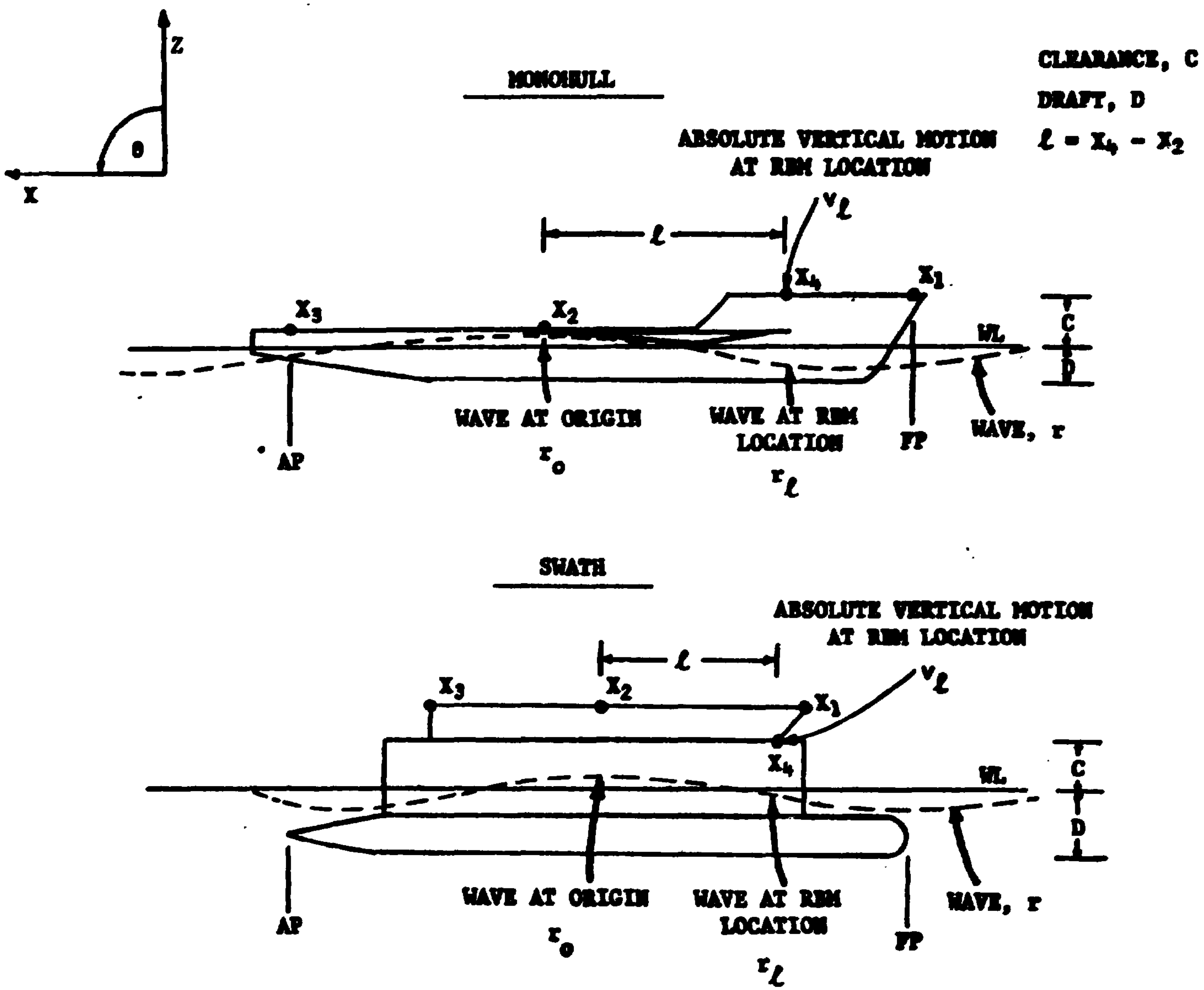

Figure A.1 – Definition of Relative Bow Motion on Ship Centerline

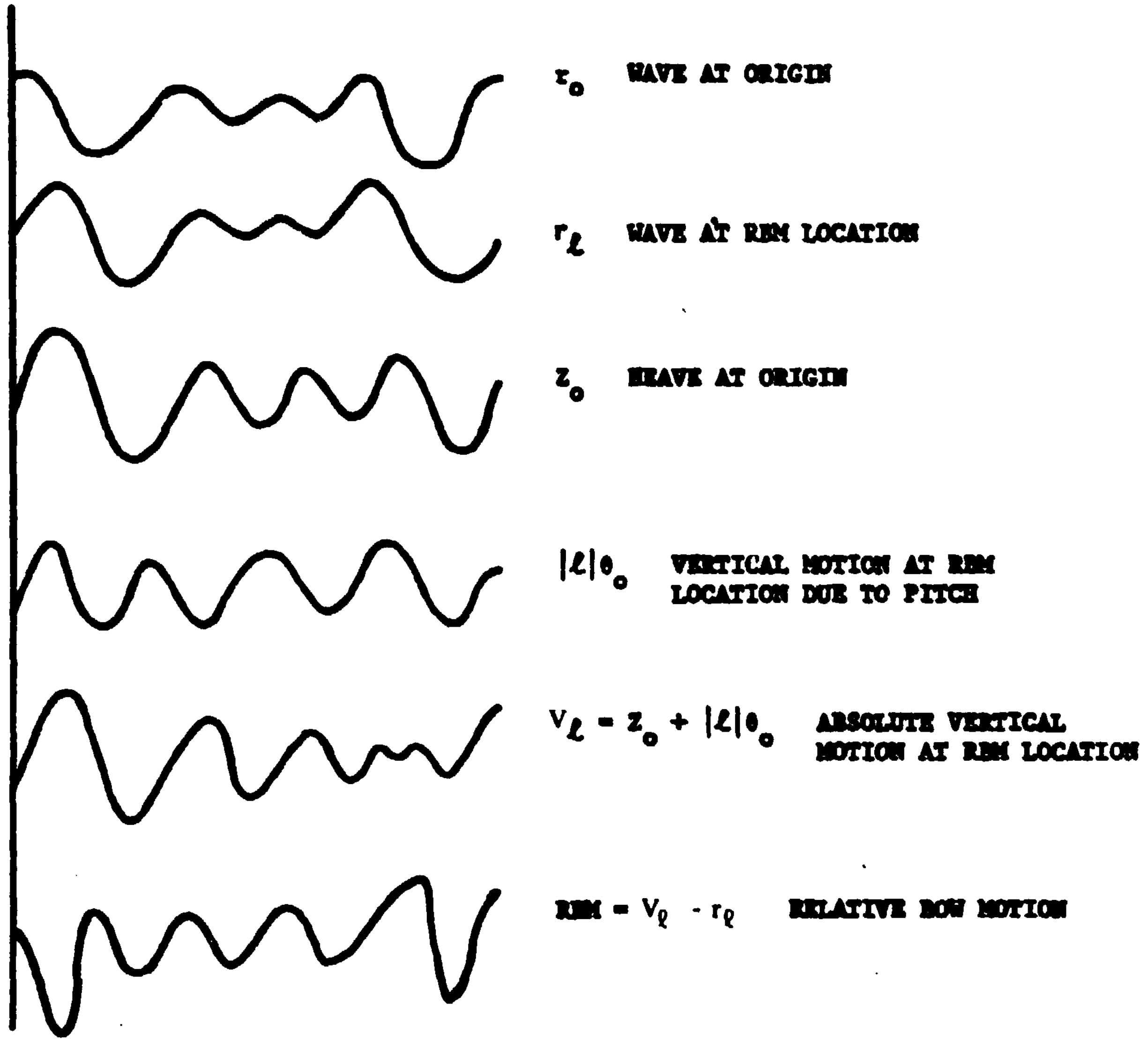

Figure A.2 – Summary of Relative Bow Motion Calculations

APPENDIX B

WAVE-EXCITING FORCES AND MOMENTS FOR WORKBOAT CANDIDATES AND FEASIBILITY OF ACTIVE FIN STABILIZERS

The wave-exciting forces and moments that act on the various workboat candidates are presented in graphical form (Figure B.1) in order (1) to provide data from which the feasibility of motion reduction by means of active fins can be established and (2) to illustrate some of the reasons for the basic differences in the responses of the various ship types.

The results of Figure B.1 are for excitation at zero speed in head (pitch and heave) and beam (roll) seas. Since the effect of forward speed on the magnitude of the wave excitations is small, the zero-speed excitations are considered to represent the excitations at all speeds insofar as fin feasibility and basic response characteristics are concerned.

Pitch and roll moments are given per unit of ship displacement times wave amplitude; heave force is given in the same units and then multiplied by ship length in feet. The waves which correspond to the resonance periods of roll and pitch are denoted by vertical lines labeled by ship type. Note that these resonance periods, or waves, correspond to the waves which produce the maximum ship response per unit of wave height as determined from the RAOs, i.e., roll in beam seas and pitch in head seas.

The basic reason for the differences in the responses of the low waterplane area ship candidates and the monohulls/catamarans is demonstrated by the location (frequency) of the maximum values of the wave excitations and the resonant ship response periods. Maximum values of the monohull and catamaran wave excitation moments tend to occur near the maximum value of the ship roll and pitch responses, i.e., near the resonance values labeled in Figure B.1; in contrast, wave excitations are quite small for the SWATH ship candidates in the vicinity of the resonant roll and pitch motions.

Before discussing the feasibility of active fins for ship motion reduction, it should be mentioned that ship responses depend on the magnitude of the wave excitations and their frequencies. Thus wave excitations at frequencies near the angular ship response resonances tend to produce large responses and those far removed from these motion resonances tend to produce small responses. Essentially, wave excitations are a function only of ship geometry and the waves. On the other hand, the location of motion resonances* (and thus the expected response magnitudes) depend on the load distribution (metacentric height (GM) and mass moment of inertia) of the ship once displacement and LCG have been fixed. Thus substantial reductions in motion may be realized if the load distribution can be altered sufficiently to

*SWATH motion resonance frequencies are also quite sensitive to waterplane area distribution.

move the resonant motion period from the peak of the wave excitation. For example, an increase in the roll period of Ship A from 1 to 1.5 seconds would reduce roll.

It is considered appropriate to develop fins which reduce ship motions that occur near the ship response resonances. Thus fins intended to reduce the heave and pitch of SWATHs should be designed for periods of around 12.5 seconds for Ship D and for about 17.4 seconds for Ship E. The forces generated by the fins must approach the magnitude of the wave excitations in order to reduce motion substantially. For purposes of this fin feasibility examination it may be assumed that the fins should provide a moment which exactly cancels the ship motions. This assumption will, of course, result in relatively large fins at the fin design conditions. Nevertheless, the fin sizes that can be developed on the basis of this assumption will establish the appropriate relative ranking for motion stabilizers for the various workboat candidates. It is evident from Figure B.1 that the wave excitations for monohulls and catamarans are very much larger than for SWATHs.

The feasibility of motion stabilization is now demonstrated by considering the nondimensional roll and pitch wave excitations at resonance for Ships C, E, and F:

	Ship C	Ship E	Ship F
Pitch Moment	4.2	0.13	2.25
Roll Moment	0.19	0.06	0.55

We convert these pitch moments into forces (tons) by locating the fins, say, 0.4 L_{pp} from the LCG. Similarly, we convert the roll moments into forces (tons) by locating the fins rather arbitrarily at a certain distance from the centerline: 1.2 times the draft for Ships C and E and 24 feet for Ship F. The following forces result:

	Ship C	Ship E	Ship F
Pitch, tons	38.9	2.1	34.2
Roll, tons	11.7	3.2	23.6

These are wave excitation forces per foot of wave amplitude that stabilizers must provide in order to completely cancel the ship motions due to waves.

Now assume a fin design speed of 15 knots and select 0.040 lift curve slopes per degree of fin angle, as obtained from some typical full-scale roll fin experiments.[21] The resulting total sizes for fin travel-limited to ±28 degrees is given below for seas with a significant wave height of 6 feet. (The limit of ±28-degree fin angle was taken from the fin limits employed on the Vosper fins installed on the U. S. Navy PG 100; see Reference 21.)

	Ship C	Ship E	Ship F
Pitch, feet^2	363	20	319
Roll, feet^2	110	30	235

On the basis of these preliminary fin area results as well as the sizes of roll fins installed on monohulls, it is concluded that pitch stabilization is impractical for monohulls and catamarans. In other words, pitch reduction to zero by means of fins in 6-foot significant seas is impractical though not impossible. On the other hand, pitch and roll reduction appears to be quite practical for the SWATH ship. Finally, stabilization of the monohull to zero roll in 6-foot beam seas is also somewhat impractical although much less so than is true for the catamarans. It should be noted that for adequate conventional roll stabilization, fin size for Ship C can be reduced to about 60 square feet.

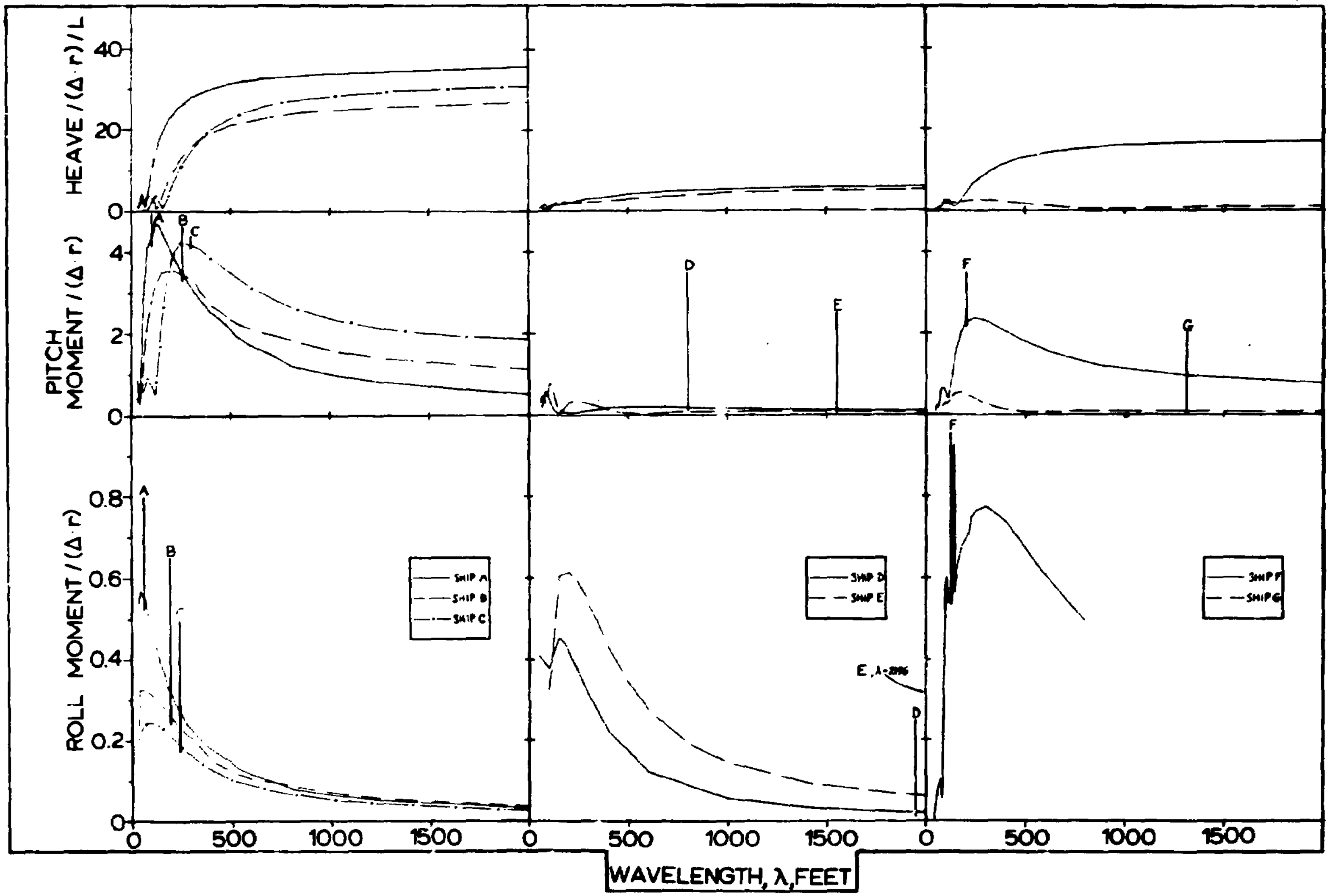

Figure B.1 – Wave-Exciting Forces and Moments for the Ship Candidates

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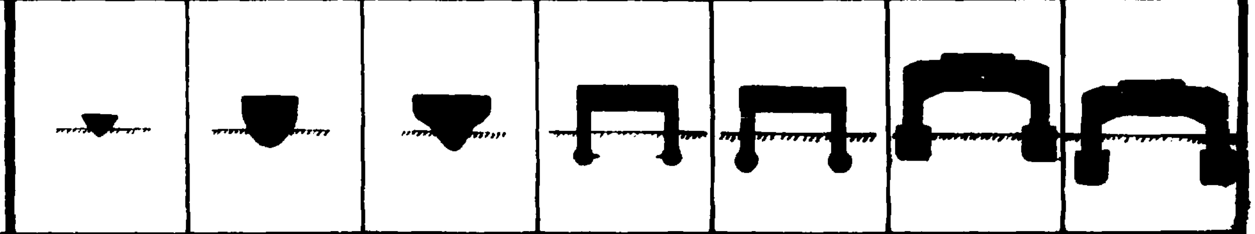
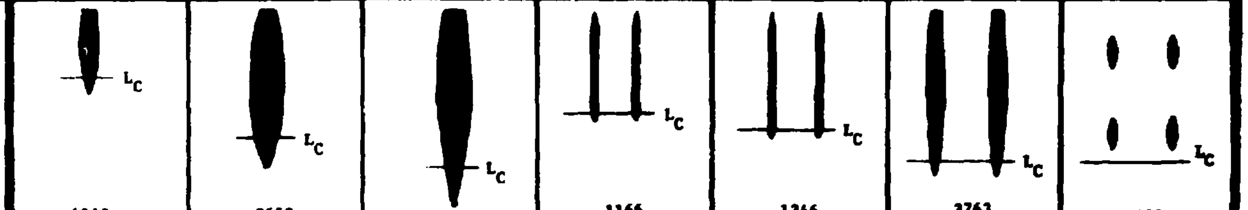
SHIP	MONOHULLS			SWATH		COLUMN STABILIZED	
DESCRIPTION	SHIP A 85 FOOT HARDCHINE	SHIP B 15 KNOT	SHIP C 20 KNOT	SHIP D 15 KNOT	SHIP E 20 KNOT	SHIP F SURFACED	SHIP G SUBMERGED
HULL FORM AT SECTION L_C							
LENGTH (FT.)	85	160	200	155	200	170	170
BEAM AT L_C (FT.)	9.5	19.1	16.5	49.5	53.5	64.0	64.0
DRAFT (FT.)	3.77	8.0	9.35	16.5	19.4	12.5	24.0
CLEARANCE (FT.)	6.82	18.0	17.65	12.0	12.1	4.2	12.0
L_C (FT.) } SEE FIG. 4	17.0	32.0	40.0	30.0	41.44	14.4	14.4
B (FT.) } SEE FIG. 4	7.5	10.0	10.0	25.0	27.0	35.0	35.0
DISPLACEMENT (L.T.)	74	565	741	785	1286	1032	1614
DESIGN SPEED (KT.)	20	15	20	15	20	15	5
TOTAL PROJECTED FIN OR BILGE KEEL AREA (SQ. FT.)	--	192	240	AFT 240 FWD 60	AFT 318 FWD 80	--	--
WATERPLANE AREA (SQ. FT.)	 1142	3650	4404	1166	1346	3763	690
GM_L (FT.)	-	216.0	-	20.0	20.0	150.7	14.2
GM_T (FT.)	5.3	3.6	4.0	4.0	4.0	85.4	2.24
T_Z (SEC.)	4.7	4.4	4.8	6.6	8.5	4.3	14.4
T_ϕ (SEC.)	3.4	6.1	6.8	19.5	20.7	5.0	-
T_θ (SEC.)	4.5	7.1	7.7	12.5	17.4	6.3	16.0

Figure 1 – Ship Particulars

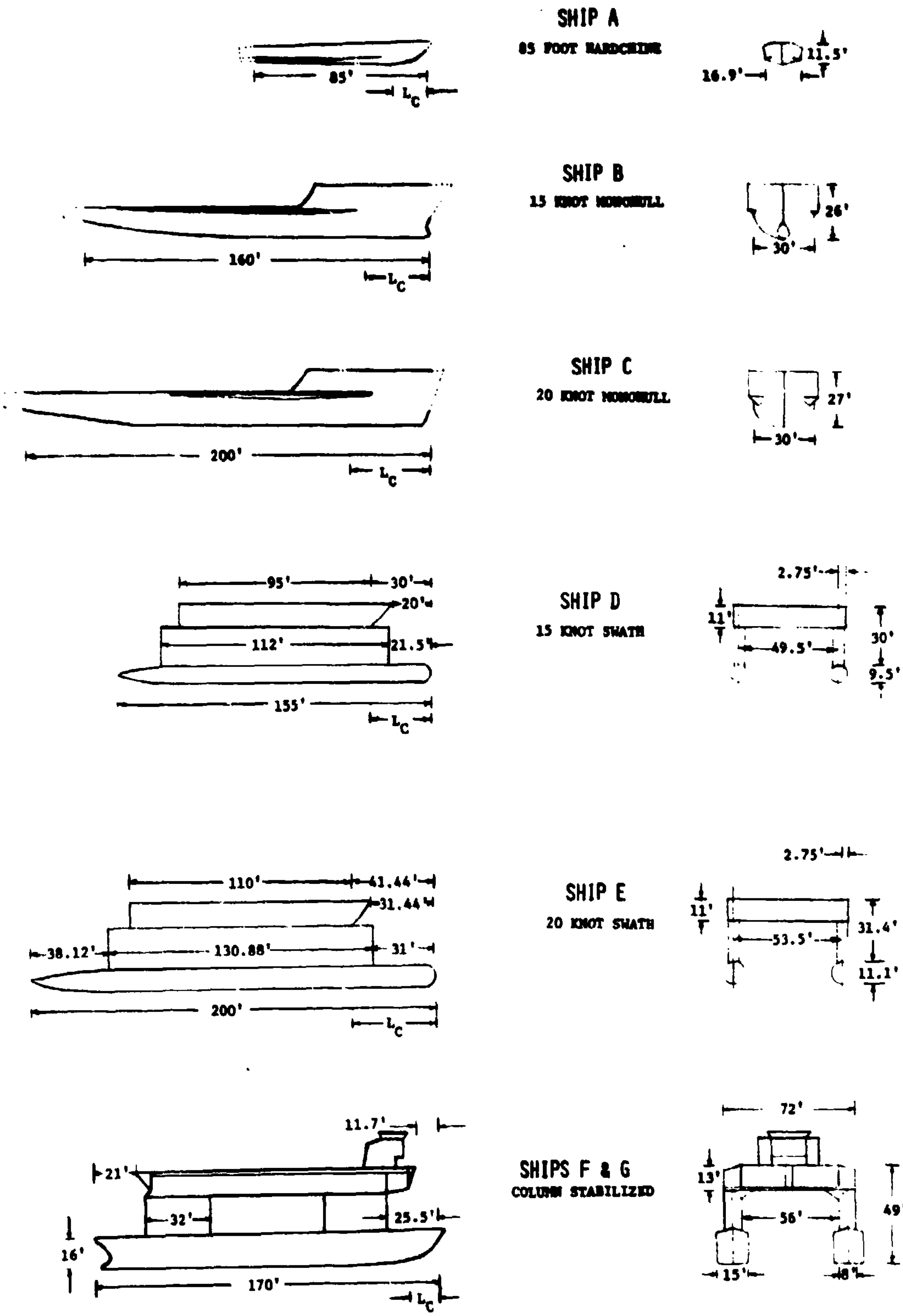


Figure 2 – Comparison of Candidate Ship Types

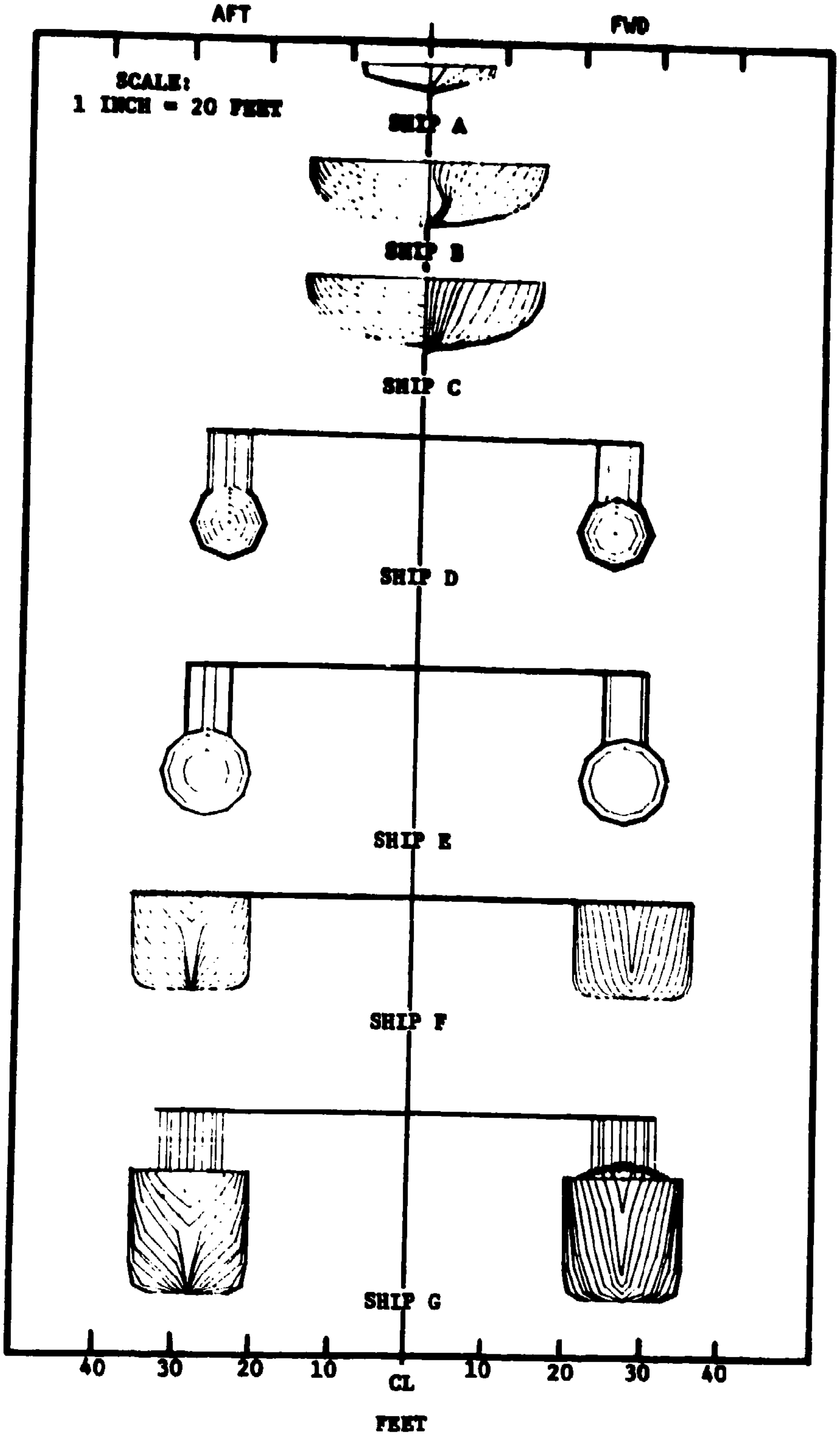


Figure 3 – Computer Fit of Body Plans for Candidate Ship Types

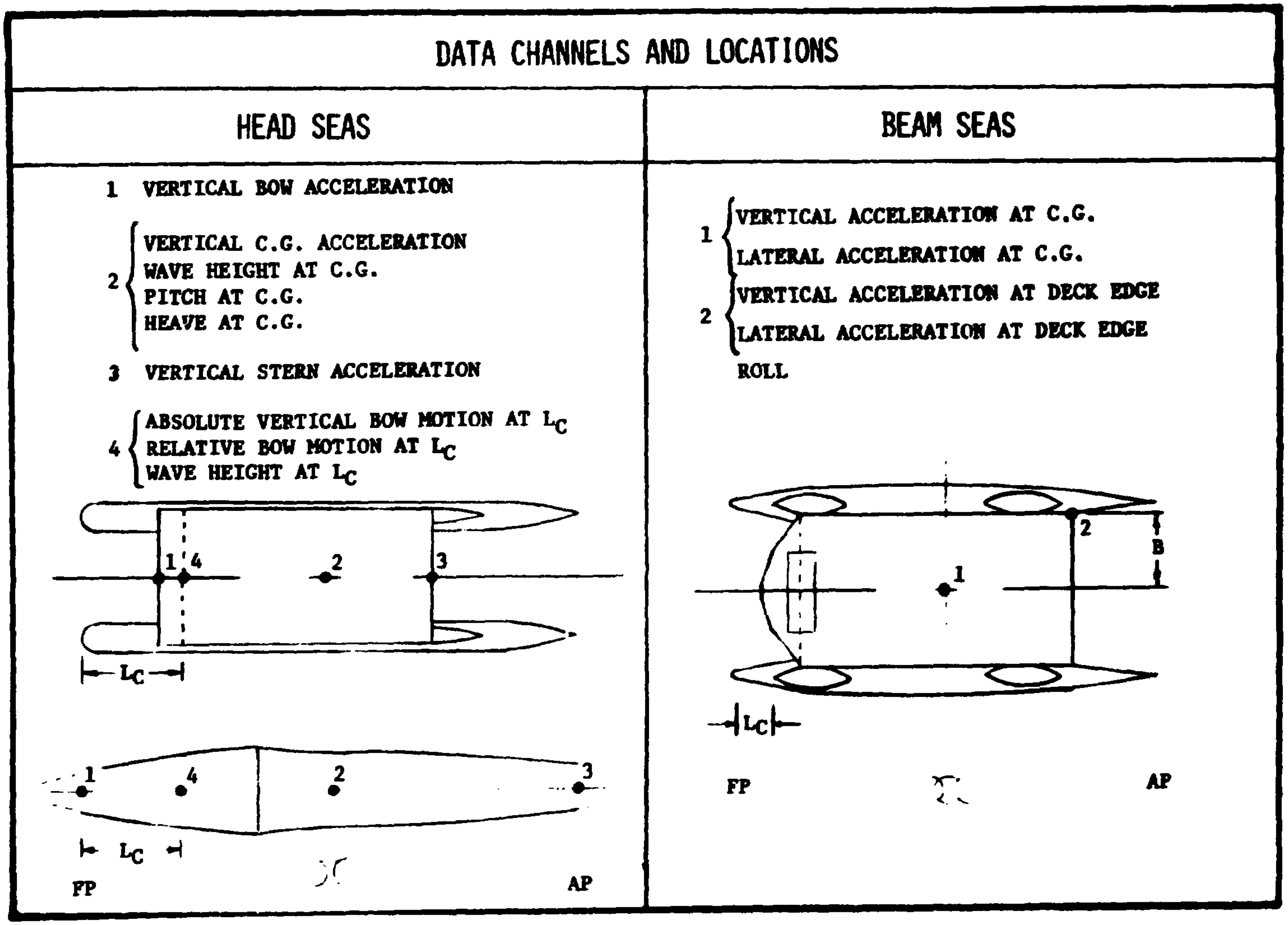


Figure 4 – Data Channels and Ship Locations for Which Responses Calculated

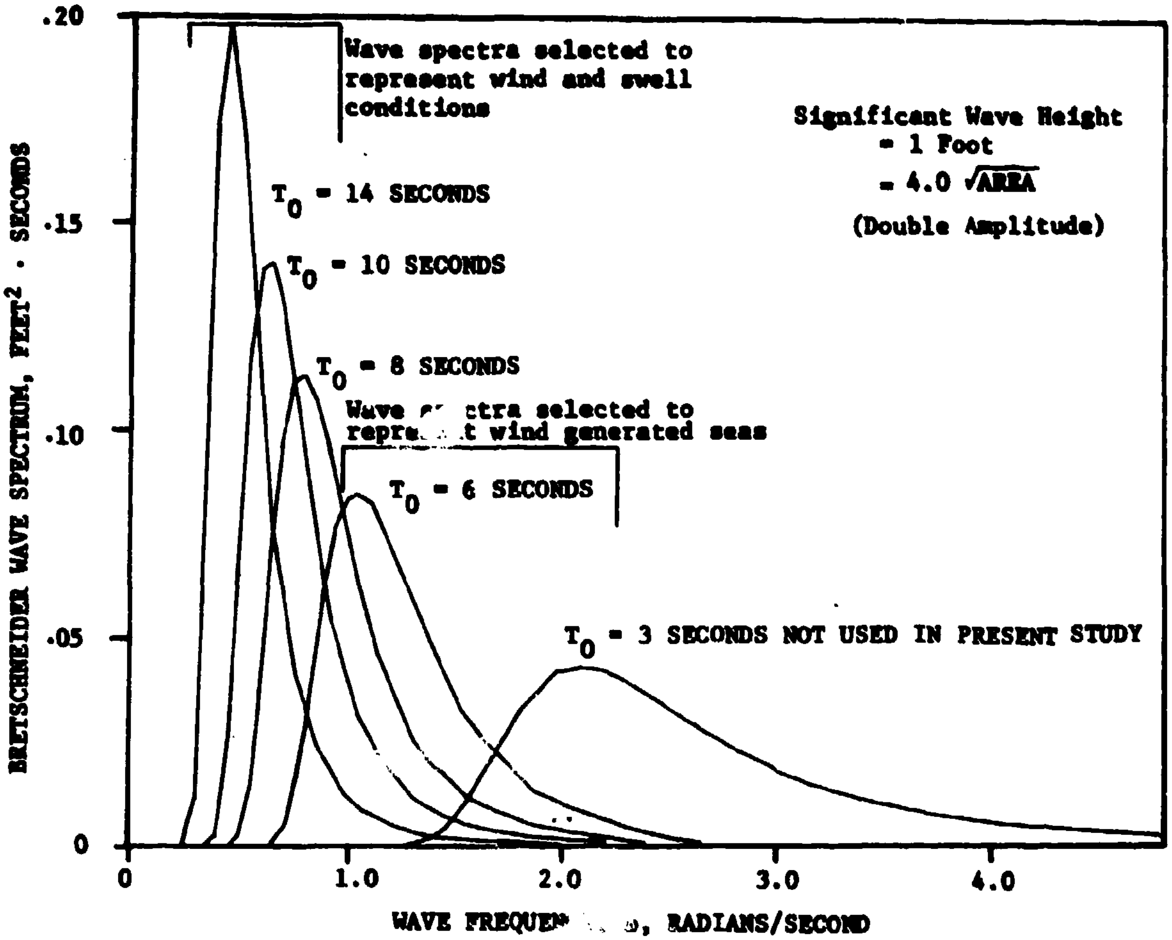
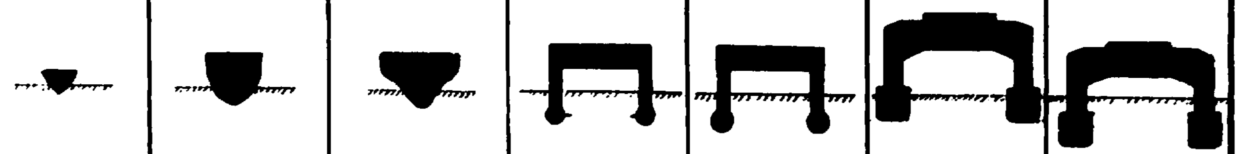


Figure 5 – Theoretical Wave Spectra Used to Represent Sea Conditions

SHIP	MONOHULLS			SWATH		COLUMN STABILIZED	
DESCRIPTION	SHIP A 55 FOOT HARDCHINE	SHIP B 15 KNOT	SHIP C 20 KNOT	SHIP D 15 KNOT	SHIP E 20 KNOT	SHIP F SURFACED	SHIP G SUBMERGED
HULL FORM AT SECTION L_C							
HULL DAMPING CONDITIONS	WITHOUT BILGE KEELS	WITH AND WITHOUT BILGE KEELS	WITH AND WITHOUT BILGE KEELS	WITH FINS WITH AND WITHOUT BILGE KEELS	WITH FINS	WITHOUT DAMPING PLATES	WITHOUT DAMPING PLATES
SPEED (KNOTS) (180°)	0, 5, 15, 20	0, 5, 15	0, 5, 15, 20	0, 5, 15	0, 5, 15, 20	0, 5, 15, 20	0, 5
(90°)	0	0	0	0	0	0	NA
HEADINGS (DEGREES)	180, 90	180, 90	180, 90	180, 90	180, 90	180, 90	180
SEA STATE MODAL PERIODS (SECONDS)	6, 8, 10, 14	6, 8, 10, 14	6, 8, 10, 14	6, 8, 10, 14	6, 8, 10, 14	6, 8, 10, 14	6, 8, 10, 14
SEA STATE SIGNIFICANT WAVE HEIGHTS (FEET)	2, 4, 6	2, 4, 6	2, 4, 6	2, 4, 6	2, 4, 6	2, 4, 6	2, 4, 6

180° = HEAD SEAS
90° = BEAM SEAS

Figure 6 – Summary of Calculation Conditions

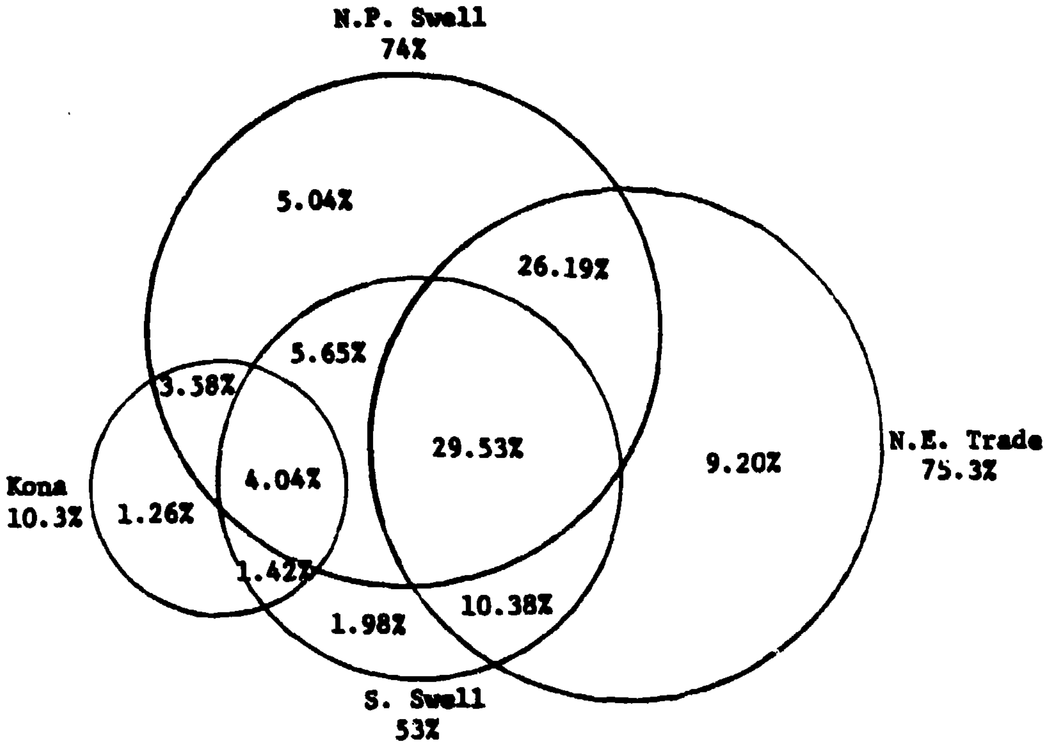


Figure 7 – Relative Frequencies at Which Individual Wave Systems or Combined Systems Occur

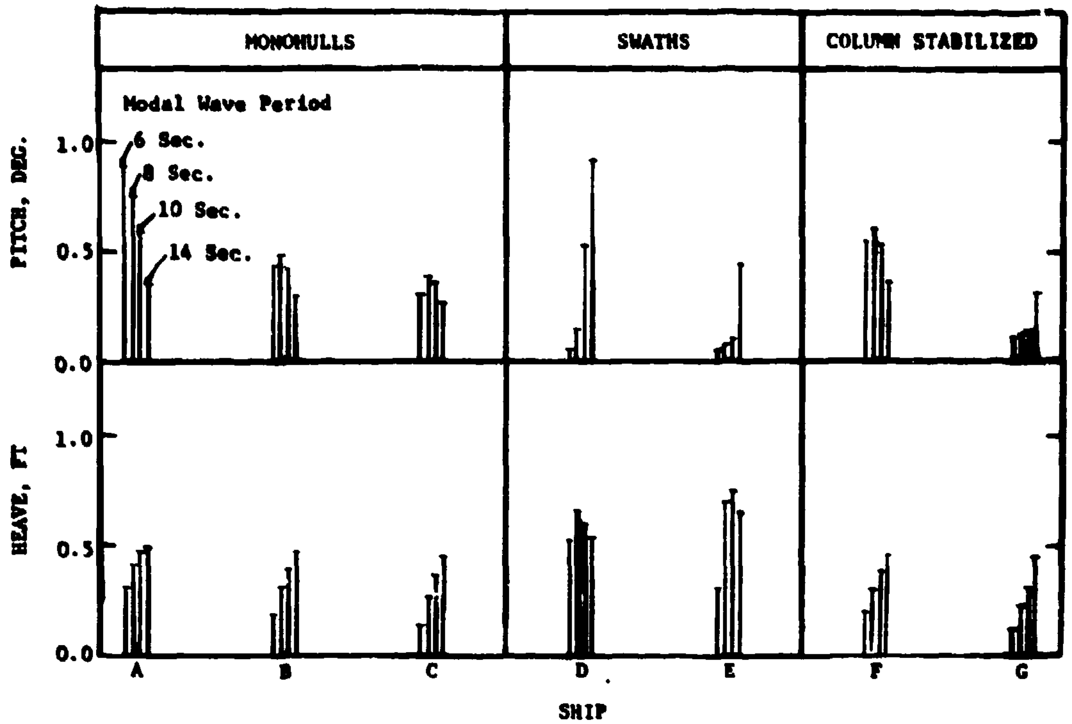


Figure 8a -- At 0 Knots

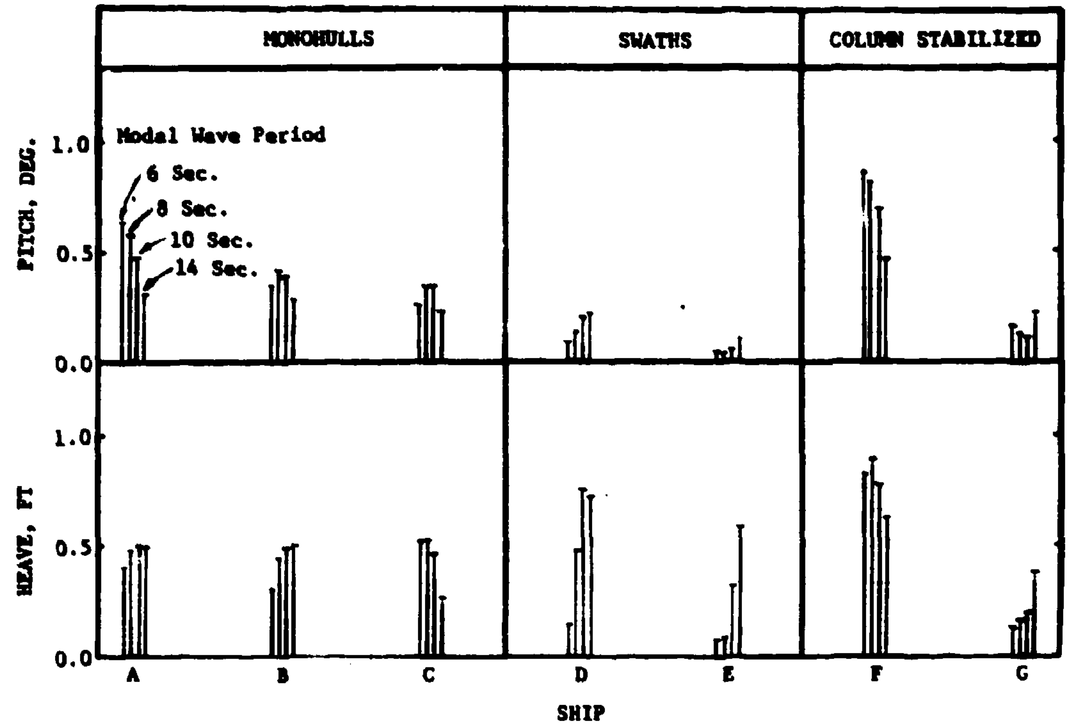


Figure 8b – At Design Speeds

Figure 8 – Influence of Modal Sea Period on the Significant Single Amplitude Pitch and Heave of Ship Candidates

(In seas with 1-foot significant wave height)

Figure 9 – Influence of Modal Sea Period on the Significant Single Amplitude Relative Bow Motion and Vertical Accelerations of the Ship Candidates

(Data for three positions on the centerline in seas with 1-foot significant wave height)

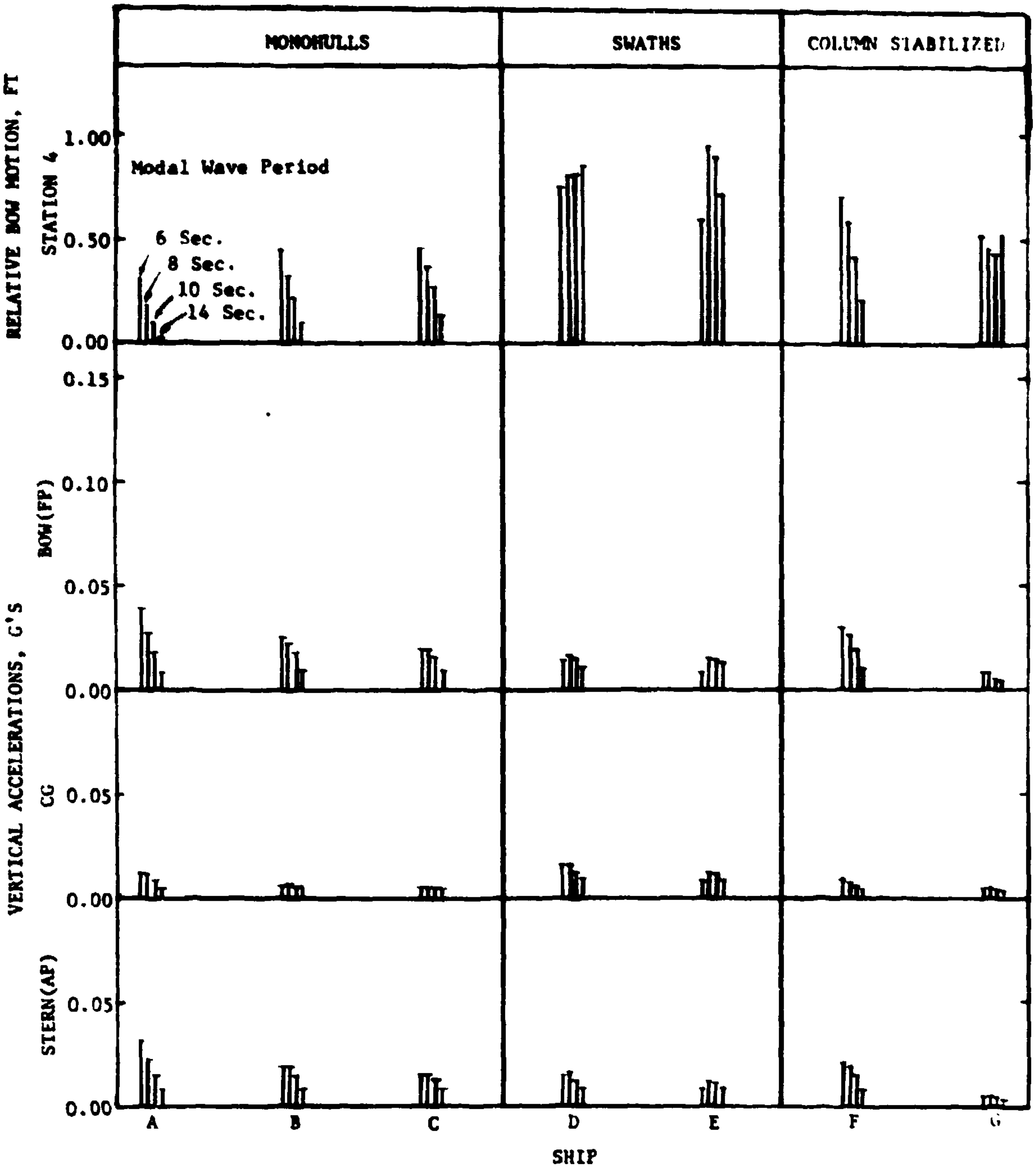


Figure 9a – At 0 Knots

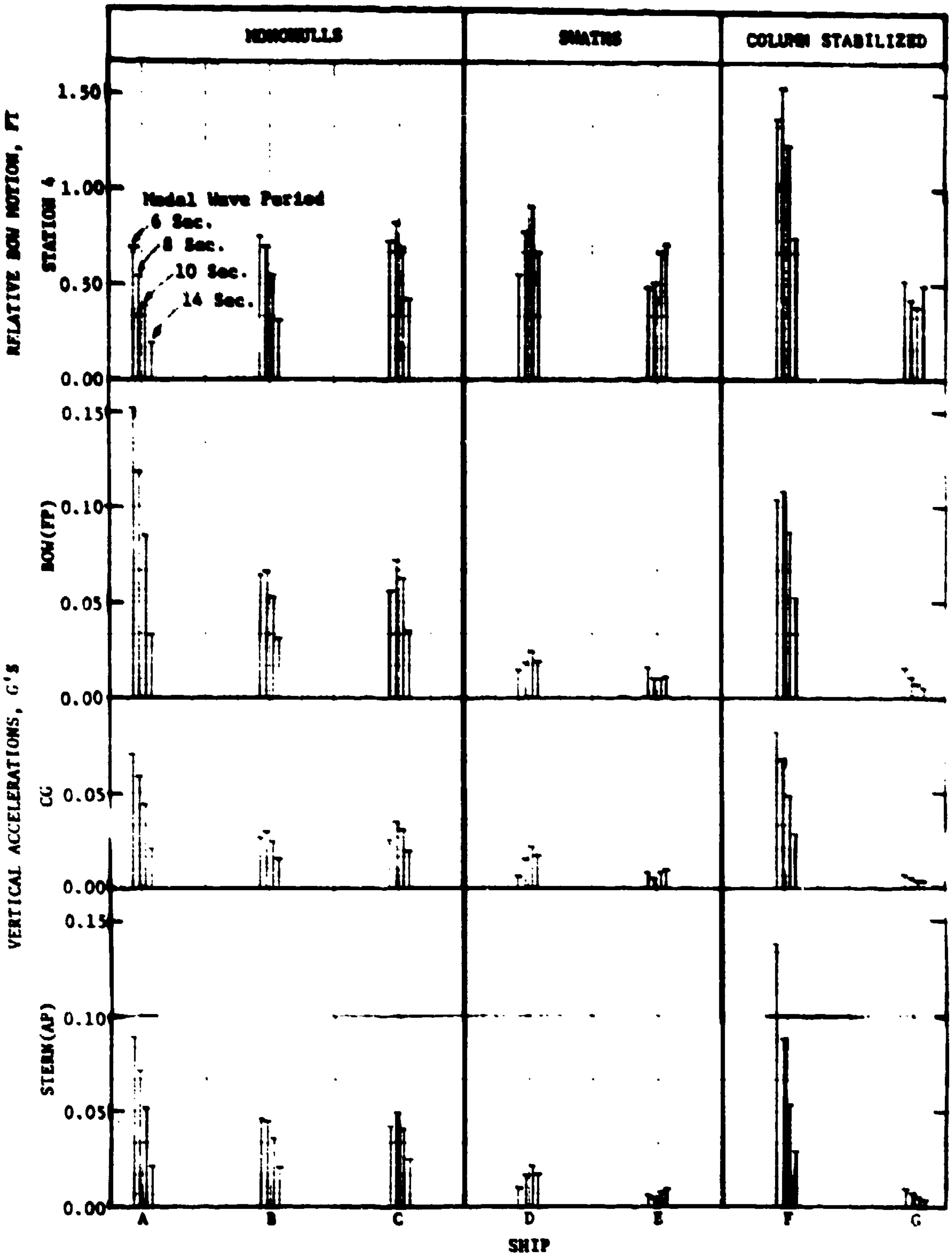


Figure 9b – At Design Speeds

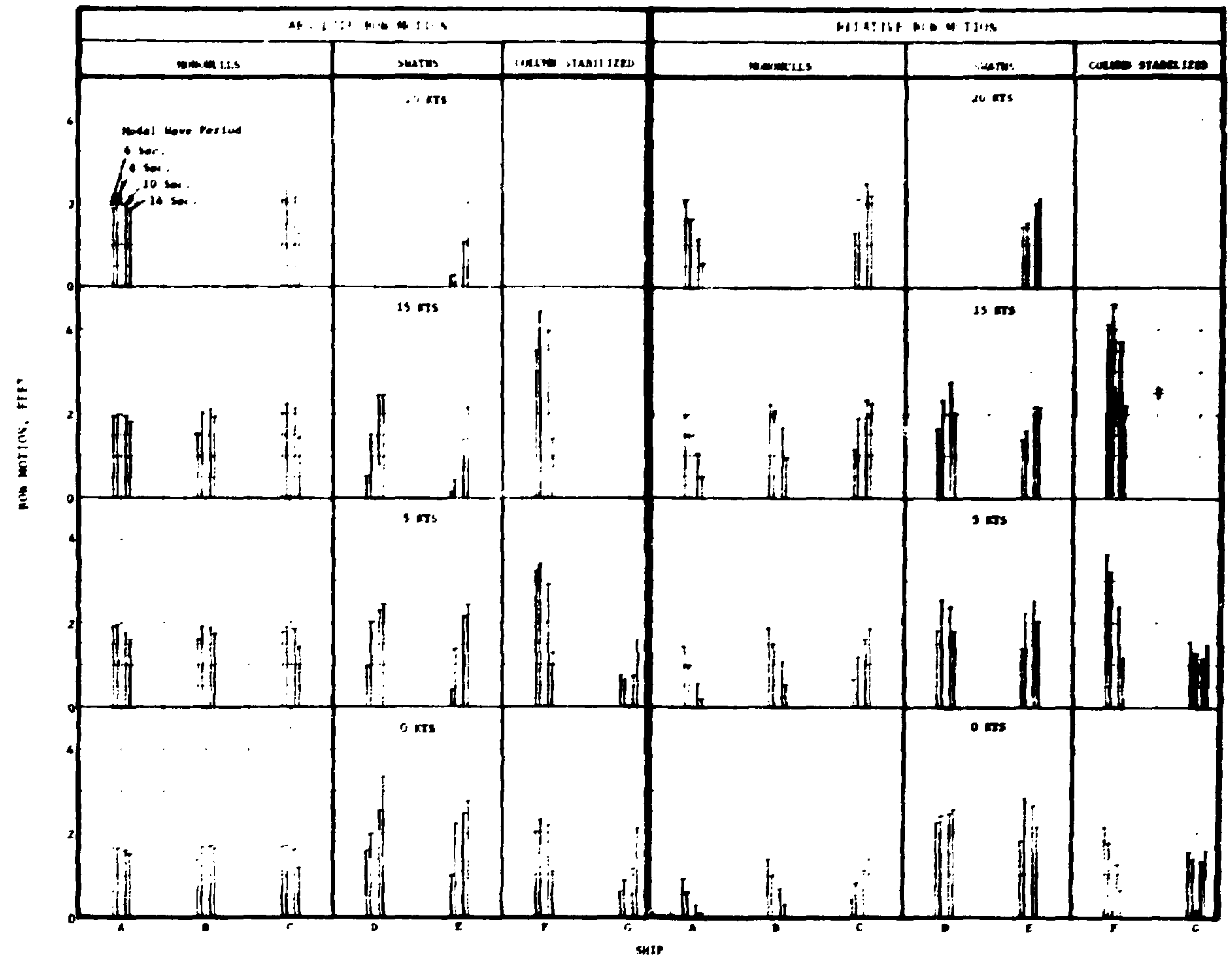


Figure 10 – Influence of Ship Speed and Modal Sea Period on the Significant Single Amplitude Relative Bow Motion and Comparable Absolute Vertical Motion of the Candidate Ships

(In seas with 6-foot significant wave height)

Figure 11 – Influence of Ship Speed and Modal Sea Period on Significant Wave Height Levels Critical for Various Ship Candidates

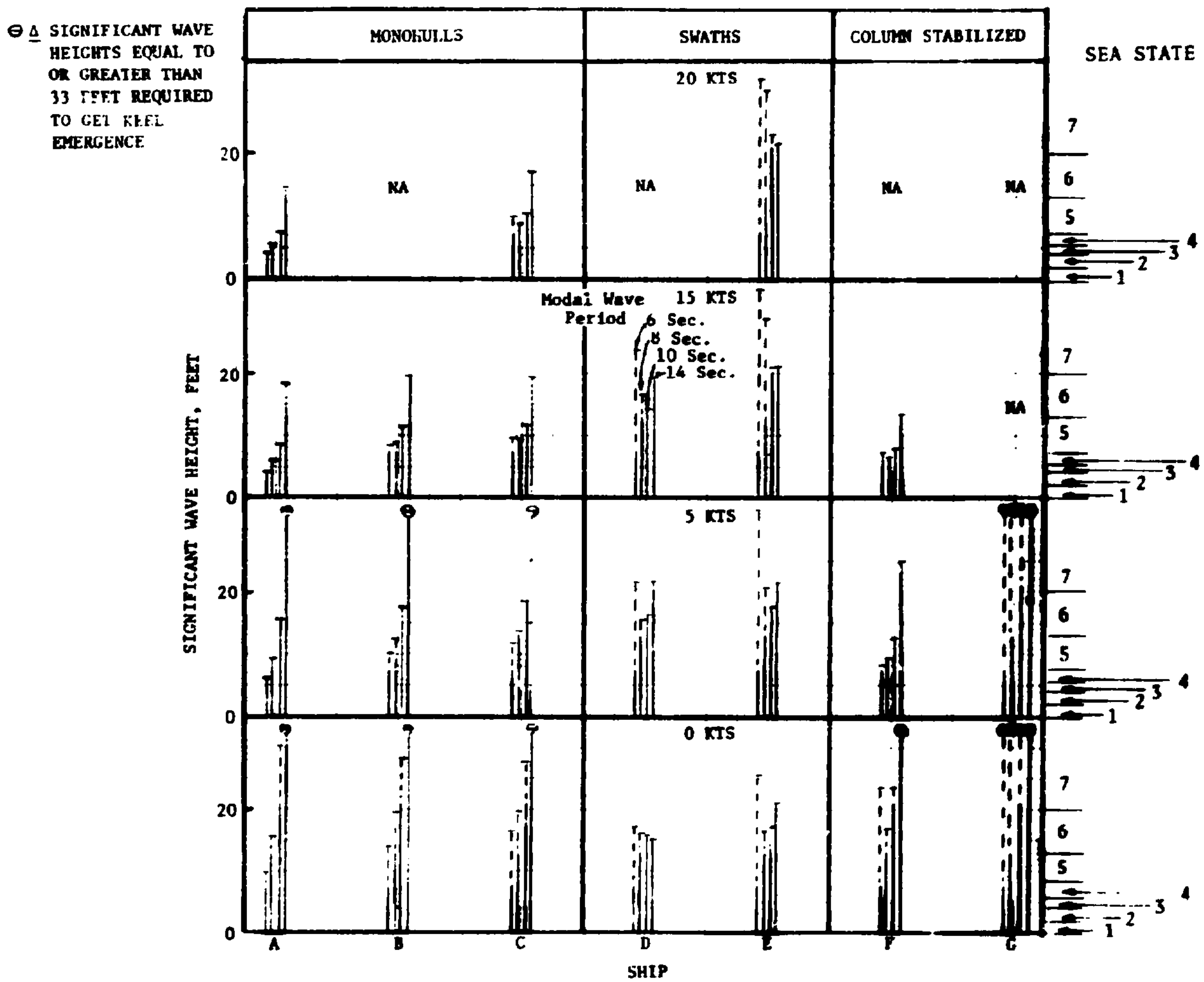


Figure 11a – Level at Which Average 1/10 Highest Relative Bow Amplitudes Exceed Ship Draft

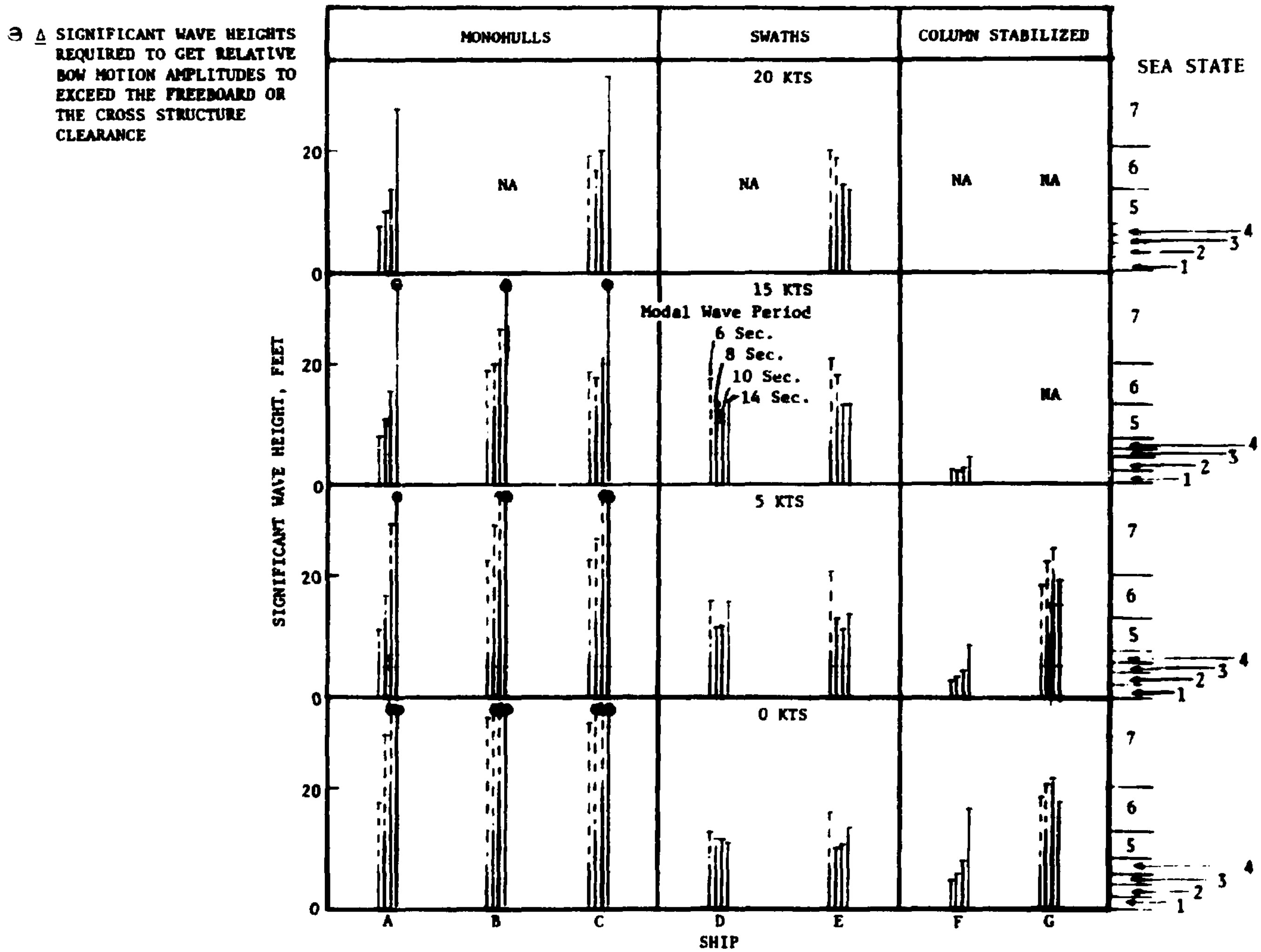


Figure 11b – Levels at Which Average 1/10 Highest Relative Bow Motion Amplitudes Exceed the Freeboard or Above-Water Clearance to the Hull Cross Structure

Figure 12 – Influence of Ship Speed and Modal Sea Period on the Mission-Interrupting Events

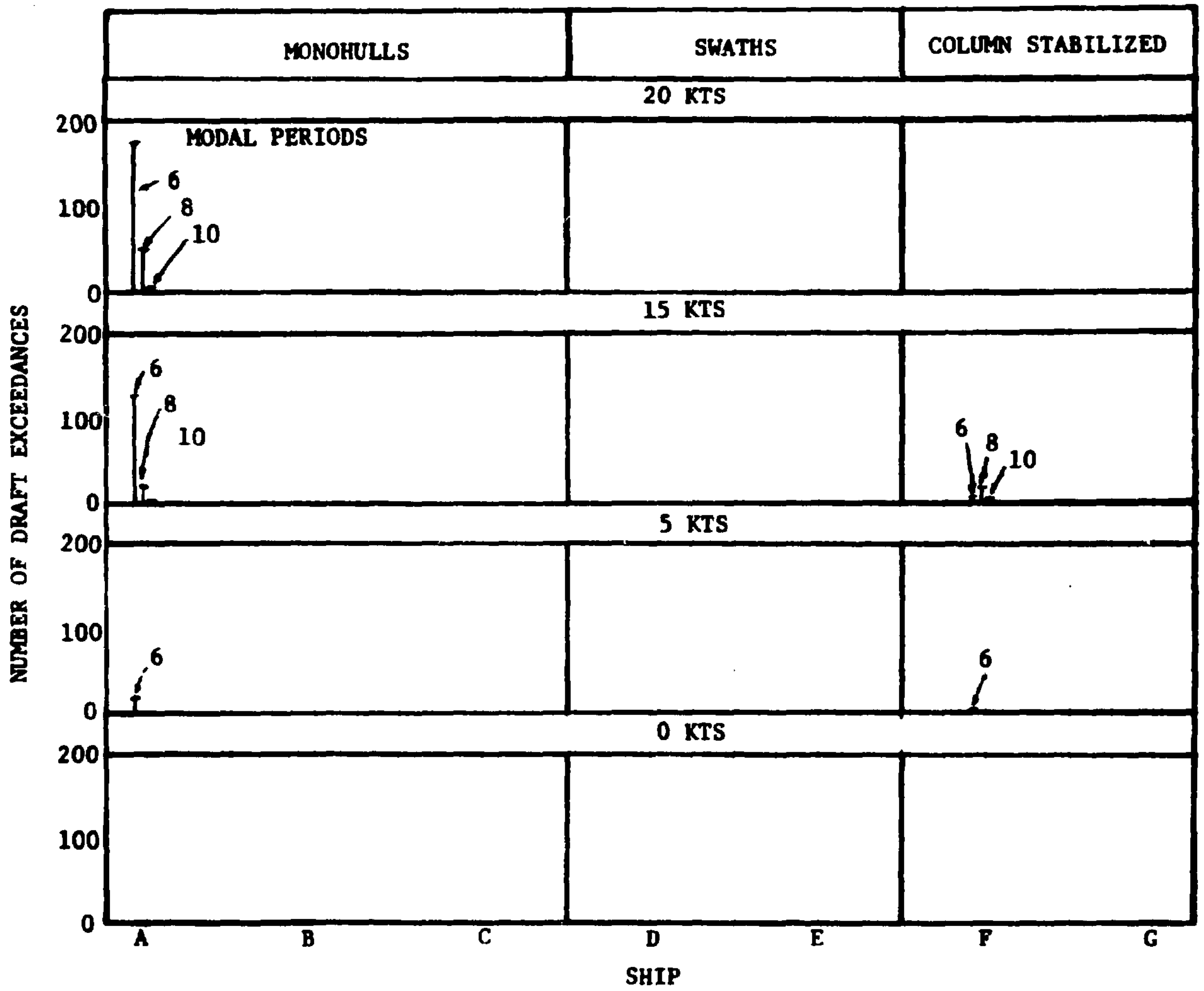


Figure 12a – Number of Slams per 30 Minutes of Operation in 6-Foot Significant Wave Height Seas

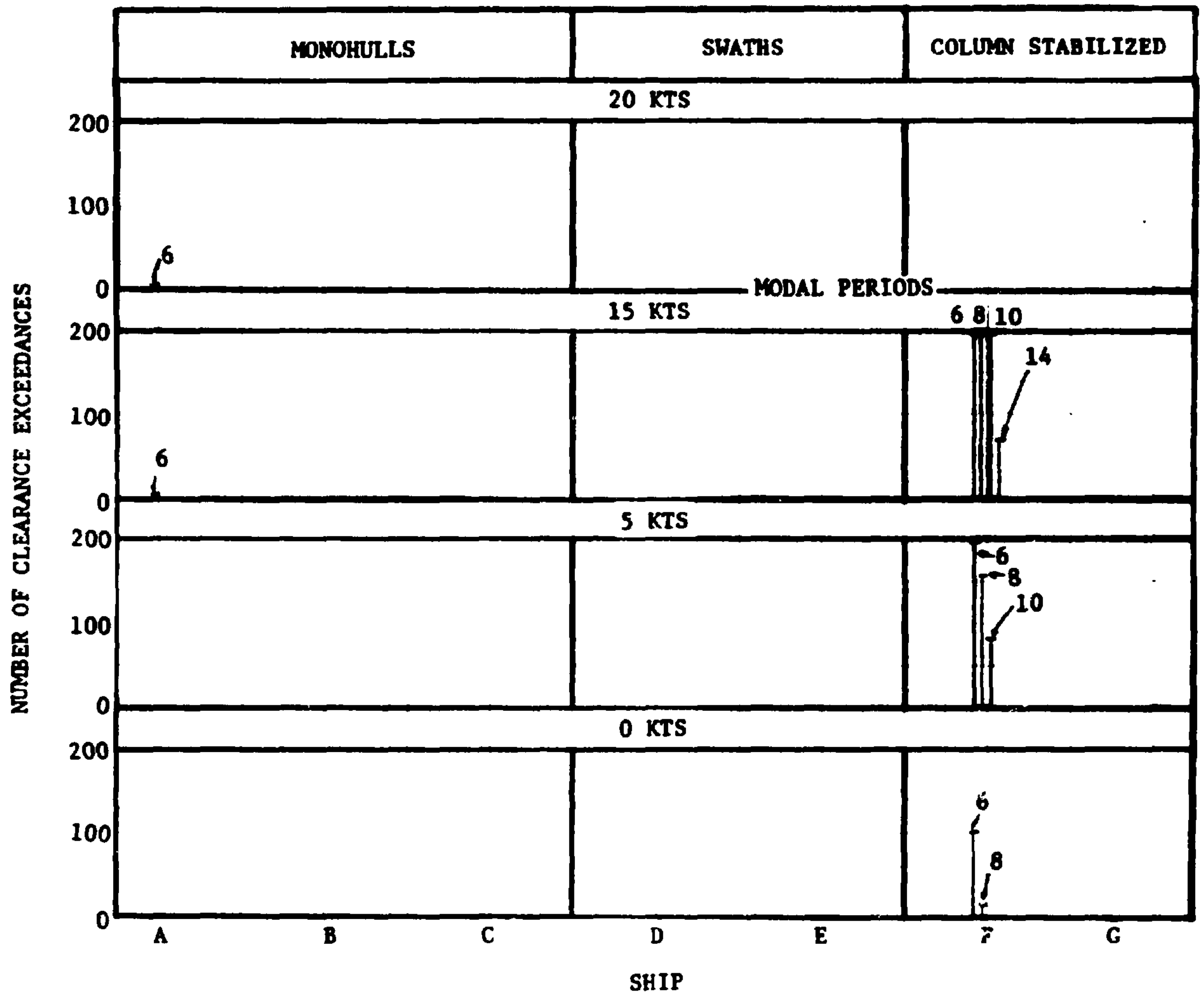


Figure 12b – Number of Deck Wetness Occurrences or Cross-Structure Impacts per 30 Minutes of Operation in 6-Foot Significant Wave Height Seas

TABLE 1 – DEFINITION OF SEA STATES

State	Ranges of Significant Wave Heights $(\tilde{\zeta}_w)_{1/3}$ ft	Ranges of Modal Wave Periods T_0 sec
1	0 – 1.92	0 – 3.08
2	1.92 – 4.13	3.08 – 4.52
3	4.13 – 5.66	4.52 – 5.29
4	5.66 – 7.35	5.29 – 6.03
5	7.35 – 13.04	6.03 – 8.03
6	13.04 – 20.80	8.03 – 10.15
7	20.80 – 40.33	10.15 – 14.13
8	40.33 – 61.58	14.13 – 17.45

NOTE:
1. T_0 periods corresponding to the steepest, partially developed wind-generated waves, short fetch, high wind, moving hurricane, Bretschneider Reference 14.
2. Steeper waves do occur, but they are rare and are generally associated with land locked bays or lakes, References 15 and 16.
3. $T_0 = [(\tilde{\zeta}_w)_{1/3}/0.202]^{1/2}$ Modal period of partially developed hurricane sea (Bretschneider).
4. $T_0 = [(\tilde{\zeta}_w)_{1/3}/0.127]^{1/2}$ Modal period of fully developed wind sea (Pierson-Neumann-James).
5. $\lambda_0/(\tilde{\zeta}_w)_{1/3} = 1/40$ Pierson-Moskowitz wave spectra, i.e., (4)
6. $\lambda_0/(\tilde{\zeta}_w)_{1/3} = 1/25$ Bretschneider, i.e., (3)
7. $\lambda_0/(\tilde{\zeta}_w)_{1/3} = 1/10$ Steepest observed, Hogben and Lumb Reference

λ_0 = Wavelength corresponding to period of spectrum peak, T_0

TABLE 2 – CONSTANTS FOR SINGLE-AMPLITUDE STATISTICS AND EQUATION FOR TWO-PARAMETER BRETSCHNEIDER SPECTRUM

SINGLE AMPLITUDE STATISTICS

Root mean square amplitude, rms	$1.00\,\sigma$
Average amplitude	$1.25\,\sigma$
Average of highest 1/3 amplitudes, significant	$2.00\,\sigma$
Highest expected amplitude in 10 successive amplitudes	$2.15\,\sigma$
Average of highest 1/10 amplitudes	$2.55\,\sigma$
Highest expected amplitude in 30 successive amplitudes	$2.61\,\sigma$
Highest expected amplitude in 50 successive amplitudes	$2.80\,\sigma$
Highest expected amplitude in 100 successive amplitudes	$3.03\,\sigma$
Highest expected amplitude in 200 successive amplitudes	$3.25\,\sigma$
Highest expected amplitude in 1000 successive amplitudes	$3.72\,\sigma$

BRETSCHNEIDER SPECTRUM $S_\zeta(\omega)$

$S_\zeta(\omega)$	=	$A\omega^{-5} \exp\left[-B/\omega^4\right]$ in ft^2/sec
A	=	$483.5\,(\tilde{\zeta}_w)^2_{1/3}/T_0^4$, $ft^2\ sec^{-4}$
B	=	$1944.5/T_0^4$, sec^{-4}
$(\tilde{\zeta}_w)_{1/3}$	=	Average of highest 1/3 wave heights
T_0	=	Modal period of spectrum, i.e., period corresponding to peak of spectrum

DEFINITIONS

σ^2 = Statistical variance of time history

N = Number of successive amplitudes

CONSTANT = $\sqrt{2}\,(\ln N)^{1/2}$, where CONSTANT relates σ to the highest expected amplitude in N successive amplitudes.

NOTES:

1. The highest expected amplitude in N amplitudes is the most probable extreme value in N amplitudes. This value may be exceeded 63 percent of the time.
2. To obtain wave height or double amplitude statistics from rms values, multiply single amplitude constants by 2.0.

TABLE 3 – YEARLY AVERAGE STATISTICS OF FOUR MAJOR HAWAIIAN WAVE SYSTEMS

(From St. Denis[17])

Wave Group	Direction of Origin deg true	Average Significant Height ft	Average Significant Period sec	Frequency of Occurrence percent
NE trade wind-generated waves	78	4.79	8.63	75.3
North Pacific swell	320	4.79	13.89	74.0
Kona Storm waves	187	3.52	6.18	10.3
Southern swell	194	2.60	13.07	53.0

TABLE 4 – RMS RESPONSES OF SHIP A, 85-FOOT HARDCHINE MONOHULL

HEAD SEAS
H1/3= 6. FEET

LPP= 85.0 FEET
CLEARANCE, C = 6.82 FEET
DRAFT, D = 3.77 FEET

T_0 SEC.	CHANNEL	SPEEDS 0. KTS	5. KTS	15. KTS	20. KTS
6	WAVE HEIGHT AT ORIGIN	1.43532	1.43685	1.43512	1.43801
	WAVE HEIGHT AT STA. 4	1.43535	1.43753	1.43517	1.43432
	HEAVE	.90941	.92588	1.18788	1.23011
	PITCH	2.64230	2.47992	2.04841	1.89570
	VERT. MOT. AT STA. 4	1.64730	1.89017	1.94914	1.87705
	RBM AT STA. 4	.90777	1.44765	1.99654	2.09672
	VERT. ACC. AT STERN (AP)	.09463	.12838	.22180	.26845
	VERT. ACC. AT CG	.03275	.06093	.16693	.21095
	VERT. ACC. AT BOW (FP)	.11826	.23296	.40437	.45740
	H1/3 AT WHICH RBM/C=1	17.7	11.1	8.0	7.7
	H1/3 AT WHICH RBM/D=1 (FEET)	9.8	6.1	4.4	4.2
8	WAVE HEIGHT AT ORIGIN	1.46770	1.45368	1.44783	1.45394
	WAVE HEIGHT AT STA. 4	1.46691	1.45371	1.44787	1.45380
	HEAVE	1.21393	1.17642	1.37029	1.43826
	PITCH	2.24693	2.14374	1.82673	1.73244
	VERT. MOT. AT STA. 4	1.64826	1.85147	2.00839	2.00400
	RBM AT STA. 4	.58461	.96043	1.47251	1.61223
	VERT. ACC. AT STERN (AP)	.06993	.09424	.16677	.21127
	VERT. ACC. AT CG	.03092	.05163	.13443	.17660
	VERT. ACC. AT BOW (FP)	.08430	.16231	.30047	.35547
	H1/3 AT WHICH RBM/C=1	28.4	16.7	10.9	10.0
	H1/3 AT WHICH RBM/D=1 (FEET)	15.7	9.2	6.0	5.5
10	WAVE HEIGHT AT ORIGIN	1.47176	1.45895	1.46667	[illegible]
	WAVE HEIGHT AT STA. 4	1.47201	1.45892	1.46943	[illegible]
	HEAVE	1.35274	1.31020	1.45322	1.50505
	PITCH	1.74723	1.70149	1.51114	[illegible]
	VERT. MOT. AT STA. 4	1.57584	1.74294	1.96377	1.97094
	RBM AT STA. 4	.29269	.50395	1.04159	1.18666
	VERT. ACC. AT STERN (AP)	.04741	.06371	.11902	[illegible]
	VERT. ACC. AT CG	.02577	.03986	.10030	[illegible]
	VERT. ACC. AT BOW (FP)	.05435	.10215	.21203	.25372
	H1/3 AT WHICH RBM/C=1	54.8	28.5	15.4	13.8
	H1/3 AT WHICH RBM/D=1 (FEET)	30.3	15.7	8.5	7.6
14	WAVE HEIGHT AT ORIGIN	1.49330	1.47626	1.46407	1.46176
	WAVE HEIGHT AT STA. 4	1.49360	1.47624	1.46407	1.46180
	HEAVE	1.48309	1.41745	1.46291	1.50296
	PITCH	1.02055	1.05345	.98748	.92046
	VERT. MOT. AT STA. 4	1.44282	1.60510	1.92354	1.85447
	RBM AT STA. 4	.08474	.20009	.49580	.59417
	VERT. ACC. AT STERN (AP)	.02186	.02774	.04563	.06216
	VERT. ACC. AT CG	.01639	.02296	.04652	.06281
	VERT. ACC. AT BOW (FP)	.02228	.03805	.07753	.10061
	H1/3 AT WHICH RBM/C=1	149.4	80.2	33.0	27.0
	H1/3 AT WHICH RBM/D=1 (FEET)	104.7	44.3	18.3	14.9

TABLE 5 – RMS RESPONSES OF SHIP B, 15-KNOT MONOHULL

HEAD SEAS
H1/3= 6. FEET

LPP= 160.0 FEET
CLEARANCE, C = 18.00 FEET
DRAFT, D = 8.00 FEET

T_0 SEC.	CHANNEL	SPEEDS 0. KTS	5. KTS	15. KTS
6	WAVE HEIGHT AT ORIGIN	1.43532	1.43645	1.43512
	WAVE HEIGHT AT STA. 4	1.43533	1.43775	1.43530
	HEAVE	.53651	.66436	.92149
	PITCH	1.29037	1.30792	1.05129
	VERT. MOT. AT STA. 4	1.36919	1.61351	1.52204
	RBM AT STA. 4	1.34167	1.88512	2.22595
	VERT. ACC. AT STERN (AP)	.05966	.08538	.13871
	VERT. ACC. AT CG	.01798	.03578	.08087
	VERT. ACC. AT BOW (FP)	.07389	.13439	.19428
	H1/3 AT WHICH RBM/C=1	31.6	22.5	19.0
	H1/3 AT WHICH RBM/D=1 (FEET)	14.0	10.0	8.5
8	WAVE HEIGHT AT ORIGIN	1.46770	1.45368	1.44783
	WAVE HEIGHT AT STA. 4	1.46609	1.45409	1.44777
	HEAVE	.91511	1.00476	1.34793
	PITCH	1.42479	1.44340	1.29910
	VERT. MOT. AT STA. 4	1.65544	1.90047	2.05794
	RBM AT STA. 4	.99930	1.50771	2.10700
	VERT. ACC. AT STERN (AP)	.05540	.07667	.13654
	VERT. ACC. AT CG	.01985	.03617	.09053
	VERT. ACC. AT BOW (FP)	.06592	.12015	.19967
	H1/3 AT WHICH RBM/C=1	42.6	29.1	24.1
	H1/3 AT WHICH RBM/D=1 (FEET)	19.0	12.5	8.9
10	WAVE HEIGHT AT ORIGIN	1.44717	1.45895	1.46867
	WAVE HEIGHT AT STA. 4	1.44727	1.45894	1.47000
	HEAVE	1.16358	1.21350	1.49156
	PITCH	1.26239	1.20216	1.17361
	VERT. MOT. AT STA. 4	1.68729	1.86368	2.11909
	RBM AT STA. 4	.66578	1.07597	1.64611
	VERT. ACC. AT STERN (AP)	.04370	.06118	.10704
	VERT. ACC. AT CG	.01933	.03040	.07574
	VERT. ACC. AT BOW (FP)	.07174	.09138	.15918
	H1/3 AT WHICH RBM/C=1	53.6	39.4	25.7
	H1/3 AT WHICH RBM/D=1 (FEET)	27.3	17.5	11.4
14	WAVE HEIGHT AT ORIGIN	1.44326	1.47627	1.46607
	WAVE HEIGHT AT STA. 4	1.44372	1.47628	1.46608
	HEAVE	1.44552	1.39472	1.52119
	PITCH	.87091	.89994	.84669
	VERT. MOT. AT STA. 4	1.65365	1.74588	1.43585
	RBM AT STA. 4	.62372	.55613	.95411
	VERT. ACC. AT STERN (AP)	.02420	.03371	.06167
	VERT. ACC. AT CG	.01362	.02083	.04802
	VERT. ACC. AT BOW (FP)	.02778	.04774	.09364
	H1/3 AT WHICH RBM/C=1	148.2	43.4	44.4
	H1/3 AT WHICH RBM/D=1 (FEET)	65.9	37.0	19.7

TABLE 6 – RMS RESPONSES OF SHIP C, 20-KNOT MONOHULL

HEAD SEAS
H1/3= 6. FEET

LPP= 200.0 FEET
CLEARANCE, C = 17.65 FEET
DRAFT, D = 9.35 FEET

T_0 SEC.	CHANNEL	SPEEDS 0. KTS	5. KTS	15. KTS	20. KTS
6	WAVE HEIGHT AT ORIGIN	1.43532	1.43685	1.43512	[illegible]
	WAVE HEIGHT AT STA. 4	1.43530	1.43776	1.43576	[illegible]
	HEAVE	.59449	.53010	.81512	[illegible]
	PITCH	.90305	.95924	.81228	[illegible]
	VERT. MOT. AT STA. 4	1.17002	1.42119	1.45822	1.28533
	RBM AT STA. 4	1.35402	1.88844	2.25245	2.1448[illegible]
	VERT. ACC. AT STERN (AP)	.04635	.07031	.11072	.12522
	VERT. ACC. AT CG	.01245	.02695	.06568	.077[illegible]
	VERT. ACC. AT BOW (FP)	.05946	.10672	.16700	.156[illegible]
	H1/3 AT WHICH RBM/C=1	30.7	22.2	18.4	19.[illegible]
	H1/3 AT WHICH RBM/D=1 (FEET)	15.2	11.8	9.8	10.1
8	WAVE HEIGHT AT ORIGIN	1.46770	1.45368	1.44783	1.45394
	WAVE HEIGHT AT STA. 4	1.46693	1.45431	1.44765	1.45377
	HEAVE	.77839	.87391	1.27602	1.41170
	PITCH	1.14712	1.19610	1.12226	1.03844
	VERT. MOT. AT STA. 4	1.59101	1.84826	2.15682	2.13989
	RBM AT STA. 4	1.10383	1.60524	2.32784	2.47024
	VERT. ACC. AT STERN (AP)	.04592	.07090	.11829	.14788
	VERT. ACC. AT CG	.01554	.02923	.08006	.10514
	VERT. ACC. AT BOW (FP)	.05940	.10597	.19211	.21560
	H1/3 AT WHICH RBM/C=1	37.0	25.9	17.8	16.8
	H1/3 AT WHICH RBM/D=1 (FEET)	19.9	13.7	9.5	8.9
10	WAVE HEIGHT AT ORIGIN	1.47176	1.45895	1.46887	[illegible]
	WAVE HEIGHT AT STA. 4	1.47254	1.45897	1.47032	1.46956
	HEAVE	1.05456	1.12002	1.44255	[illegible]
	PITCH	1.05289	1.12579	1.08814	1.03222
	VERT. MOT. AT STA. 4	1.66597	1.59621	2.24584	2.30345
	RBM AT STA. 4	.79550	1.19488	1.88415	2.09965
	VERT. ACC. AT STERN (AP)	[illegible]	.05756	.09610	.1232[illegible]
	VERT. ACC. AT CG	.01554	.02640	.05897	[illegible]
	VERT. ACC. AT BOW (FP)	.04793	.08438	.15913	[illegible]
	H1/3 AT WHICH RBM/C=1	52.2	34.8	22.0	19.9
	H1/3 AT WHICH RBM/D=1 (FEET)	27.7	18.4	11.7	10.5
14	WAVE HEIGHT AT ORIGIN	1.44328	1.47627	1.46407	1.4617[illegible]
	WAVE HEIGHT AT STA. 4	1.44380	1.47034	1.46405	1.4621[illegible]
	HEAVE	[illegible]	1.35088	1.49461	1.58092
	PITCH	[illegible]	.84182	.82045	.74067
	VERT. MOT. AT STA. 4	1.55738	1.70628	2.02145	[illegible]
	RBM AT STA. 4	.39121	.62808	1.13630	[illegible]
	VERT. ACC. AT STERN (AP)	[illegible]	.03463	.05839	.07457
	VERT. ACC. AT CG	.01257	.01883	.04498	[illegible]
	VERT. ACC. AT BOW (FP)	[illegible]	.04905	.09787	[illegible]
	H1/3 AT WHICH RBM/C=1	106.2	65.1	36.5	32.[illegible]
	H1/3 AT WHICH RBM/D=1 (FEET)	55.2	35.0	19.4	17.1

TABLE 7 – RMS RESPONSES OF SHIP D, 15-KNOT SWATH WITH AND WITHOUT BILGE KEELS

TABLE 7A – WITHOUT BILGE KEELS

HEAD SEAS
H1/3= 6. FEET

LPP= 155.0 FEET
CLEARANCE, C = 12.00 FEET
DRAFT, D = 16.50 FEET

T_0 SEC.	CHANNEL	SPEEDS 0. KTS	5. KTS	15. KTS
6	WAVE HEIGHT AT ORIGIN	1.43532	1.43691	1.43519
	WAVE HEIGHT AT STA. 4	1.43534	1.43775	1.43512
	HEAVE	1.57699	.97868	.43980
	PITCH	.14835	.20737	.29123
	VERT. MOT. AT STA. 4	1.56568	.98439	.53615
	RBM AT STA. 4	2.24630	1.80406	1.63606
	VERT. ACC. AT STERN (AP)	.04875	.03620	.03211
	VERT. ACC. AT CG	.04757	.03355	.01984
	VERT. ACC. AT BOW (FP)	.04768	.03556	.04300
	H1/3 AT WHICH RBM/C=1	12.6	15.7	17.3
	H1/3 AT WHICH RBM/D=1 (FEET)	17.3	21.5	23.7
8	WAVE HEIGHT AT ORIGIN	1.46770	1.45370	1.44800
	WAVE HEIGHT AT STA. 4	1.46858	1.45389	1.44793
	HEAVE	1.88792	1.97080	1.45092
	PITCH	.42643	.22781	.40994
	VERT. MOT. AT STA. 4	1.97902	2.02167	1.51799
	RBM AT STA. 4	2.41634	2.52825	2.33429
	VERT. ACC. AT STERN (AP)	.04993	.05651	.05119
	VERT. ACC. AT CG	.04962	.05639	.04827
	VERT. ACC. AT BOW (FP)	.05040	.05744	.05490
	H1/3 AT WHICH RBM/C=1	11.7	11.2	12.1
	H1/3 AT WHICH RBM/D=1 (FEET)	16.1	15.4	16.6
10	WAVE HEIGHT AT ORIGIN	1.47176	1.45905	1.46861
	WAVE HEIGHT AT STA. 4	1.47217	1.45907	1.46934
	HEAVE	1.77663	2.12053	2.27609
	PITCH	1.60120	.46952	.62215
	VERT. MOT. AT STA. 4	2.52865	2.31182	2.43789
	RBM AT STA. 4	2.46368	2.38472	2.73606
	VERT. ACC. AT STERN (AP)	.03988	.05238	.06607
	VERT. ACC. AT CG	.03984	.05350	.06546
	VERT. ACC. AT BOW (FP)	.04436	.05558	.07117
	H1/3 AT WHICH RBM/C=1	11.5	11.8	10.3
	H1/3 AT WHICH RBM/D=1 (FEET)	15.8	16.3	14.2
14	WAVE HEIGHT AT ORIGIN	1.49326	1.47639	1.46422
	WAVE HEIGHT AT STA. 4	1.49368	1.47634	1.46421
	HEAVE	1.59790	1.67017	2.20473
	PITCH	2.75560	1.03322	.68665
	VERT. MOT. AT STA. 4	3.34315	2.45692	2.43245
	RBM AT STA. 4	2.56385	1.79303	2.02525
	VERT. ACC. AT STERN (AP)	.02476	.03333	.05111
	VERT. ACC. AT CG	.02358	.03546	.05236
	VERT. ACC. AT BOW (FP)	.03559	.03953	.05711
	H1/3 AT WHICH RBM/C=1	11.0	15.7	13.9
	H1/3 AT WHICH RBM/D=1 (FEET)	15.1	21.7	19.2

TABLE 7B – WITH BILGE KEELS

T_0 SEC.	HEAD SEAS LPP= 155.0 FEET H1/3= 6. FEET CLEARANCE, C = 12.00 FEET DRAFT, D = 16.50 FEET CHANNEL	SPEEDS 0. KTS
6	WAVE HEIGHT AT ORIGIN	1.43532
	WAVE HEIGHT AT STA. 4	1.43534
	HEAVE	1.41789
	PITCH	.16039
	VERT. MOT. AT STA. 4	1.40660
	RBM AT STA. 4	2.19786
	VERT. ACC. AT STERN (AP)	.04552
	VERT. ACC. AT CG	.04389
	VERT. ACC. AT BOW (FP)	.04452
	H1/3 AT WHICH RBM/C=1	12.8
	H1/3 AT WHICH RBM/D=1 (FEET)	17.7
8	WAVE HEIGHT AT ORIGIN	1.46770
	WAVE HEIGHT AT STA. 4	1.46858
	HEAVE	1.66797
	PITCH	.40017
	VERT. MOT. AT STA. 4	1.79418
	RBM AT STA. 4	2.41890
	VERT. ACC. AT STERN (AP)	.04466
	VERT. ACC. AT CG	.04450
	VERT. ACC. AT BOW (FP)	.04563
	H1/3 AT WHICH RBM/C=1	11.7
	H1/3 AT WHICH RBM/D=1 (FEET)	16.1
10	WAVE HEIGHT AT ORIGIN	1.47176
	WAVE HEIGHT AT STA. 4	1.47217
	HEAVE	1.60833
	PITCH	1.16592
	VERT. MOT. AT STA. 4	2.24615
	RBM AT STA. 4	2.31990
	VERT. ACC. AT STERN (AP)	.03455
	VERT. ACC. AT CG	.03571
	VERT. ACC. AT BOW (FP)	.03996
	H1/3 AT WHICH RBM/C=1	12.2
	H1/3 AT WHICH RBM/D=1 (FEET)	16.7
14	WAVE HEIGHT AT ORIGIN	1.49328
	WAVE HEIGHT AT STA. 4	1.49368
	HEAVE	1.51875
	PITCH	1.85952
	VERT. MOT. AT STA. 4	2.75525
	RBM AT STA. 4	2.00309
	VERT. ACC. AT STERN (AP)	.01928
	VERT. ACC. AT CG	.02128
	VERT. ACC. AT BOW (FP)	.03032
	H1/3 AT WHICH RBM/C=1	14.1
	H1/3 AT WHICH RBM/D=1 (FEET)	19.4

TABLE 8 – RMS RESPONSES OF SHIP E, 20-KNOT SWATH

HEAD SEAS
H1/3= 6. FEET

LPP= 200.0 FEET
CLEARANCE, C = 12.10 FEET
DRAFT, D = 14.40 FEET

T_0 SEC.	CHANNEL	SPEEDS 0. KTS	5. KTS	15. KTS	20. KTS
6	WAVE HEIGHT AT ORIGIN	1.43532	1.43691	1.43520	1.43727
	WAVE HEIGHT AT STA. 4	1.43532	1.43790	1.43501	1.43823
	HEAVE	.94573	.32356	.17980	.21279
	PITCH	.17164	.23081	.16740	.15341
	VERT. MOT. AT STA. 4	.99697	.40237	.16354	.28444
	RBM AT STA. 4	1.78703	1.38054	1.37074	1.43130
	VERT. ACC. AT STERN (AP)	.02269	.02517	.02473	.01847
	VERT. ACC. AT CG	.02196	.01285	.02315	.02118
	VERT. ACC. AT BOW (FP)	.02530	.02742	.02837	.04491
	H1/3 AT WHICH RBM/C=1	15.9	20.6	20.8	19.9
	H1/3 AT WHICH RBM/D=1 (FEET)	25.5	33.1	33.3	31.9
8	WAVE HEIGHT AT ORIGIN	[illegible]	[illegible]	[illegible]	[illegible]
	WAVE HEIGHT AT STA. 4	[illegible]	[illegible]	[illegible]	[illegible]
	HEAVE	[illegible]	[illegible]	[illegible]	[illegible]
	PITCH	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. MOT. AT STA. 4	[illegible]	[illegible]	[illegible]	[illegible]
	RBM AT STA. 4	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. ACC. AT STERN (AP)	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. ACC. AT CG	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. ACC. AT BOW (FP)	[illegible]	[illegible]	[illegible]	[illegible]
	H1/3 AT WHICH RBM/C=1	[illegible]	[illegible]	[illegible]	[illegible]
	H1/3 AT WHICH RBM/D=1 (FEET)	[illegible]	[illegible]	[illegible]	[illegible]
10	WAVE HEIGHT AT ORIGIN	[illegible]	[illegible]	[illegible]	[illegible]
	WAVE HEIGHT AT STA. 4	[illegible]	[illegible]	[illegible]	[illegible]
	HEAVE	[illegible]	[illegible]	[illegible]	[illegible]
	PITCH	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. MOT. AT STA. 4	[illegible]	[illegible]	[illegible]	[illegible]
	RBM AT STA. 4	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. ACC. AT STERN (AP)	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. ACC. AT CG	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. ACC. AT BOW (FP)	[illegible]	[illegible]	[illegible]	[illegible]
	H1/3 AT WHICH RBM/C=1	[illegible]	[illegible]	13.1	[illegible]
	H1/3 AT WHICH RBM/D=1 (FEET)	[illegible]	[illegible]	[illegible]	[illegible]
14	WAVE HEIGHT AT ORIGIN	[illegible]	[illegible]	[illegible]	[illegible]
	WAVE HEIGHT AT STA. 4	[illegible]	[illegible]	[illegible]	[illegible]
	HEAVE	[illegible]	[illegible]	[illegible]	[illegible]
	PITCH	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. MOT. AT STA. 4	[illegible]	[illegible]	[illegible]	[illegible]
	RBM AT STA. 4	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. ACC. AT STERN (AP)	[illegible]	[illegible]	[illegible]	[illegible]
	VERT. ACC. AT CG	.02551	[illegible]	[illegible]	[illegible]
	VERT. ACC. AT BOW (FP)	[illegible]	[illegible]	[illegible]	[illegible]
	H1/3 AT WHICH RBM/C=1	[illegible]	[illegible]	13.2	[illegible]
	H1/3 AT WHICH RBM/D=1 (FEET)	21.1	21.5	21.1	[illegible]

TABLE 9 – RMS RESPONSES OF SHIP F, COLUMN STABILIZED UP

HEAD SEAS
H1/3= 6. FEET

LPP= 170.0 FEET
CLEARANCE, C = 4.20 FEET
DRAFT, D = 12.50 FEET

T_0 SEC.	CHANNEL	SPEEDS 0. KTS	5. KTS	15. KTS
6	WAVE HEIGHT AT ORIGIN	1.43532	1.43716	1.43444
	WAVE HEIGHT AT STA. 4	1.43530	1.43750	1.43588
	HEAVE	.59705	1.01266	2.49285
	PITCH	1.03628	2.33550	2.58193
	VERT. MOT. AT STA. 4	2.02455	3.26283	3.48908
	RAM AT STA. 4	2.11507	3.63107	4.11296
	VERT. ACC. AT STERN (AP)	.06310	.13283	.41356
	VERT. ACC. AT CG	.02823	.06091	.24485
	VERT. ACC. AT BOW (FP)	.09025	.21630	.31096
	H1/3 AT WHICH RAM/C=1	4.7	2.7	2.4
	H1/3 AT WHICH RAM/C=1 (FEET)	13.9	8.1	7.2
8	WAVE HEIGHT AT ORIGIN	1.46770	1.45347	1.44763
	WAVE HEIGHT AT STA. 4	1.46895	1.45435	1.44737
	HEAVE	.90138	1.20568	2.69180
	PITCH	1.80712	2.42490	2.46615
	VERT. MOT. AT STA. 4	2.31360	3.41189	4.41654
	RAM AT STA. 4	1.74080	3.20760	4.60245
	VERT. ACC. AT STERN (AP)	.05593	.10538	.26589
	VERT. ACC. AT CG	.02348	.05285	.20230
	VERT. ACC. AT BOW (FP)	.07950	.19266	.32556
	H1/3 AT WHICH RAM/C=1	5.7	3.1	2.1
	H1/3 AT WHICH RAM/C=1 (FEET)	15.9	9.2	6.4
10	WAVE HEIGHT AT ORIGIN	1.47176	1.45877	1.45903
	WAVE HEIGHT AT STA. 4	1.47257	1.45885	1.47095
	HEAVE	1.13752	1.31444	[illegible]
	PITCH	1.59205	2.02088	2.09904
	VERT. MOT. AT STA. 4	2.19114	2.93103	3.96132
	RAM AT STA. 4	1.25902	2.36075	3.70335
	VERT. ACC. AT STERN (AP)	.04291	.07717	[illegible]
	VERT. ACC. AT CG	.01995	.04119	[illegible]
	VERT. ACC. AT BOW (FP)	.05478	.14276	.25995
	H1/3 AT WHICH RAM/C=1	7.9	4.2	2.7
	H1/3 AT WHICH RAM/C=1 (FEET)	21.9	12.5	7.9
14	WAVE HEIGHT AT ORIGIN	1.44328	1.47611	1.46396
	WAVE HEIGHT AT STA. 4	1.44381	1.47635	1.46396
	HEAVE	1.37350	1.42302	1.88505
	PITCH	1.09911	1.24104	1.40326
	VERT. MOT. AT STA. 4	1.87541	2.10572	2.81418
	RAM AT STA. 4	.50844	1.18260	2.21804
	VERT. ACC. AT STERN (AP)	.02384	.04046	.08901
	VERT. ACC. AT CG	.01342	.02347	.08649
	VERT. ACC. AT BOW (FP)	.03165	.07245	.15719
	H1/3 AT WHICH RAM/C=1	16.1	8.4	4.5
	H1/3 AT WHICH RAM/C=1 (FEET)	49.5	24.9	13.3

TABLE 10 – RMS RESPONSES OF SHIP G, COLUMN STABILIZED DOWN

HEAD SEAS
H1/3= 6. FEET

LPP= 170.0 FEET
CLEARANCE, C = 12.00 FEET
DRAFT, D = 24.00 FEET

T_0 SEC.	CHANNEL	SPEEDS 0. KTS	SPEEDS 5. KTS
6	WAVE HEIGHT AT ORIGIN	1.43532	1.43654
	WAVE HEIGHT AT STA. 4	1.43530	1.43804
	HEAVE	.36235	.39104
	PITCH	.35648	.48698
	VERT. MOT. AT STA. 4	.58666	.72563
	RBM AT STA. 4	1.52347	1.56123
	VERT. ACC. AT STERN (AP)	.01439	.03061
	VERT. ACC. AT CG	.01115	.02113
	VERT. ACC. AT BOW (FP)	.02262	.04664
	H1/3 AT WHICH RBM/C=1 (FEET)	18.5	19.1
	H1/3 AT WHICH RBM/D=1 (FEET)	37.1	36.2
8	WAVE HEIGHT AT ORIGIN	1.46770	1.45325
	WAVE HEIGHT AT STA. 4	1.46695	1.45413
	HEAVE	.55530	.47929
	PITCH	.40477	.39756
	VERT. MOT. AT STA. 4	.86029	.60474
	RBM AT STA. 4	1.35585	1.27502
	VERT. ACC. AT STERN (AP)	.01617	.02341
	VERT. ACC. AT CG	.01367	.01583
	VERT. ACC. AT BOW (FP)	.02262	.03169
	H1/3 AT WHICH RBM/C=1 (FEET)	20.7	22.1
	H1/3 AT WHICH RBM/D=1 (FEET)	41.3	44.3
10	WAVE HEIGHT AT ORIGIN	1.47176	1.45905
	WAVE HEIGHT AT STA. 4	1.47254	1.45925
	HEAVE	.91378	.61092
	PITCH	.40946	.34605
	VERT. MOT. AT STA. 4	1.15473	.73267
	RBM AT STA. 4	1.31276	1.15487
	VERT. ACC. AT STERN (AP)	.01456	.01564
	VERT. ACC. AT CG	.01344	.01387
	VERT. ACC. AT BOW (FP)	.01979	.02169
	H1/3 AT WHICH RBM/C=1 (FEET)	21.5	24.2
	H1/3 AT WHICH RBM/D=1 (FEET)	43.0	45.5
14	WAVE HEIGHT AT ORIGIN	1.44324	1.47654
	WAVE HEIGHT AT STA. 4	1.44382	1.47664
	HEAVE	1.33250	1.14511
	PITCH	.43044	.58200
	VERT. MOT. AT STA. 4	2.10132	1.59913
	RBM AT STA. 4	1.58345	1.48320
	VERT. ACC. AT STERN (AP)	.01058	.01282
	VERT. ACC. AT CG	.01145	.01138
	VERT. ACC. AT BOW (FP)	.01714	.01650
	H1/3 AT WHICH RBM/C=1 (FEET)	17.8	19.0
	H1/3 AT WHICH RBM/D=1 (FEET)	35.7	38.1

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TABLE 11 – BEAM SEA RMS ACCELERATIONS AND ROLL OF CANDIDATE SHIPS

$(\zeta_w)_{1/3}$ = 6 feet Speed = 0 knots	Monohulls																			
	Ship A				Ship B without Bilge Keels				Ship B with Bilge Keels				Ship C without Bilge Keels				Ship C with Bilge Keels			
Modal Wave Periods (seconds)	6	8	10	14	6	8	10	14	6	8	10	14	6	8	10	14	6	8	10	14
Point 1 $L_{\ddot{V}}$ (G's x 100)	8.1	5.7	4.1	2.4	5.4	4.4	3.4	2.1	5.4	4.4	3.4	2.1	7.4	5.4	4.0	2.4	7.4	5.4	4.0	2.4
Point 1 $L_{\ddot{A}}$ (G's x 100)	4.9	3.7	2.9	1.8	3.6	3.1	2.5	1.7	3.6	3.1	2.5	1.6	4.7	3.7	2.9	1.8	4.7	3.7	2.8	1.8
Point 2 $L_{\ddot{V}}$ (G's x 100)	11.2	7.5	5.3	3.0	4.7	3.9	3.1	2.0	4.5	3.6	2.9	1.8	6.7	4.8	3.6	2.2	6.6	4.7	3.4	2.1
Point 2 $L_{\ddot{A}}$ (G's x 100)	4.7	3.7	2.9	1.8	2.9	2.7	2.3	1.6	2.9	2.7	2.3	1.6	3.9	3.0	2.4	1.6	3.9	3.0	2.4	1.6
Roll (degrees)	10.1	6.4	4.3	2.3	5.5	6.7	5.4	3.2	4.6	5.6	4.6	2.8	4.0	6.4	5.7	3.5	3.5	5.4	4.8	3.0

$(\zeta_w)_{1/3}$ = 6 feet Speed = 0 knots	SWATHs								Column Stabilized SWATH				
	Ship D with Bilge Keels				Ship E with Bilge Keels				Ship F without Bilge Keels				Ship G
Modal Wave Periods (seconds)	6	8	10	14	6	8	10	1	6	8	10	14	
Point 1 $L_{\ddot{V}}$ (G's x 100)	5.0	5.0	4.0	2.5	2.8	4.2	3.8	2.5	3.8	3.1	2.5	1.6	N.A.
Point 1 $L_{\ddot{A}}$ (G's x 100)	2.1	2.1	1.9	1.4	1.7	1.9	1.8	1.3	2.6	2.2	1.9	1.2	
Point 2 $L_{\ddot{V}}$ (G's x 100)	5.0	5.0	4.0	2.5	2.8	4.2	3.8	2.5	8.8	6.7	4.9	2.8	
Point 2 $L_{\ddot{A}}$ (G's x 100)	1.9	2.1	2.1	1.6	1.4	1.7	1.7	1.4	9.0	6.4	4.4	2.4	
Roll (degrees)		0.3	0.6	1.3	0.2	0.2	0.3	0.9	3.3	2.5	1.8	1.0	

DEFINITIONS

Point 1 is CG location on main deck

Point 2 is furthest outboard location aft on main deck

$L_{\ddot{V}}$ is vertical acceleration

$L_{\ddot{A}}$ is lateral acceleration