Seakeeping Characteristics of Small-Waterplane-Area-Twin-Hull Ships

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In this paper, an up-to-date evaluation of the seakeeping characteristics of small-waterplane-area-twin-hull (SWATH) ships is made. A brief review is given of the most recent experimental data and theoretical results applicable to the prediction of the seaworthiness characteristics of SWATH ships. Using these data and results, the seakeeping characteristics of SWATH ships are compared with the characteristics of conventional monohulls and conventional catamarans. It is shown that the SWATH configuration has some very promising seakeeping characteristics. For example, a 220-ft SWATH ship in a sea state 5 at normal operating speeds and without any foil or control surfaces will have practically no pitch, heave, or roll motions in head, bow, and beam seas. In very severe headseas and particularly in long swells, this study indicates that SWATH ships without foils or control surfaces will exhibit motions of considerable magnitude. At zero forward speed in head seas, the vertical motions of SWATH ships will be of approximately the same magnitude as those for a monohull with equivalent length. On the other hand, in quartering and following seas, a SWATH ship will pitch more than a conventional monohull with equivalent displacement if not equipped with foils or control surfaces. There is also some indication that in beam seas, a SWATH ship will experience larger sway motions than conventional hull forms.

I. Introduction

IT has been demonstrated in several earlier investigations that the small-waterplane-area-twin-hull (SWATH) ships† can have extremely small wave-induced motions in head seas and that they can maintain, therefore, high speed in quite severe sea states. It is known, on the other hand, that conventional ships of the monohull displacement type must reduce their speed in head seas at higher sea states due to large vertical bow motions. The hydrofoil craft is the only present type of Navy ships which can maintain high speeds in relatively severe sea states; however, the hydrofoil craft has a very small payload and hence, is very restricted in its missions. In other words, one of the primary reasons that the SWATH ship is attractive to the Navy is that in addition to its large deck area, the SWATH ship seems to have seaworthiness characteristics similar to a hydrofoil craft (although not the same speed), but payload characteristics more like a conventional hull.

In order that a hull configuration can be considered to have good seakeeping characteristics, it is not only necessary that the motions be small at high speeds in head seas, but it is also desirable that they be small or at least within acceptable bounds in other operating conditions, such as beam seas, following seas and zero speed at any heading. The ship designer is fully aware of the importance of good seakeeping characteristics in all operating conditions; however, very little information is available on the seakeeping of SWATH ships. It has been difficult, therefore, to consider in a more general way the seakeeping characteristics of the SWATH ship in the over-all performance evaluation of this new ship design concept. The main objective of this investigation has been to make an up-to-date evaluation of the seakeeping characteristics of the SWATH ships including the responses at zero speed at any heading, as well as at operating speeds in head, beam, and following seas. Furthermore, it has been the objective to present the results in such a form that it can be utilized most effectively by the ship designer in evaluating the potential use for SWATH ships.

The present investigation was performed on a crash-basis over a short period of time utilizing available experimental data and as far as possible, available computer results. This paper reports on the results of this short study. Due to the time limitation, the investigation has many limitations; however, in spite of its limitations, it is hoped that this paper will serve at least two purposes: 1) give the concept designer some additional information on seakeeping of SWATH ships and 2) focus attention on some specific areas where more detailed studies may be needed.

A brief review is given in Sec. II of this paper of the state-of-the-art for predicting the dynamic responses of SWATH ships. It was felt that the most useful results with regard to the seakeeping characteristics of SWATH ships could be obtained by comparing their responses with those of conventional monohull and conventional catamarans. In Sec. III, the principle dimensions of the three selected hull configurations are presented and the basis for the comparison is discussed. A comparison of the vertical motions in head seas at normal operating speeds for the different ship forms is presented in Section IV and it shows that the vertical motion of a 220-ft SWATH ship can be reduced throughout sea state 5 by a factor of about 5 in comparison to a conventional monohull with equivalent displacement. On the other hand, it is shown that a conventional catamaran has considerably larger motions in head seas than a monohull. An attempt has also been made, in Sec. IV, to explain why the SWATH ship has less motions than a monohull in head seas while a conventional catamaran has greater motions than the monohull.

In Sec. V of this paper, the dynamic responses of SWATH ships have been evaluated in operating conditions other than normal forward speed in head seas. First, it is shown that in all beam conditions, except for extremely long waves (about five times ship length) at zero forward speed, the roll motions of SWATH ships are much smaller than the roll motions of conventional monohulls as well as conventional catamarans. Further, it is shown that at zero speed in head seas the vertical motions are approximately the same as those of conventional catamarans or of monohulls of the same length. This seems to imply that SWATH ships will have no seakeeping advantage over conventional hull forms when used for missions requiring operations at zero speed. Finally, it is shown that SWATH ships which are not equipped with fins or

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†In previous works the SWATH ships usually are referred to as low-water-plane (LWP) catamarans.

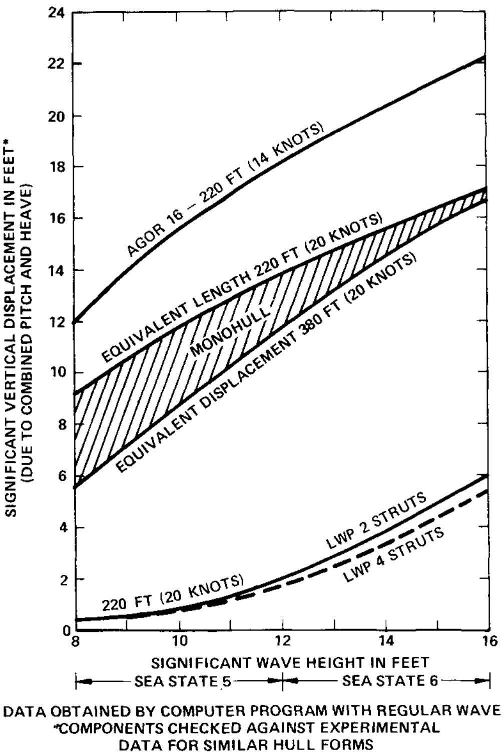


Fig. 1 Curves of significant vertical displacement vs significant wave height comparing a low waterplane catamaran, a monohull, and the AGOR 16.

stabilizers, will experience pitch and heave motions in following seas which will be larger than for conventional monohulls of the same length. This is an important fact to recognize since it may restrict the SWATH ships from performing its mission when operating in following seas if stabilizing devices are not utilized for reducing the vertical motions.

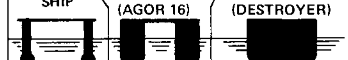
The main concern of this study has been to investigate the motions of SWATH ships which are not equipped with any fins or control surfaces. Therefore, all of the pitch, heave, and roll motion data used in the study are for bare hull SWATH ships. It is recognized that considerable reduction in the vertical motions can be obtained by use of active fins; however, such fins would result in additional drag and mechanical complexity. For example, the Naval Undersea Center (NUC) has demonstrated with their automatically controlled SWATH ship models that the motions in following seas can be reduced substantially.‡ It should be noted that the motions of conventional catamarans can also be reduced by use of fins and control surfaces; however, since the conventional catamarans have much larger waterplane areas than the SWATH ships, this would require quite large fins or control surfaces. For conventional monohulls, on the other hand, it has not been possible to obtain any satisfactory reduction of the pitch and heave motions by use of fins.

II. State-of-the-Art for Predicting the Dynamic Responses of SWATH Ships

It must be recognized that the SWATH ship is a completely new ship concept and that the methods for predicting the dynamic responses of monohulls cannot be applied directly to such unusual hull configurations. In order to make accurate design predictions of the dynamic characteristics of SWATH ships, it is necessary to go back to the fundamental hydrodynamic formulation and completely rework many of those prediction schemes presently used in the design of conventional monohulls. For example, it is well known that for a monohull, the added mass in heave is approximately equal to the mass of the ship and by using this approximate value, one can easily obtain a good estimate of the natural frequency of the ship in heave motions. On the other hand, if the added mass for a SWATH ship is approximated by the displaced mass, one will get erroneous results for the natural frequency in heave since the added mass is usually close to zero and can even be negative for certain SWATH ship configurations.

Since the computational methods used for predicting the motions of monohulls were not directly applicable to catamarans, parts of existing computer programs had to be completely redeveloped. First, "The Frank Close-Fit Ship-Motion Computer Program,"[1] which predicts the head sea motions for monohulls in regular and irregular waves, was extended so that it now includes SWATH ships as well as conventional catamarans.[2] To accomplish this, a new method had to be developed for predicting the inviscid added-mass and damping coefficients for twin cylinders[3] and the viscous damping for SWATH ships experiencing pitch and heave motions. The pitch and heave computer program for SWATH ships is now completed and gives results which agree reasonably well with experimental data. This computer program is also applicable to following seas; however, a general comparison between the computed following-sea results and experimental data has not been completed. Work has also been started on developing a complete six-degree-of-freedom motion and load program for SWATH ships in oblique seas similar to the six-degree program for monohulls.[4] On the other hand, experimental results[2,5] seem to indicate that the most important seakeeping characteristics for SWATH ships can be obtained from the pitch and heave motions in head and following seas and the roll and sway motions in beam seas. Furthermore, experimental results have shown that the maximum bending moment for SWATH ships, as well as conventional catamarans, occur in beam seas at zero speed.[2,5] Therefore, a computer program for predicting the roll and sway as well as the bending moments in beam seas is now being developed and will soon be completed. This means that computation methods will be available in the near future for performing parametric studies of 1) pitch and heave in head seas; 2) pitch and heave in fol-

Table 1 Basic hull dimensions for the three ship forms.



	SWATH SHIP	CONVENTIONAL CATAMARAN (AGOR 16)	CONVENTIONAL MONOHULL (DESTROYER)	
			EQUIV. LENGTH	EQUIV. DISPL.
LENGTH IN FEET*	220	220	220	380
DISPLACEMENT IN TONS	3200	3200	700	3200
BEAM (EACH HULL) IN FEET	8	24	23	40
HULL SPACING IN FEET**	100	54	–	–
DRAFT IN FEET	32	18.5	8	13
SPEED IN KNOTS***	20	14	20	20
FROUDE NUMBER	0.40	0.28	0.40	0.30

*LENGTH IS DEFINED AS THE OVERALL LENGTH OF THE SUBMERGED HULL.
**HULL SPACING IS DEFINED AS THE DISTANCE BETWEEN THE CENTERLINES OF EACH INDIVIDUAL HULL.
***NORMAL OPERATING SPEED IN A SEAWAY.

‡Sufficient data are not available in order to state precisely how effective fins and control surfaces will be in actual operating conditions, hence additional work seems to be needed in this area.

lowing seas; 3) roll, sway, and bending moments in beam seas.

Now turning to the experimental investigations of the seakeeping characteristics of SWATH ships, complete motion and sea-load experiments have been conducted for two SWATH ship configurations, the Mod Cat I and the Mod Cat II (Blue Goose).[5] Pitch, heave, and roll motions, plus shearing forces, bending and torsional moments have been measured at several speeds in head, bow, beam, quartering, and following seas. Some experiments have also been conducted on two-dimensional cylinders in order to obtain realistic values for the viscous damping coefficients for heave and pitch. Additional seakeeping experiments on SWATH ships are currently in progress.

At the time of this investigation, satisfactory agreement had been found between the pitch and heave, head-seas computer program and experimental data for the SWATH ship as well as for conventional catamarans. The experimental data are given in Refs. 3 and 5 while the comparison between theory and experiment for SWATH ships and conventional catamarans has not yet been documented. In a previous report,[1] good agreement between theory and experiment has been shown for conventional monohulls. Considering this satisfactory verification of the computer program, it was decided to use computer results for all of the head sea investigations; while, on the other hand, for the beam and following sea investigations, it was felt that satisfactory accuracy could be achieved only by using experimental data.[3,5]

III. Basis for Selected Ship Forms

In evaluating the performance of a new concept such as the SWATH ship, it is quite difficult to select the most appropriate conventional hull form for use as a basis for comparison. The question is whether one should select a conventional ship with equivalent length, displacement, usable deck area, operating speed, or payload. This all depends upon the mission requirement; however, for a new ship concept, its missions cannot be clearly specified before its performance characteristics are known sufficiently well.

For this evaluation of the seakeeping characteristics of the SWATH ship, it was felt that the most useful results could be obtained by comparing the responses for SWATH ships with those of conventional catamarans as well as conventional monohulls. A length of 220 ft was selected for the SWATH ship which gives approximately 3200 tons displacement. The AGOR 16 (length 220 ft and displacement 3200 tons) was selected as a representative hull form for a conventional catamaran while a destroyer hull (FRIESLAND) was chosen to represent a conventional monohull. The conventional destroyer hull with equivalent displacement to the SWATH ship would be approximately 380 ft long, while with equivalent length, the displacement of the destroyer hull would be about 700 tons. In this study it would be appropriate to use a monohull with both equivalent displacement and equivalent length; however, in some of the comparisons made here, only equivalent length has been used due to the time limitation imposed on this study. This should not result in any severe restriction since the differences in the motions between the equivalent length and the equivalent displacement monohull are not that large, as can be seen from those comparisons where both equivalent length and displacement are used.

Some of the more significant hull parameters and the normal operating speeds for the three hull configurations (the SWATH ship, the conventional catamaran, and the conventional monohull) are given in Table 1. For the conventional catamaran, AGOR 16, the maximum operating speed is about 14 knots while a 220-ft SWATH ship may be designed with a maximum speed of at least 30 knots and with a normal operating speed in a seaway of approximately 20 knots. Therefore, in this investigation, 20 knots have been selected as normal operating speed for the SWATH ship and the monohull, while only 14 knots has been used for the conventional catamaran.

It should be noted again that all of the motion studies presented in this study for bare hulls without any passive or active fins or stabilizers except for the roll motions in the case of the monohull which was equipped with normal size bilge keels.

IV. Pitch and Heave Motions in Head Seas at Operating Speeds

A. Comparison Between SWATH Ships, Conventional Catamarans, and Monohulls

The vertical displacements due to combined pitch and heave motions are presented in Fig. 1 as a function of sea state for the SWATH ship, the conventional monohull, and for the conventional catamaran (the AGOR 16). For purposes of comparison, these motions are given for monohulls of both equivalent length and equivalent displacement. For the SWATH ship, results are shown for both two-strut and four-strut configurations in order to demonstrate that the two configurations have practically the same motions in head seas. The vertical displacements presented in Fig. 1 are for the point along the length of the ship where the largest vertical displacement is experienced. Due to the phase relationships between the pitch and heave motions, the largest vertical displacement is at the bow for the monohull and the AGOR 16 while for the SWATH ship it occurs at the stern.

The results presented in Fig. 1 have all been obtained by "The Frank Close-Fit Ship-Motion Computer Program"[1] which originally was applicable only to monohulls but has now been extended to include catamarans and SWATH ships.[2] In this computer program, the regular-wave responses are first obtained by strip theory and then a statistical description of the responses in irregular waves is computed by using linear superposition, representing the sea by a Pierson-Moskowitz one-parameter fully-developed energy spectrum. The procedure for computing the statistical responses is as follows. First the response energy spectrum is obtained by multiplying the responses in regular waves (the response amplitude operator square) with the sea energy spectrum. Then the significant displacement (which is the average of the one-third largest displacements) according to the theory of statistics, is equal to four times the square root of the area under the response spectrum.

The computed pitch and heave amplitudes and phases for regular waves have in the case of the monohull been checked against experiments,[1] and in the case of the AGOR 16 and the SWATH ship satisfactory agreement between computer results and experiment has been found for catamarans very similar to AGOR 16 and the SWATH ships similar to the one used here. The verification studies for the catamarans and the SWATH ships have not yet been published.

For irregular seas, linear superposition is now accepted generally as a valid and accurate tool for computing the irregular sea responses of conventional monohulls. Ogilvie[7] states that the principle of linear superposition as applied to the head-sea responses for conventional hull forms "may now be considered as proven beyond the fondest hopes of earlier investigators." The present investigator is convinced that it should be just as applicable to SWATH ships in head seas, while it is probably less applicable to conventional catamarans of the AGOR 16 type since the AGOR 16 has a very narrow and peaked response curve

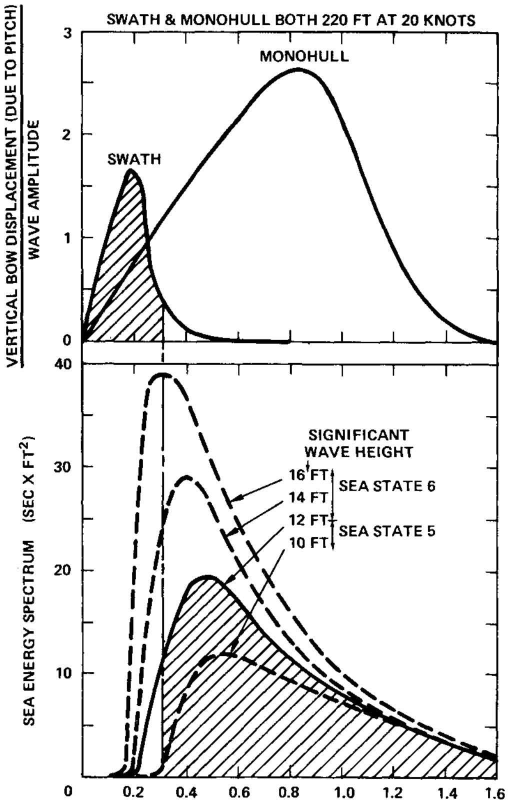


Fig. 2 A comparison of the pitch function of a small-water-plane-area-twin-hull ship and a monohull and its relationship to the sea energy spectrum.

(see Fig. 3). It is felt, however, that linear superposition as applied to the AGOR 16 is sufficiently accurage for this comparative study for sea states lower than 7. For more severe seas, linear superposition in general becomes less accurate and therefore no results are given in sea states higher than 6.

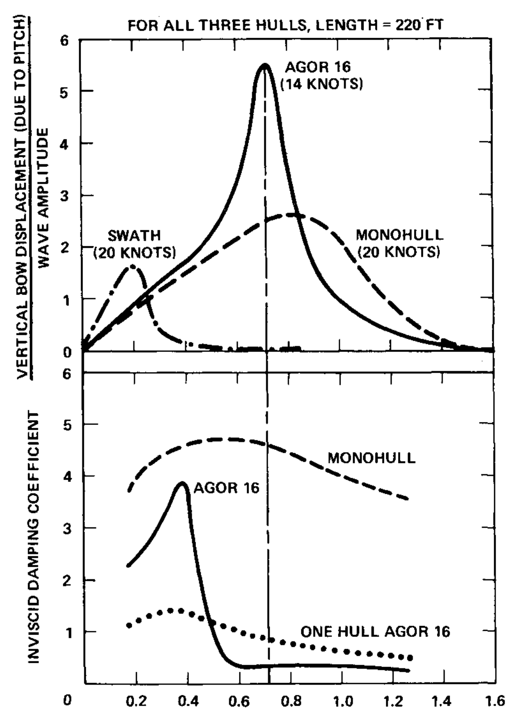


Fig. 3 A comparison of the pitch and damping functions of a monohull and a catamaran (AGOR 16).

It can be seen in Fig. 1 that a 220-ft SWATH ship has vertical displacements in head seas at sea state 5 which are less than one-fifth of those of a monohull with equivalent displacement. Furthermore, the SWATH ship can operate in a high sea state 6 with significant wave height of 16 ft before she will have approximately the same motions as a monohull operating in a low sea state 5 with significant wave height of 8 ft. It is also seen from Fig. 1 that the conventional catamaran (the AGOR 16) has head-sea motions which are inferior to the monohull. The vertical bow displacements for AGOR 16 are twice that of a monohull with equivalent displacement in a low sea state 5.

B. Explanation of Why the SWATH Ship has Less Motions than the Monohull in Moderately High Sea States

The major difference in the head-seas responses for a SWATH ship and a conventional monohull is demonstrated in Fig. 2. The upper part of this figure presents pitch motions for a SWATH ship and a monohull in regular waves as a function of ship length divided by wave length. In other words, the two upper curves show the pitch response amplitude operators for these two hull forms. The pitch is here presented as the vertical bow motion due to pitch nondimensionalized by the wave amplitude.§ At the time of this investigation, numerical computations for the total vertical motion due to combined pitch and heave motions were not available. However, since the pitch motion accounts for the largest portion of the vertical bow or stern displacement, it was felt that in explaining the differences in the head-sea motions between hull forms, sufficient information could be obtained from curves as given in Fig. 2 which only includes the vertical motion due to pitch.

The important difference between the pitch curves for the SWATH ship and for the monohull, as shown in Fig. 2, is not the difference in the magnitude of the maximum pitch but rather the fact that for the SWATH ship, the maximum pitch occurs at a wave length which is approximately five times the ship length while for the monohull the maximum pitch occurs at a wave length approximately equal to ship length. This means that for a 220-ft SWATH ship, one needs a swell of approximately 1100 ft in length to obtain the maximum pitch motions.

In order to better demonstrate the practical implication of this shift in pitch response curve, Pierson-Moskowitz sea-energy spectra are given in the lower part of Fig. 2. The sea-energy spectrum is a function which specified the statistical fraction of the total energy in the seaway which is associated with any given frequency band. In other words, the energy spectrum which has the units of ft^2 sec, gives a combined measure of the magnitude of the wave amplitude and the frequency of occurrence of the individual wave-length component. Hence, if a ship's pitch curve has its maximum at a wave length close to the maximum point of the energy spectrum, this indicates that the ship will encounter frequently large pitch responses in the sea condition represented by this spectrum. By comparing the response curve with the spectral curve, one is in effect comparing the response to individual regular waves of unit wave amplitude with sea energy associated with the particular wave lengths.

§Pitch is most often presented as the pitch angle divided by wave slope; however, such curves can be very misleading because the maximum point on such a pitch curves is not necessarily at the wave length of maximum pitch angle since the nondimensionalizing factor, the wave slope, is a function of wave length.

Making such comparisons between the pitch responses and the energy spectrums given in Fig. 2, it is interesting to note that for the case of a significant wave height equal to twelve feet, which is equivalent to a sea condition bordering between sea states 5 and 6, practically all of the energy of the seaway is confined to ship length to wave-length ratios larger than 0.3 (the shaded area of the sea-energy curve) while the pitch response of the SWATH ship is mainly confined to ship-length to wave-length ratios less than 0.3 (the shaded area of the pitch curve). In other words, throughout sea state 5, there are relatively few waves long enough to excite head-sea motions of a 220-ft SWATH ship operating at 20 knots. On the other hand, it is seen that the monohull has considerable pitch response throughout the wave-length range where the major portion of the energy is confined. This difference in the wave length, at which the maximum pitch motion occurs for the SWATH ship and the monohull is due to the very low natural frequency resulting from the small water-plane area of the SWATH ship.

Hence, the main reason that the 220-ft SWATH ship has so much smaller average motions than the monohull in sea states 5 and 6, as shown in Fig. 1, is that the maximum response for the SWATH ship occurs in the long wave-length range where there is little energy at these particular sea states. However, one cannot design a ship only according to its performance in a full-developed sea state 5 or 6. One should also consider the ship's performance in very severe sea conditions, as well as in swell seas. In severe sea conditions, linear superposition is not applicable, but it is quite clear from Fig. 2 that at sea states with significant wave heights larger than 16 ft, a 220-ft SWATH ship will have considerable pitch motions. The reason for this is that at these severe sea conditions, there will be a large amount of energy in the wave-length range where the pitch responses are the maximum for the SWATH ship, waves approximately five times ship length ($L/\lambda = 0.2$). This characteristic is completely different from those of conventional hull forms. A conventional hull will have practically no pitch motion in waves five times its own length. In investigating problems related to the survival of SWATH ships operating in extreme sea conditions, consideration must be given to these large pitch responses in the severe sea conditions.

Furthermore, it follows from Fig. 2 that SWATH ships will have rather large pitch motions in swell seas (regular waves) approximately five times its own length and it may be that the swell condition will be more critical than the severe irregular sea conditions. Recent unpublished work has indicated that ships with very narrow peaked response curves will often have larger responses in swell conditions than in an irregular seaway.

C. Explanation of Why the Conventional Catamaran has Greater Motions than the Monohull and SWATH Ship

The main reason for the large vertical bow motions of the conventional catamaran (the AGOR 16) is that such hull forms have small inviscid damping (damping due to wave generation) in pitch and heave motions. This is demonstrated in Fig. 3 which shows the pitch response curves in regular waves for the AGOR 16, a conventional monohull, and a SWATH ship. Also presented in this figure are the pitch damping curves for a monohull, the AGOR 16 catamaran and one single hull of the AGOR 16.

The damping curves in Fig. 3 show that a single hull of AGOR 16 has a much smaller damping than a conventional monohull. The reason for this difference is that the AGOR 16 hulls have a much larger draft (18.6 ft) than the monohull (8 ft). The magnitude of the inviscid damping (the wave generation part of the damping) decreases exponentially with the draft of the hull. The interesting fact is that for L/λ larger than 1/2 the damping is reduced further for the AGOR 16 catamaran configuration due to interacion between the two hulls. As can be seen in Fig. 3, the result of this interaction is that at ship-length to wave-length ratios larger than 0.6, the AGOR 16 has negligibly small inviscid damping. It should be noted that in addition to the inviscid damping, there is also some viscous damping. For conventional monohulls the additional viscous damping is only a small percent of the total damping and can be disregarded in computing the pitch and heave motons without introducing any significant errors. For catamarans and SWATH ships where the inviscid damping is very small the viscous damping becomes a more significant part of the total damping, and must be included in estimating the pitch and heave motions. However, for conventional catamaran hulls, the viscous damping is quite small resulting in a very large maximum response at the natural frequency, while for the SWATH ships, there is more viscous damping, due to the circular cross sections, resulting in smaller maximum responses. For all of the catamaran and SWATH ship computations shown in this report, estimated viscous damping factors have been included in the prediction. The methods for predicting the viscous damping for catamarans and SWATH ships will be published in the near future.

As seen in Fig. 3, for AGOR 16 at 14 knots, the maximum pitch occurs at $L/\lambda = 0.7$ which is equivalent to a wave length of 315 ft, while for the SWATH ship at 20 knots, the maximum pitch occurs at a wave length of approximately 1100 ft. Hence, AGOR 16 has very poor head-seas motion characteristics, not only because the maximum bow displacement due to pitch is more than five times the wave amplitude, but also because this maximum response occurs at a wave length of 315 ft, which is quite commonly encountered in the open sea.

Furthermore, it is seen in Fig. 3 that the pitch curve for the AGOR 16 is very narrow and peaked, while the conventional monohull has a much flatter response curve. This means that for AGOR 16, there is a larger difference between the pitch responses in waves having relatively small differences in the wave length. For example, she will have a pitch displacement in a 315-ft wave which is about four times the pitch in a 250-ft wave. It should be recalled that these regular waves responses are periodic responses. Hence, in an irregular sea, where all wave components are randomly distributed, the ship must go through a sufficient number of cycles at a particular wave length in order to reach the larger periodic pitch motions. This could imply that a ship with such a narrow and peaked response curve may not have as large a response in an irregular wave as predicted by linear superposition using periodic response amplitude operators. On the other hand, in swell conditions where all of the waves have practically the same length (wave lengths between 300 and 340 in the case of AGOR 16 at 14 knots) the ship would reach the larger periodic responses. Hence, it is important to note that for certain ships, swell conditions may result in much larger responses than irregular-sea conditions.

V. Other Operating Conditions

It has been shown in Sec. IV that the SWATH ships have promising seakeeping characteristics in head seas at operating speeds; however, the ship must also be able to perform without any unreasonably large responses at other operating conditions. In this section, the motions at zero speed in head seas, and the motion in beam and following seas will be discussed. The pitch, heave, and roll motions in oblique seas will not be treated here since these responses can easily be characterized directly from the results for head, beam, and following seas.

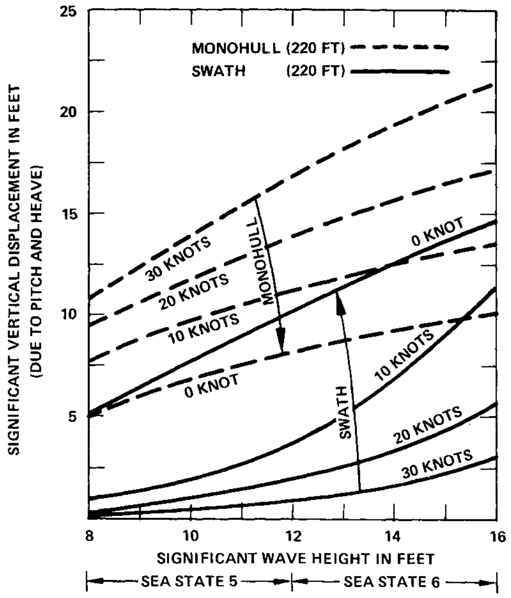


Fig. 4a A comparison of the effect of forward speed on the vertical displacement of a small-waterplane-twin-hull ship and a monohull.

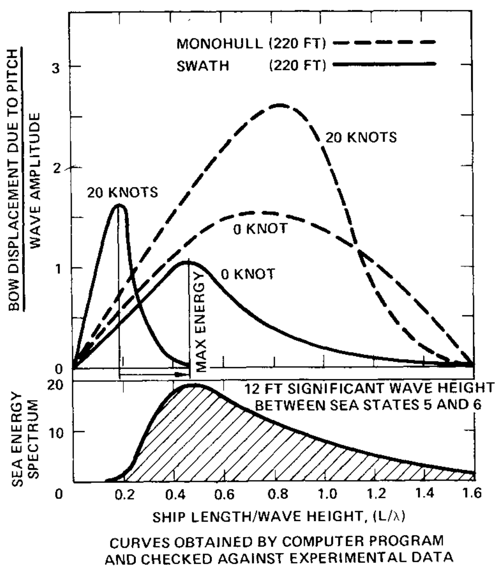


Fig. 4b Comparison of the effect of speed on the pitch displacement of a small-waterplane-twin-hull ship and a monohull.

A. Zero Forward Speed in Head Seas

Figure 4 shows the vertical motion as a function of sea state for a SWATH ship and a monohull, both with a 220-ft length. Response curves are given for both hulls at 0, 10, 20, and 30 knots. These data indicate that the motion increases for the SWATH ship with decreasing speed. This is different from a monohull where the motions decrease with decreasing speeds. It is interesting to note that at zero speed, the motions are approximately the same for both the SWATH ship and the monohull. This comparison is based on equivalent length (220 ft) for the two hulls. If equivalent displacement was used for this comparison, the monohull would be approximately 380 ft long and would have approximately 20% to 50% less motions than the 220-ft SWATH ship at zero speed in head seas.

The two lower plots in Fig. 4 have been included in order to demonstrate why, with increasing speeds, the motions increase for the SWATH ship while they decrease for the monohull. The middle graph presents the pitch displacement for the two hull forms at speeds of zero and 20 knots. For the SWATH ship it can be seen that in regular waves the pitch amplitude is smaller at zero speed than at 20 knots; however, more important, the peak of the pitch response curve which is at $L/\lambda \approx 0.20$ for the 20-knot case has shifted to the right with decreasing speed and is for the SWATH ship at $L/\lambda \approx 0.50$ for zero speed. Hence, comparing with the sea-energy spectrum which is also shown in Fig. 4, it can be seen that with decreasing speeds the maximum response in regular waves moves into the wave-length range where most of the energy is confined in sea states 5 and 6. Therefore, even though the SWATH ship has a smaller maximum response at zero speed than at 20 knots, the statistical average responses in sea states 5 and 6 will be larger at zero speed than at 20 knots as shown in the upper plot of Fig. 4.

For the monohull it can also be seen that in regular waves the pitch responses are smaller at zero speed than at 20 knots; however, in this case the wave-length at which the maximum responses occurs is effected only slightly by the change in speed, and hence, in all sea states the monohull will have a reduction in pitch motion with decreasing forward speed.

The effect of forward speed on the vertical motions in head seas is demonstrated further in Fig. 5. In this figure, the significant vertical displacements at the stern of the SWATH ship and at the bow of the AGOR 16 and the monohull are presented for equivalent lengths and equivalent displacements over a range of ship speeds. The significant vertical displacement is presented in this figure as function of ship speed for the SWATH ship and the AGOR 16 and also for monohull with equivalent length and equivalent displacement. These results are for sea state 5 with a significant wave height of 10 ft. It can be seen that all of the four hull forms have approximately the same vertical motion at zero speed and that as speed increases the motions increase for both of the monohulls and for AGOR 16, while a substantial decrease in the motions can be realized with increasing speeds for the SWATH ship. It is interesting to note that a reduction in speed is relatively more effective in decreasing the motions for the AGOR 16 than for conventional monohulls.

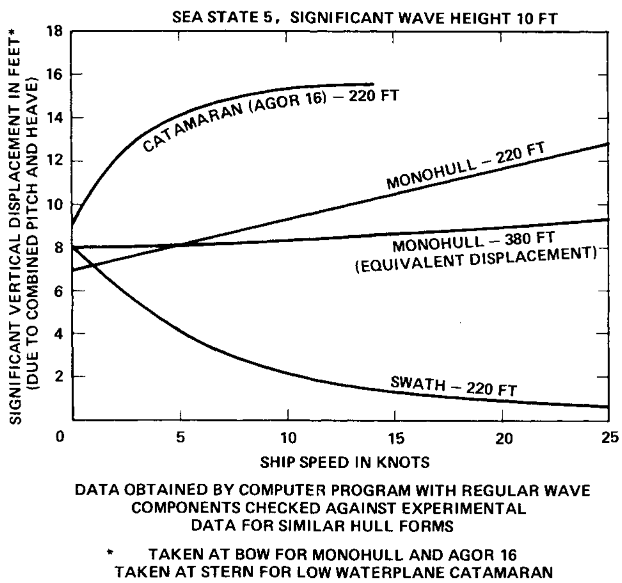


Fig. 5 Curves of significant vertical displacement vs ship speed comparing a small-waterplane-area-twin-hull ship, a monohull, and a catamaran (AGOR 16).

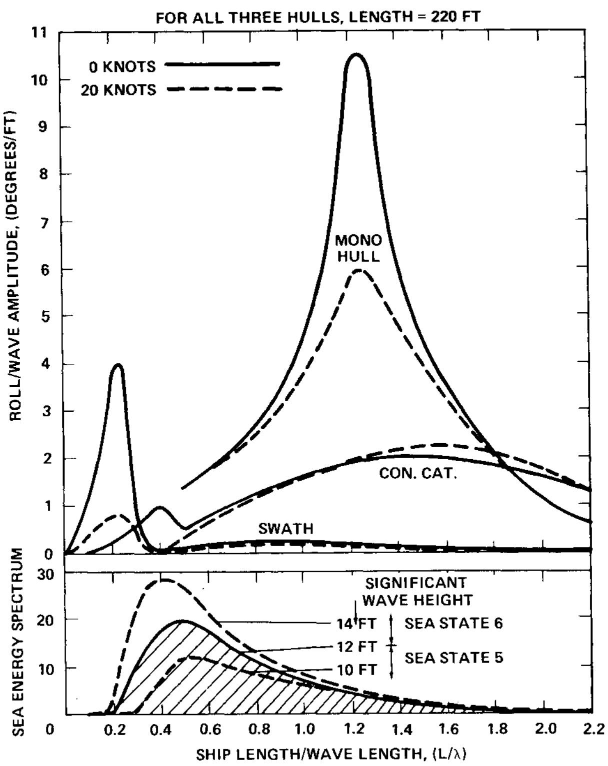
B. Beam Seas

The roll displacements in beam seas are presented in Fig. 6 for the SWATH ship, conventional monohull, and conventional catamaran. It is seen that the maximum roll response of the SWATH ship is much smaller than for both the monohull and the conventional catamaran and particularly at an operating speed of 20 knots. Furthermore, comparing the roll response curve for the SWATH ship with the sea energy spectrum, it is evident that the maximum roll responses occur outside the range of significant energy in the sea spectrum.

The deck edge displacements and accelerations due to roll motions may be or more importance than the actual roll amplitudes themselves when evaluating the seakeeping characteristics of SWATH ships. Figure 7 shows the deck edge displacement and acceleration as functions of ship length divided by wave length for the SWATH ship, the equivalent length monohull, and the conventional catamaran. It can be seen that the deck edge acceleration is much smaller for the SWATH ship than for both the monohull and the conventional catamaran.

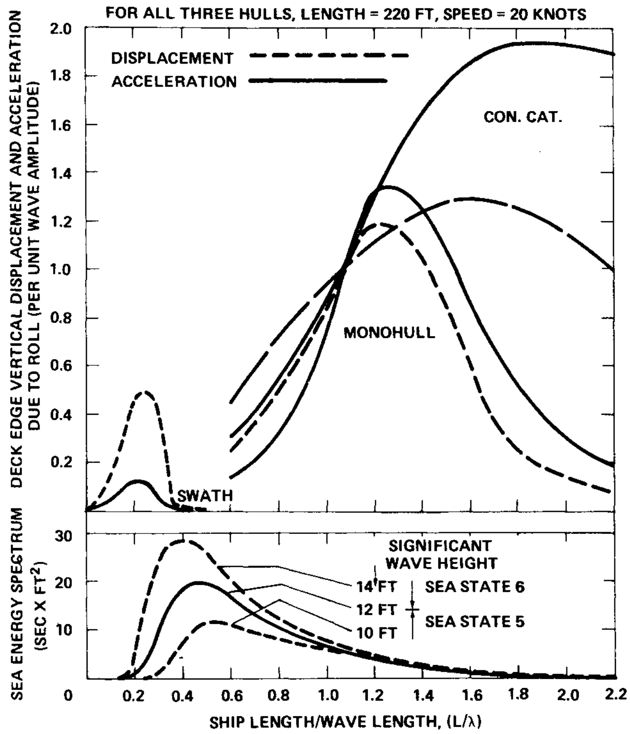
In general, it can be concluded that the roll motions for the SWATH ship will be very small at operating speeds in any sea condition; however, at zero saed in very high sea states (significant wave heights larger than 16 ft for a 220-ft hull) the roll motions could possibly be of considerable magnitude.

There exists very little information on the sway motions of SWATH ships in beam seas. It has been reported that the ooerators aboard a small prototype SWATH ship (Litton Industries Inc.) experienced sway motions in beam seas which they felt were larger than would be expected for a monohull. However, more data on the sway motions of SWATH ships is required in order to draw any conclusions with respect to sway in beam seas.



ALL ROLL DATA OBTAINED EXPERIMENTALLY
(LWP – REF. 5, CON. CAT. – REF. 2, MONOHULL – REF. 6)

Fig. 6 Curves of roll response in beam seas for a monohull, a conventional catamaran, and a small-waterplane-area-twin-hull ship and its relationship to the sea energy spectrum.



ALL ROLL DATA OBTAINED EXPERIMENTALLY
(SWATH – REF. 5, CON. CAT. – REF. 2, MONOHULL – REF. 6)

Fig. 7 Curves of deck edge displacement and acceleration in beam seas for a small-waterplane-area-twin-hull ship, a conventional catamaran, and a monohull.

C. Following Seas

The heave and pitch responses in following seas are presented in Fig. 8 for the SWATH ship, conventional monohull, and conventional catamaran. These curves show the responses in regular waves as a function of ship length divided by wave length for the three hull forms at equal length (220 ft) and at a speed of 20 knots.[1] It is seen that both the heave and pitch of a SWATH ship are larger than for a monohull or for a conventional catamaran. Comparing the pitch curve for the SWATH ship with the sea-energy spectrum given in the lower part of Fig. 8, one notes that the largest pitch responses occur over a wave-length range where the maximum energy in the sea spectrum is concentrated; the largest heave responses occur at a wave-length range where the wave amplitudes are quite small.

In order to get a better feeling for how this effects the seaworthiness of the SWATH ships in following seas, we may compare the pitch curve for the SWATH ship in following seas given in Fig. 8 with the pitch curve for the monohull in head seas given in Fig. 3, and it is seen that the two curves are quite similar. This is an indication that a SWATH ship in a following seaway may have approximately the same order of magnitude of pitch motions as a monohull of the same length heading into the same seaway.

It may be concluded that the seakeeping characteristics of the SWATH ship in following seas are not as attractive as in head seas and that the SWATH ship will have more pitch and heave motions in following seas than a conventional monohull. It should be pointed out that all of the results given here are for a SWATH ship without any foils or control surfaces. Recent unpublished studies at the

[1] At zero speed, the pitch and heave motions for SWATH ships in following seas are very similar to its head seas responses due to the fore-and-aft symmetry of the hulls and therefore, the zero-speed following seas data have not been included in this paper.

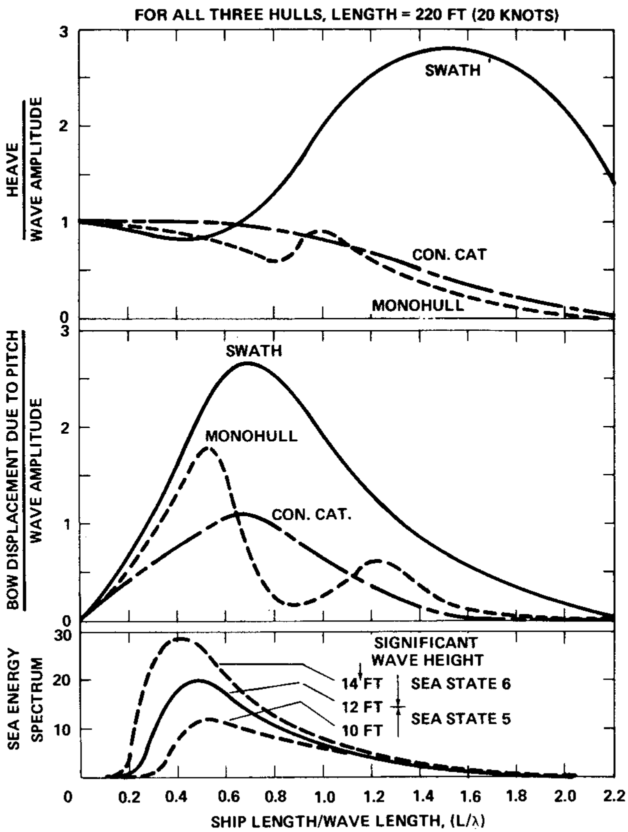


Fig. 8 A comparison of the heave and pitch function in following waves of a monohull, a conventional catamaran, and a small-waterplane-area-twin-hull ship and their relationship to the sea energy spectrum.

Naval Undersea Center has shown that use of fins and active foils are very effective in reducing the motions of SWATH ships in following seas.

VI. Conclusions

The results presented in this paper clearly show that the SWATH configuration has some promising seakeeping characteristics. In particular, at normal operating speeds in moderately severe head seas with moderate wave lengths and in all beam seas, the motions seem to be far superior to both conventional catamarans and conventional monohulls. In very severe head-seas and particularly in long swells, this study indicates that SWATH ships without foils or control surfaces will exhibit motions of considerable magnitude. At zero forward speed in head seas, the vertical motions of SWATH ships will be of approximately the same magnitude as those for a monohull with equivalent length. On the other hand, in quartering and following seas, a SWATH ship will pitch more than a conventional monohull with equivalent displacement if not eouipped with foils or control surfaces. There is also some indication that in beam seas, a SWATH ship will experience larger sway motions than conventional hull forms.

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