Hydrofoil Performance in Rough Water

D. A. Jewell*
Naval Ship Research and Development Center, Bethesda, Md.

All ships go slower and consequently have less range in rough seas than in calm water for fixed power and fuel load, but hydrofoil speed and range losses are small. The combined effects of wave height, ship motion, calm water speed, and size of the ship on speed and range are determined by use of empirical data on hydrofoil performance, including recently released TUCUMCARI data. Rough water has little effect on the overall performance of fully-submerged, automatically controlled hydrofoils. An 1100 ton hydrofoil can operate foilborne in a state 7 sea with modest speed and range losses.

Introduction

GROWING operational experience documenting the rough water capabilities of fully-submerged, automatically controlled hydro foils makes it possible to identify the operational advantages more explicitly than in the past. The fact that small ship motions and high sustained speeds are attained by such hydrofoils in small sizes has been recognized before by Oakley,[1] Lacey,[2] Ellsworth,[3] Silverleaf and Cook,[4] and Acosta.[5] The Patrol Gunboat Hydrofoil TUCUMCARI (PGH-2) has demonstrated outstanding rough water performance for a craft of her size in several seas of the world. Indeed the U.S. Navy/NATO Patrol Hydrofoil Missile (PHM) acquisition testifies to the value of small seaworthy vessels in naval operations. As a consequence of its ability to maintain its calm water speed in waves of increasing height (referred to craft weight), fully-submerged hydrofoils have better transport efficiency than several other high-speed marine craft.[4,5] It appears not to have been recognized that range is directly proportional to transport efficiency. This dependence makes it a simple matter to determine the explicit effect of wave height on ship range. Furthermore, range and payload are interrelated because the useful load, which depends on ship size, equals the sum of fuel load and payload.

The process, by which wind-generated waves affect several measurable performance factors of ships, is outlined in Fig. 1. Generally there exists a cause-and-effect relation between successive boxes. Both the local wind (not necessarily the wind which generated the waves), and the waves change the resistance, which can be either increased or decreased. The wind and waves also cause motions which in turn cause crew discomfort. The changed resistance changes the speed-power relation for the ship. In following seas, the resistance is decreased with constant power, and the ship will increase speed.[6] Often the ship moves in some direction other than that of unidirectional waves, or more commonly, the seas are mixed in direction. In either case, the resistance increases and the ship slows, unless power is increased to maintain speed. Since the ratio of speed to power is changed, then by definition the value of the transport efficiency or effective lift-drag ratio is changed, as is the range for a given payload.

The seaworthiness of hydrofoils is expected to improve with ship size. In addition, the advantageous implications of hydrofoil size on both calm water and rough water range are just now becoming apparent. Existing hydrofoils, the largest of which is PLAINVIEW (AGEH-1) at 320 tons, can operate far from the coast when provided with the necessary replenishment support. Larger hydrofoils, which have larger useful load fractions, can attain cross-ocean ranges in addition to their improved seaworthiness. Hydrofoils of 1100-1400 tons displacement can provide range and payload commensurate with operations on the high seas. Craft of this size can take full advantage of all of the rough water capabilities of hydrofoils.

Based on the availability of current information on fully-submerged, automatically controlled hydrofoils, it is the purpose of this paper to provide updated data on ship motions and sustained speeds in rough water and to extend these data to the effects of rough water on the range and payload of large hydrofoils. Pertinent similarities or differences in specific performance factors between naval hydrofoils and other ships are noted. Some highlights of operational experiences of U.S. Navy hydrofoils in the conduct of naval operations in real oceans are given.

The evidence is that rough water has little effect on the overall performance of fully-submerged, automatically controlled hydrofoils, and that the ability of large hydrofoils to conduct mission operations in the open ocean is not significantly affected.

Presented as Paper 74-307 at the AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, Calif., February 25-27, 1974; submitted March 14, 1974.

Index categories: Marine Vessel Systems, Surface; Marine Hydrodynamics, Vessel and Control Surface.

*Naval Architect, Advanced Concepts Office, Systems Development Department.

Background

General Effects of Rough Seas on Ships

Waves affect the performance of ships in many ways. Waves cause ship motions and reduce speed, range, endurance, payload, crew effectiveness, or the effective use of mission equipment; likewise waves can increase the requirements for power, fuel, or ship size, and cost. In this section, a typical example of seas which occur in the North Atlantic is given to indicate the wave heights to be considered. Some significant ways in which rough seas are taken into account in ship design are described. This is followed by a brief discussion of ways in which rough seas affect ship operations.

Ships often encounter large waves in the North Atlantic. Based on over 1700 observations made in mid-Atlantic in the fall of 1949, waves were observed to equal or exceed 6 ft in

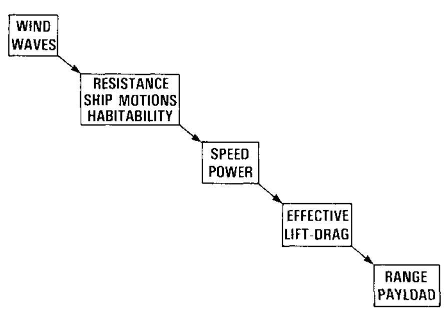

Fig. 1 Causal relation between rough weather and ship performance.

height 55% of the time, to equal or exceed 8 ft 37% of the time, to equal or exceed 10 ft 25% of the time, to equal or exceed 12 ft over 15% of the time, to equal or exceed 16 ft 5% of the time, and to equal or exceed 20 ft about 3% of the time.[6] It has been found that an observer's judgment is biased toward the higher waves, which tend to have about the same height as significant waves. The significant wave height *h* is the average of the highest one-third of all waves, and is related to the "sea state" scale used for description of the gross character of the sea surface elevation. The numerical sea state values for the average and significant heights of waves and the corresponding generating winds are shown in Fig. 2.

Ship Design Effects

Ships are ordinarily designed to operate in some specified sea state, rather than in calm water. Propulsion power will be increased somewhat beyond calm water power requirements to overcome the added resistance in waves; the structure will be designed to withstand the loads imposed by the sea; and the hull will be shaped to reduce motions, slamming, and deck wetness. These features interact with other design criteria unrelated to rough seas so that the end effects of sea state are pervasive in the final integrated design. Therefore while the effects of rough water on ship design may not be visible, they are embodied in the design and construction.

Ship Operation Effects

Ships are operated in conditions ranging from calm water to above the design sea state, so it is possible to determine the effects of waves on performance. Tests of performance in various sea states may indicate how to change future designs to achieve better performance. Unfortunately our knowledge of several effects is rudimentary and qualitative. Operational experience regarding crew effectiveness, vulnerability, the abilities to employ mission equipment and to accomplish operational assignments, for example, are difficult to put in quantitative terms and to relate to environmental conditions.

Most sea conditions in the ocean are a mixture of two or more wave systems. This fact, together with the limited accuracy of visual observations and measurements, often result in data in which the heading of the ship relative to the wind or waves is indeterminant or absent. Some of the information contained in this report was derived from operations or trails in such mixed seas. Under such conditions, virtually all ships evidence speed reductions in moderate seas due to increased drag and because of the need to reduce ship motions to a tolerable level. As long as the motion is tolerable, it is possible that the increased drag can be overcome by additional power. Unless there is some urgency to accomplish a specific goal, however, operators may accept the lower speeds.

If the seas have a predominant direction then both the resistance and motions depend on the heading of the ship relative to the waves. The Oceanographic Atlas of the North Atlantic Ocean[6] shows that speeds of ships encountering waves of various heights is greatest in following seas, least in head seas and intermediate in beam seas. Speed performance curves are given there for various ships in sizes ranging from about 6000 to 25,000 tons and calm water cruise speeds between 10 and 20 knots. Ships of this size range exhibit a small increase in speed in waves up to 10 or 12 ft in height in following waves. In following seas about 12 ft in height and in head seas, all of these ships show the characteristic loss of speed with increasing wave height. The loss of speed in waves up to 26 ft in height varies from about 25 to over 60%. In extreme cases, ships may be required to reduce power to the minimum needed to maintain steerageway. In commercial operations, the loss of speed and the inability to maintain shipping schedules results in measurable and significant economic losses; so much so that ships are routinely routed to achieve the best speeds. Observations show that seas (12 ft or more) requiring significant reductions in speed were en-

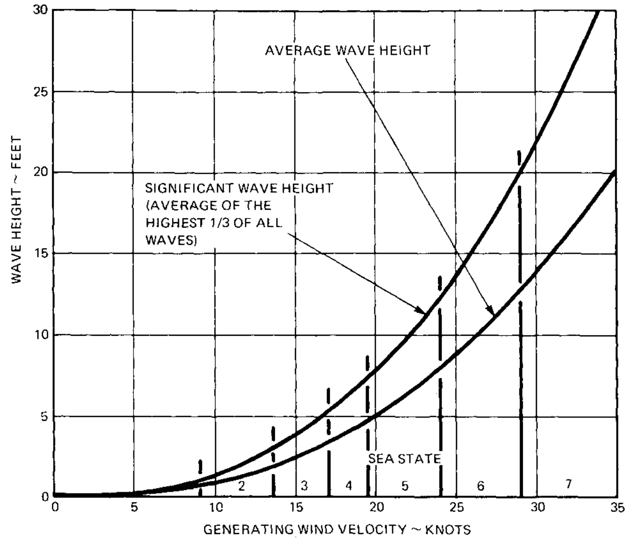

Fig. 2 Sea state definitions.

countered in the mid-Atlantic from 15 to 25% of the time in February 1949.[6] Seas which required reductions of speed occurred at least 5% of the time over virtually all of the North Atlantic regardless of ship heading.

Military ships are not only more dependent than commerical ships on the ability to deliver a certain payload to a specified destination at a certain time, but also need to be able to conduct several specialized operations while at sea. These may include alongside replenishment, search and detection, and weapon engagements with enemy ships. Ship motions and deck wetness can limit the capability to replenish, to launch and retrieve aircraft, to employ towed sensors, to fire weapons, or for crewmen to stand watches. The ability to maintain high speed in real seas must be counted as an essential quality.

Since World War II, the development of advanced marine vehicles has shown that constraints on speed and seakeeping can be overcome by innovative approaches. Several types of advanced marine vehicles are now maturing in sizes from 600 to 20,000 tons at a time when many naval ships need to be replaced. Of these maturing vehicles, hydrofoils have been shown to be both seaworthy and fast.

Highlights of Hydrofoil Operations

Ever since the spectacular demonstrations by Bell and Baldwin in their surface-piercing Hydrodome HD-4,[7] the combination of seaworthiness and high speeds of hydrofoils have been recurring theme. A U.S. Navy research hydrofoil (XCH-4 in 1955 and 1956) with a surface-piercing foil system demonstrated adequate seakeeping in sea state 3. Ever since SEA LEGS, with its automatic control system (ACS) demonstrated its seakeeping ability in sea state 4, though only 5 tons in displacement, the Navy has focused its efforts on fully-submerged hydrofoils. The three U.S. Navy hydrofoils still in service, HIGH POINT (PCH-1), PLAINVIEW (AGEH-1), and FLAGSTAFF (PGH-1) all combine greater seakeeping capability with calm water speeds of 50 knots.

The unfortunate grounding of TUCUMCARI in November 1972, and consequent deactivation of this very successful hydrofoil, has resulted in the end of her service life. For the first time, much of her seakeeping data can be revealed. These valuable data gathered in over 1100 hr of foilborne operation across the world, aid greatly in the development of the subject of this paper. Although designed for sea state 4 TUCUMCARI operated rather successfully in sea state 5 and occasionally even in sea state 6. HIGH POINT, PLAINVIEW, and the PHM are expected to demonstrate even better rough water performance as a consequence of their larger sizes. Still larger hydrofoils, such as the Developmental Big Hydrofoil (DBH), nominally 800 tons, and the Deep-water Escort Hydrofoil (DEH) of between 1100 and 1400 tons, promise still better rough water performance which is obviously commensurate with open ocean operations.

Ships need not go too far offshore to encounter high sea states. TUCUMCARI, for instance, operated in sea states of 5 or more several times within 50 miles of the South Viet Nam coast in late 1969 and early 1970. The sea states reported by TUCUMCARI during patrols are shown in Fig. 3. Her capability to operate at high sustained speeds in all kinds of weather helped her achieve various assigned missions.

U.S. Navy hydrofoils have often demonstrated the ability to be replenished under way and in all kinds of weather. TUCUMCARI was replenished under way ten times during her European deployment in sea conditions through state 5 and into state 6. Small hydrofoils need replenishment to make long transits. TUCUMCARI was able to make the longest continuous transit of any hydrofoil of over 1600 nautical miles from Brest to Toulon with three replenishments in rough waters. In another case, a hydrofoil operated both hullborne and foilborne in a sea state in which she could not be replenished. One of the reasons was that the delivery ship could not maintain heading well enough. Hydrofoils have also conducted several replenishment exercises with helicopters. Thus the current capability of hydrofoils to be replenished is as good as can be exploited.

There are many testimonials to the ride quality of hydrofoils but the subject is complex and ride quality criteria are lacking. A recent paper[8] gives a good brief discussion of the subject.

On numerous occasions, the stability of hydrofoils has proven advantageous in weapon firings. In 1969, TUCUMCARI fired 40 mm and 50 cal. guns in sea state 3 with good accuracy. The 152 mm gun firing exercises by FLAGSTAFF in 1971 are also good examples of how platform stability enhanced firing accuracy. PLAINVIEW easily launched a SEA SPARROW missile while foilborne in a moderate sea. Likewise HIGH POINT recently launched two HARPOON test missiles while foilborne, once in a moderate sea. Reactions on the hydrofoil are small and weight savings are possible in the fire control of some weapon systems.

HIGH POINT demonstrated the ability to tow a sonar-type body while foilborne. Rough water was simulated by changing the foilborne height. In real rough seas, her stability would minimize tow-line stress variations. This translates to safety from cable breaking or to smaller cables. In addition, the small amount of additional power needed to sustain her speed in rough water leaves power available for towing such sensor equipment in rough water.

In the early 1960's it was recognized that hydrofoils could have a chief role in antisubmarine warfare (ASW). Indeed, HIGH POINT and PLAINVIEW, as well as the Canadian Hydrofoil Ship HMCS BRAS D'OR, were all conceived with ASW roles in mind. In 1965, Lacey[2] pointed out that the emphasis on hydrofoils was related to the desire to increase the speed of surface units to keep pace with other units, and particularly to provide a more effective platform for coping with the high-speed, continuously submerged nuclear submarine. To this may be added: submerged submarines do not need to slow when the sea surface is rough. Thus hydrofoils are still considered to have a prime role in ASW. The ability to search large areas compared to slower ships and to maintain convoy speeds on the average while slowing to employ sensors and speeding between search modes add to hydrofoil attractiveness in the ASW mission.

Large hydrofoils appear to be virtually the only escort craft which could match the speed of a modern aircraft carrier or super tanker throughout its sea state range. For many missions, a ship with a gross weight of about 1400 tons, a 90-ton payload weight, and which can cruise cross-ocean unrefueled at 35 knots in sea state 5 would appear to be highly desirable to the fleet. We estimate that a large fully-submerged hydrofoil can, in several respects, do better.

Ship Motions

Foilborne Seakeeping

The automatically controlled hydrofoil minimizes its wave-induced motions by means of a highly-responsive system which provides control forces to counteract the disturbing forces. As a result, a fully-submerged hydrofoil has less heave acceleration in waves than a surface-piercing hydrofoil. Figure 4 shows the root-mean-square (rms) vertical accelerations at the center-of-gravity (c.g.) of DENISON (surface-piercing) and TUCUMCARI (fully-submerged foils). It can be seen that the accelerations of TUCUMCARI, despite her smaller size, are about one third those of DENISON. The vertical accelerations along the length of TUCUMCARI (at the pilot house, forward foil and aft foils) are very nearly the same as those at the center of gravity. The heave accelerations depend on the heading of the ship relative to the direction of wave travel. Figure 5 shows how the acceleration decreases as HIGH POINT (PCH-1) changes from head to beam to following seas in her design sea state.

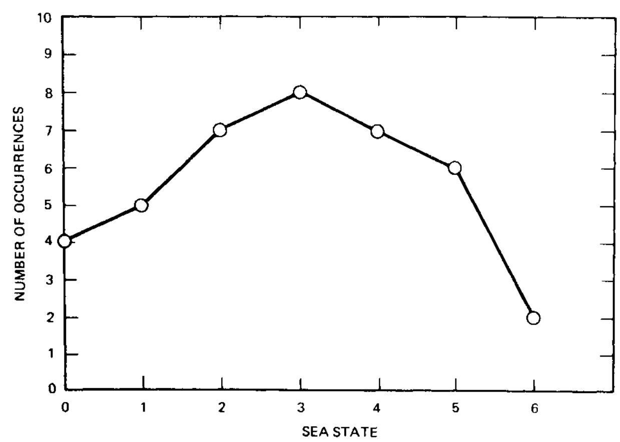

Fig. 3 Sea states reported by TUCUMCARI.

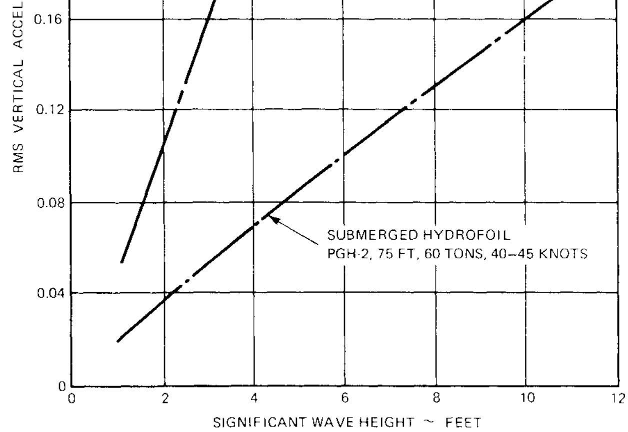

Fig. 4 Heave acceleration comparison.

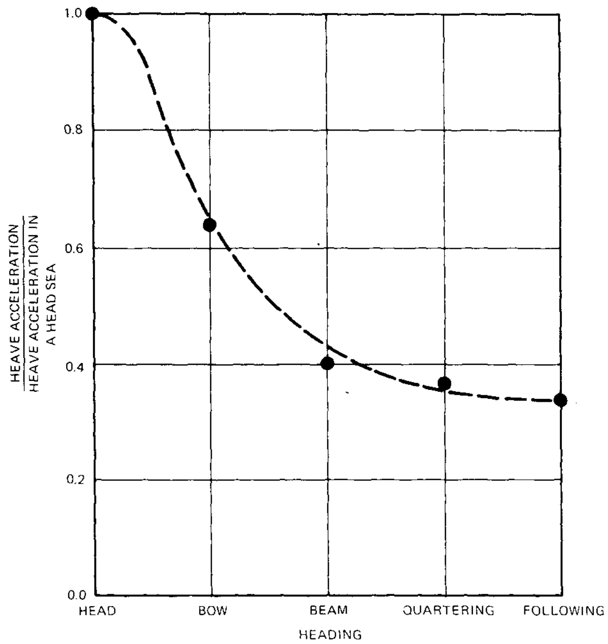

Fig. 5 Heading effect on heave acceleration.

Table 1 TUCUMCARI motion trials data

Variable	PGH-2 Trials
Significant wave height	10.6 ft
Vertical acceleration pilot house	.15g rms
Lateral acceleration pilot house	.07g rms
Pitch angle	1.1° rms
Roll angle	1.0° rms

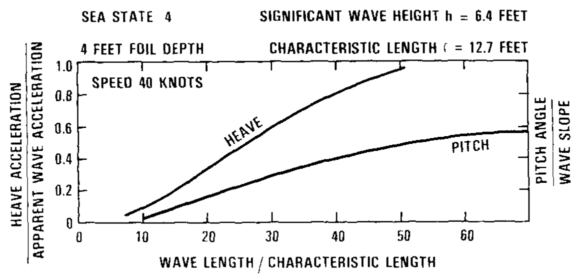

Fig. 6 Heave and pitch response curves for TUCUMCARI in a head sea.

The rms values of vertical and lateral accelerations and pitch and roll angles are listed in Table 1 for TUCUMCARI in sea state 5. These are extremely small values for such wave heights. It can be expected that larger fully-submerged, automatically controlled hydrofoils in the same sea will experience smaller motions than those shown. The pitching of many ships causes much greater vertical accelerations at the bow and stern than at the c.g. or pilot house. Hydrofoils generally experience so little pitching that the variation of vertical acceleration along the length of the ship is small.

Dimensionless heave and pitch, referred to wave-length values, are given for TUCUMCARI in Fig. 6. These data were obtained from 1967 ship motion trials of TUCUMCARI in sea state 4 at speed of 40 knots with a foil depth setting of 4 ft. The significant wave height was 6.4 ft. Other data indicate that rms heave accelerations and pitch angles generally increase with decreasing speed except at the longest wave length (about 40 or more times the characteristic ship length ℓ defined as the cube root of displaced volume ∇ [$\ell = \nabla^{1/3}$]).

Contrary to what one might expect, experience and data show that the heave and pitch motions are reduced when the

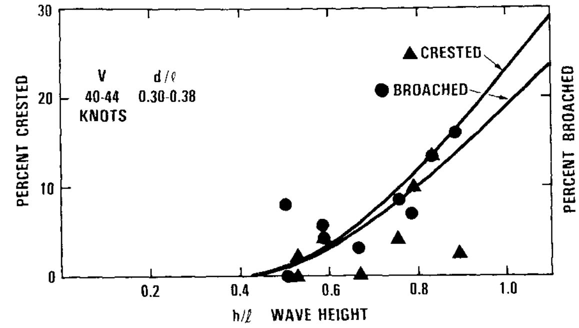

Fig. 7 Broaching and cresting of TUCUMCARI dependence on wave height.

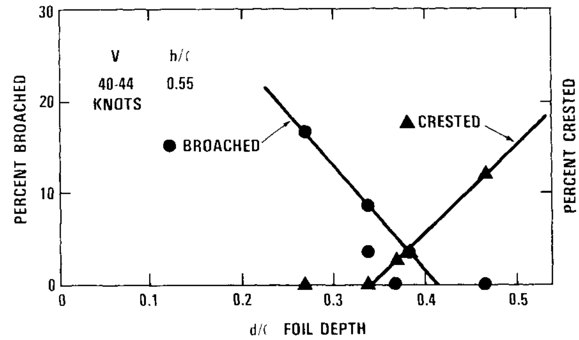

Fig. 8 Broaching and cresting of TUCUMCARI dependence on foil depth.

foilborne keel height is reduced slightly from normal calm water height, particularly at or above design sea states. If, as the wave height increases beyond the design sea state, an attempt is made to keep the keel clear of the waves, eventually the forward foil broaches. This is frequently followed by a slam. This broaching and slamming result in increased accelerations in heave and pitch. If the foilborne height is reduced as the wave height increases, however, the foil will remain immersed and the hull furrows through the wave crests. These effects are shown in Figs. 7 and 8 for TUCUMCARI. For her normal foil depth d, broaching and cresting begin when the wave height reaches about one-half the characteristic ship length. This broaching and cresting occurs with about 10% of encountered waves when the wave height reaches about 0.8 of the characteristic ship length and continues to increase to 20 or 25% at wave heights equal to the characteristic ship length ($h/\ell = 1.0$). This condition occurs well beyond the design sea state. Figure 8 indicates how increased foil depth reduces broaching and increases cresting. Thus, in seas of this height or higher, the foilborne height can be adjusted to yield the least accelerations. This flight height usually results in more cresting than broaching.

Speed Effects on Hydrofoil Seakeeping

Some 18 years ago, the Navy demonstrated the ability of an 8-ton surface-piercing hydrofoil (the XCH-4 Air-Sea Rescue Boat) to go 79 knots in calm water, between 68-79 knots in sea state 1, and between 47-52 knots in sea state 3. The 208-ton BRAS D'OR went 65 knots in calm water, 50 knots in sea state 5, and 40 knots in 10-15 ft waves.[9] More complete information on BRAS D'OR seakeeping trials is given by Schmitke and Jones.[10] It is expected that larger, fully-submerged hydrofoils equipped with an automatic control system can do better at these same speeds.

The effect of increased speed (above 50 knots or so) on the seakeeping of submerged foil hydrofoil ships is not known very well. The design, construction, and operation of the Navy research hydrofoil FRESH-1 demonstrated the capability to achieve speeds over 80 knots with fully-submerged hydrofoils, at least in the calm water for which FRESH was intended. FRESH was said to have operated in small waves, but the wave height was not measured and the speed at the time was not recorded. Of greater importance is the speed and performance in rough water. Measurements of such effects (above 50 knots) do not appear to be available. It is well within the capability of simulations of dynamic response to compute the motions of automatically controlled hydrofoils at high speeds in rough water, but the results of such calculations are not apparent in the literature. A few brief remarks can be made however. The forces on a submerged foil due to wave encounter depend on the effective angle of attack, the change in lift with angle of attack (lift curve slops), and the encounter frequency. As ship speed increases the effective angle of attack due to the orbital wave velocity is decreased. This, coupled with the lower lift curve slope at speeds about 50 knots, should result in smaller induced forces on the foil. However, the frequency of wave encounter will increase with speed and may cause the ship motion to increase or decrease. Without calculations or empirical data, however, the net effect of speed above 50 knots on ship motions can not be given. Data for speeds below 50 knots show that pitch and heave motions decrease as speed increases.

Course-Keeping

The controllers in the latest automatic control systems are now scheduled to reduce yawing due to wave action so that fully-submerged hydrofoils hold their heading in rough seas relatively well, compared with displacement craft. An automatic heading hold has been used to hold courses to closer tolerances than can a helmsman. This equipment provides an apparent operational advantage for long transits in rough water with a small crew. Further, this feature has obvious utility in underway replenishment operations in high seas where the ability to hold course is so crucial.

Hullborne Seakeeping

Hydrofoil ships with retractable foil systems and ACS can operate hullborne in three modes with attendant variations in hullborne seakeeping. They can operate with foils retracted or extended; with the foils extended, the ACS may or may not be activated.

The extended foils produce a significant effect on hullborne craft motion, particularly on roll motion which is normally not heavily damped. This finding is documented for model tests of PLAINVIEW (AGEH-1) by Chey.[11] Generally, the extended strut-foil system gives hydrofoil ships hullborne motions characteristic of conventional ships of much larger displacement.

In addition to the effects of foil extension on motions when hullborne, further reductions in lateral accelerations (30-40%) and roll angles (40-75%) in beam seas at speeds from 9-18 knots are produced by activation of the foil control system in full scale trials. Reductions in roll angles (20-60%) also occur by use of the ACS in head seas in the same speed range. In these tests, the ACS was used as adjusted for foilborne operation; adjustments were not made for such low-speed operation. These results are important because hydrofoils will need to operate hullborne for significant time periods; in addition, hydrofoils need to survive storm seas in the hullborne mode of operation. The Canadian Hydrofoil Ship HMCS BRAS D'OR with a surface piercing foil system was reported[9] to exhibit exceptional hullborne seakeeping performance up to sea state 7. It is now clear that with an operational hullborne ACS mode, larger hydrofoil ships with larger foils will further reduce hullborne hydrofoil motions, thus providing completely adequate performance in moderate and storm seas.

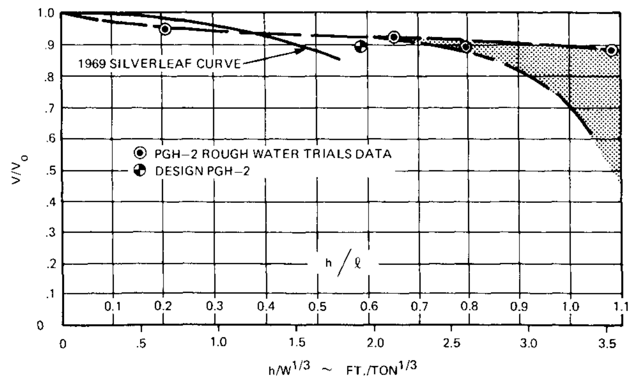

Fig. 9 Sustained speeds of hydrofoils in rough water.

Sustained Speed and Effective Lift-Drag Ratio

For the purpose of this paper we shall consider wave heights not so large as to cause voluntary reductions in power due to excessive ship motions; small adjustments in foil submergence are considered, however, and these produce slightly lower speeds. In this respect air-cushion ships, which depend on power for lift, may need to increase power to adjust cushion height upwards.

Several years ago Silverleaf and Cook[4] reported the rough water speed reductions for several kinds of craft. They showed that fully-submerged hydrofoils maintained a higher percentage of calm-water speed V_o with increasing wave height (referred to the cube root of all-up weight, W) than any other craft considered. The other craft exhibited vertical accelerations (midships) at their own speeds equal to or greater than DENISON (as was shown in Fig. 4) for the entire range of values of the wave height to characteristic length ratio. Silverleaf and Cook went further and considered the values of power (P) divided by all-up weight times speed (P/WV) in calm and moderate $(h/\ell=0.15)$ sea conditions. This showed the effect of the reduced speed on what is variously termed "specific power," or "specific resistance" and its inverse (η L/D) which is termed "effective lift-drag ratio" or "transport efficiency." Acosta[5] showed essentially the same information in a single figure for more recent hydrofoils. These studies went far towards indicating the rough water performance of fully-submerged hydrofoil ships, but those data are now outdated. For these reasons, the current values of the rough-water speed (V) will be given and extended to larger values of wave-height to characteristic ship length ratio. These speed-loss values will then be used to derive current rough water values of $\eta L/D$ $(=WV/P)$ as a function of Froude number based on characteristic ship length $[V/(g\ell)^{1/2}]$.

A review of currently available hydrofoil data has produced the curves shown in Fig. 9. These data, although the best available, are subject to unrecorded variations in relative ship-wave headings, ship operating weights, and wind velocities. Strictly speaking, there is no assurance that the power settings were the same as those used in calm water, but the departures are considered to be small. It appears that the single point in Fig. 9 at $h/\ell=1.1$ may have been obtained by "overdriving" the ship. For this reason, and because of indications of the lower sustained speeds of other hydrofoils at such values of the wave-height ship-length ratio, a shaded area is shown on the chart. The new curve appears to fit the 1969 line of Silverleaf and Cook at small values of the height-length ratio and extends the range to larger wave lengths where the sustained speed is substantially greater than might have been expected earlier. For instance, in 1965 Lacey[2] gave computer results, available at that time, which yield a maximum value of $h/\ell=0.7$ (for a full-load displacement of 450 tons). The curve indicates that $h/\ell=0.15$ termed moderate by Silverleaf should be considered as a mild sea for fully-submerged hydrofoils. A value of $h/\ell=0.4$ might be taken to indicate a "moderately rough" sea. A "rough" sea for hydrofoils would occur at about $h/\ell=0.8$. In the vicinity of this value, the data and the shaded region shown in the figure indicate the initiation of voluntary speed reduction. This corresponds to broaching and cresting of about 10% of encountered waves. The data indicate that the curve tends to be universally true for all fully-submerged hydrofoils out to $H/\ell = 0.8$. The speed loss changes little over a wide range of wave height ($0.25 < h/\ell < 0.8$). The effects of wind on the speed reductions were not apparent in the data except possibly for inconsistently high-velocity head winds at the lower wave height. For purposes of this study, $h/\ell = 0.8$ is taken as the highest value for which we can be reasonably sure that (calm water) power will be maintained by the hydrofoil operator. There are suggestions that control system variations and forward strut lengths among different hydrofoil ships affect the speed reduction at higher wave heights.

The effect of reduced speed on the effective lift-drag ratio for calm water, for "moderately rough" seas ($h/\ell = 0.4$) and for "rough" seas ($h/\ell = 0.8$) is shown in Fig. 10. Because reduced speed is equivalent to reduced Froude number, lines of constant power slope from upper right to lower left as indicated by the ends of the line segments. In fact, a 10% reduction in speed ($V/V_o = 0.9$ at $h/\ell = 0.8$) directly equates to a 10% reduction in Froude number. Because so few fully-submerged hydrofoils have been built and tested, particularly naval hydrofoils, the lines shown may not necessarily be straight and their slope should not be assigned any particular significance. These lines are meant to indicate the envelope of maximum values of $\eta L/D$ (corresponding to the maximum values of WV/P) but the data are so sparse that straight lines were used for convenience. These rough values of $\eta L/D$ will be used to derive approximate rough water range and endurance, but first we must consider the effect of ship size.

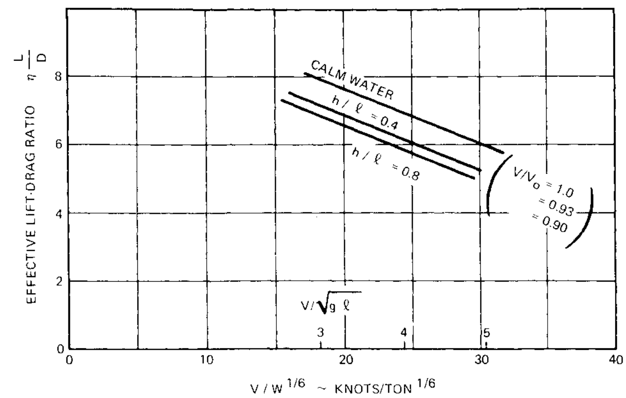

Fig. 10 Effective lift-drag ratio for rough water.

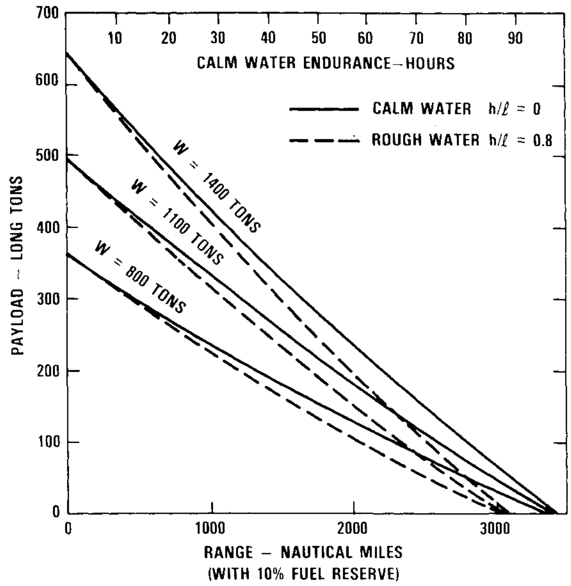

Fig. 11 Payload-range curves for large hydrofoils.

Payload and Range of Large Hydrofoils

Ship Size

It should be noted that the lack of seakeeping data for large fully-submerged hydrofoils (over 200 tons) places a premium on obtaining data from PLAINVIEW (320 tons) and the Patrol Hydrofoil Missile (PHM) ships (at 235 tons) now under construction. If the data already given here are universally applicable in that size dependence is correctly assigned by use of the characteristic length, then larger hydrofoils of approximately 1100 tons will be capable of operating in sea state 7. This is about as high a sea state for which one might conceivably want to design.

This high sea state implies large control power. Successful use of the PLAINVIEW hydraulic system is expected to establish a low-risk basis for a like system on either the Developmental Big Hydrofoil (DBH) or the Deepwater Escort Hydrofoil (DEH). Comprehensive control power studies[12] show that the hydraulic control system power now being installed in PLAINVIEW is sufficient for the DEH and would provide the required redundancy.

Hydrofoil struts designed for operation in sea state 7 would be larger than any struts built to date. However, strut lengths being considered for 1100-1400-ton hydrofoils are rapidly approaching the maximum needed for sea state 7. It seems both adequate and feasible for the DEH to operate through 95% of the waves met in the North Atlantic. As this maximum strut length is neared with large hydrofoils, the strut weight will not increase quite so rapidly with ship size and will yield more disposable weight than otherwise would obtain.

The most germane consequence of size is the larger disposable fraction of gross weight which accrues with increased hydrofoil size. Recent re-evaluations of hydrofoil weight fractions such as reported by Heller and Clark[13] show that disposable weight fractions of about 45% obtain at gross weights of DBH or DEH sizes (over 800 tons). This value of the weight fraction, which is considerably larger than earlier estimates, has very significant influence on the payload, range, and endurance of large hydrofoils, in conjunction with the improved rough water performance.

Range and Payload

Because hydrofoils are sea worthy, they require the freedom to conduct viable mission tasks without needing to refuel. To apply the values of reduced speed and effective lift-drag ratio to calculate rough water range and endurance, it is assumed that the percentage decreases in speed and effective lift-drag ratio are the same at maximum range speed as at maximum speed. This will not account for the effects of off-design operation which could occur even in calm water.

Currently available values of disposable weight fraction (45%) and calm water $\eta L/D$ for a propeller driven hydrofoil (10.1 at 35 knots) have been used with an assumed specific fuel consumption C of 0.5 lb/hp-hr to calculate payload-range curves (allowing 10% reserve fuel) for gross weights of 800, 1100, and 1400 tons. This value of specific fuel consumption applies for use of the LM 2500 gas turbine engine, which presumably would be selected for such sized hydrofoils. Then the same calculation was made for dimensionless wave heights of $h/\ell = 0.8$ using the range equation

$$R = (\eta L/CD)\ \ell n\,[W/W - W_F)$$

where R is the range and W_F is the fuel weight. These calm water and rough water payload-range curves are shown in Fig. 11 along with the calm water endurance (35 knots). Note that constant power implies constant specific fuel consumption. We find that the 10% rough water decrease in $\eta L/D$ results in a 10% decrease in range. Design studies[14] indicate that a ship of about 1370 tons can carry a 100-ton payload about 3600 nautical miles at 42 knots in calm water. In state 7 seas, it is estimated that the same ship could carry the same payload more than 3200 nautical miles at 38 knots. We know of no other ship that size which can perform as well.

Conclusion

Sustained speed and seakeeping in rough water were achieved several years ago; it remains to complement that performance with the long range of large hydrofoils to take advantage of their open-ocean capabilities.

References

[1] Oakley, O.H., "Hydrofoils – A State of the Art Summary," *Proceedings of the National Meeting on Hydrofoils and Air Cushion Vehicles,* I.A.S., Sept. 1962.

[2] Lacey, E.R., "A Progress Report on Hydrofoil Ships," *Transactions of the Institution of Naval Architects,* Vol. 107, Jan. 1965, pp. 83-104.

[3] Ellsworth, W.M., "U.S. Navy Hydrofoil Craft," *Journal of Hydronautics,* Vol. 1, Oct. 1967, pp. 66-73.

[4] Silverleaf, A. and Cook, F.R.G., "A Comparison of Some Features of High Speed Marine Craft," *Transactions of the Institution of Naval Architects,* Vol. 112, Jan. 1970, pp. 69-86.

[5] Acosta, A.J., "Hydrofoils and Hydrofoil Craft," *Annual Review of Fluid Mechanics,* Vol. 5, 1973, pp. 161-184.

[6] *Oceanographic Atlas of the Atlantic Ocean, Section IV, Sea and Swell,* Pub. No. 700, 1963, U.S. Naval Oceanographic Office, Washington, D.C.

[7] Nutting, W.W., "The HD-4," A 70-Miler with Remarkable Possibilities Developed at Dr. Graham Bell's Laboratories on the Bras d'Or Lakes," *Motor Boat,* Vol. XVI, No. 20, Oct. 1919, pp. 205-210.

[8] Ellsworth, W. M., "Hydrofoil Development—Issues and Answers," AIAA Paper 74-306, San Diego, Calif., 1974.

[9] "Jane's Surface Skimmers, Hovercraft and Hydrofoils," 5th ed., edited by R. McLeavy, p. 19, 1972-1973.

[10] Schmitke, R. T. and Jones, E. A., "Hydrodynamics and Simulation in the Canadian Hydrofoil Program," presented at the Office of Naval Research, 9th Symposium on Naval Hydrodynamics, 1972.

[11] Chey, Y., "Motions and Accelerations of AGEH when Hove-To in Extreme Sea States," Davidson Lab., Stevens Institute of Technology, Rept. 977, Aug. 1963, Hoboken, N.J.

[12] Remington, P.J. and Bender, E.K., "Hydrofoil Design for Minimum Control Power," Rept. 2511, Feb. 1973, Bolt Beranek and Newman, Cambridge, Mass.

[13] Heller, S. R., Jr. and Clark, D. J., "The Outlook for Lighter Structures in High Performance Marine Vehicles," AIAA Paper 74-330, San Diego, Calif. 1974.

[14] Aroner, R. and Hubbard, R.M., "DEH, A High Endurance Escort Hydrofoil for the Fleet," AIAA Paper 74-311, San Diego, Calif, 1974.