Rough-Water Performance of the HS Denison

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The HS Denison is the first large hydrofoil seacraft to have been built and operated in the United States. This paper briefly describes the design, principles of operation, and performance of the Denison. The effort described represents one of the most complete hydrofoil evaluation programs conducted in this country to date. The craft has accumulated approximately 250 hr of foilborne operation, corresponding to approximately 12,000 foilborne miles. Operations were conducted in seas ranging to 9 ft in amplitude over a substantial portion of the U. S. Atlantic coast line, thereby providing performance in widely varying waters. The ability to operate in higher-amplitude seas is a result of the utilization of automatic control.

Introduction

In 1955 the U. S. Maritime Administration, because of the efforts of the late Charles R. Denison (after whom the Denison was named), developed an active interest in the problem of open-sea hydrofoil travel and its potential as a means of commercial transportation. Compelled by this interest, the Administration decided to provide an actual test of the idea through direct utilization of a large seagoing hydrofoil ship (Fig. 1). In this paper the results of Grumman's government-awarded contract for test and evaluation are discussed.

The Denison design and construction phase was initiated in 1960 and terminated with launch of the craft on June 5, 1962. Since the launch date, she has undergone an extensive technical and evaluation program in a widely varied spectrum of sea conditions. The vessel has operated in waters from Maine to Florida and in waves ranging in some instances to 9 ft. The Denison is the first large seagoing hydrofoil craft in the United States to have undergone extensive testing in variable waters over significant distances, and much first-hand experience has been gained. The vessel and some of its operational considerations are described, and particular attention is given to the relationship between craft and sea state. In this context some of the test results are discussed.

I. Craft Description

Hull

The HS Denison is a strong lightweight structure. Its layout provides practical accessibility to all areas, and its flexible interior arrangements readily accommodate the requirements of research tasks (see Fig. 2). The bow incorporates a deep chine, high dead rise, and a full bow flare to generate an efficient wave-cutting shape. The dead rise is carried from stem to stern and is nowhere less than 30°. The full flare aids in reducing spray which restricts vision. A passenger area capable of accommodating 12 passengers is located forward on the lower deck. Acoustically, the environment is quiet, being superior to the best of commercial jet aircraft. Only one compartment has been outfitted for passenger operation, the remainder being unaltered. This permits demonstration of the commercial operational potential of the vessel while at the same time preserving its research capabilities.

Powerplants and Propulsion

The foilborne powerplant is a General Electric LM-1500 gas turbine rated at 14,000 shp continuous on an 80° day. The unit is comprised of a YJ 79-2 gas generator freely coupled to a power turbine designed specifically for the application. The turbine drives a shaft terminating in a single idler reduction box with a step-down gear ratio of 1.533:1. From the idler box shafting is carried through the after-deck shaft tunnel to the bevel gear box at the top of the stern strut. Split shafting is carried from the upper-bevel gear box to a lower-bevel gear box located in the pod. Torque is then transmitted through the pod to the supercavitating propeller. The maximum propeller speed is 3950 rpm.

The hullborne powerplant is a GE T-58 gas turbine that drives twin jet pumps through a mechanical transmission. The jets are three-stage axial flow pumps located on the bottom of the after-hull. The jet thrust vectors are controlled by movable gates providing directional control ahead and astern.

Foil System

The HS Denison foil system consists of two surface-piercing foils located ahead of the center of gravity and an all-movable submerged foil aft (see Fig. 3). The two surface piercing foils are termed main foils. The main foils consist of three lifting elements plus the strut. The lower element is termed the lower foot; the middle element, the dihedral element; and the upper element, the diagonal. The

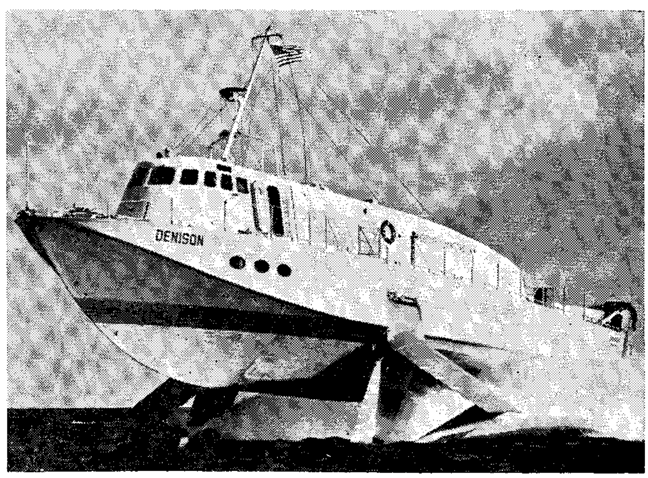

Fig. 1. HS Denison.

Presented as Preprint 64-197 at the AIAA General Aviation Aircraft Design and Operations Meeting, Wichita, Kansas, May 25–27, 1964; revision received August 14, 1964. The craft described herein was designed and built by the Grumman Corporation for the Maritime Administration of the U. S. Department of Commerce. Operation has been conducted under Contract No. MA-2619, "Contract for operational testing and evaluation of hydrofoil seacraft HS Denison."

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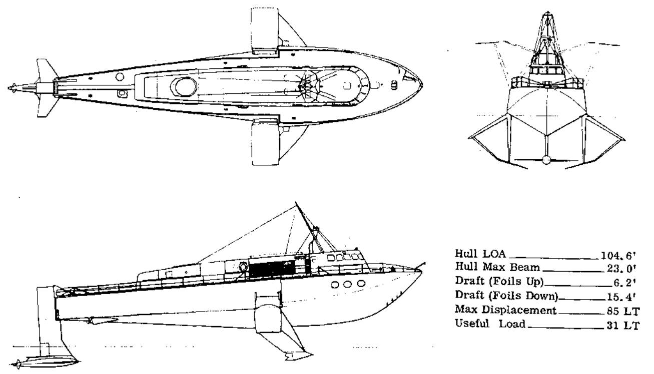

Fig. 2 Dimensions and displacements.

portion of the diagonal which overlaps the dihedral element is termed the diagonal tip. All foils are retractable. The main foils retract through a 160° arc. The stern strut raises 87° from its extended position to full retraction. One advantage of the retraction feature is that the craft may gain access to docking facilities and execute docking procedures with little difficulty. In operations to date, only a small float has been required for dockside handling. The retraction feature also provides a major saving in maintenance by preventing prolonged exposure to scum-forming organic matter and corrosive elements of salt water.

Control Systems

Denison foilborne controls may be divided into two categories: steering controls, and controls for maintaining foilborne operations.

Steering system: The Denison utilizes a split rudder system. Operation may be typified by a port turn in which the port flap deflects while the starboard stays at neutral, and vice versa.

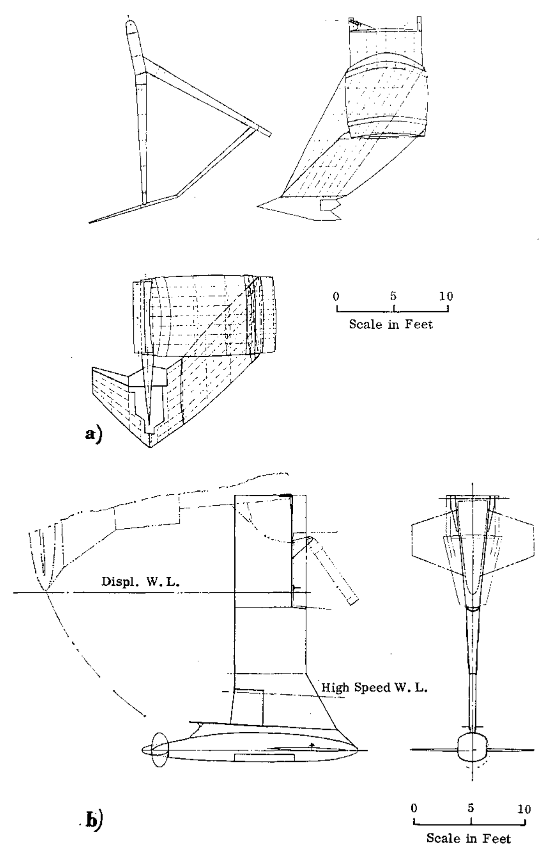

Fig. 3 a) Forward foil and strut assembly; b) tail hydrofoil and strut assembly.

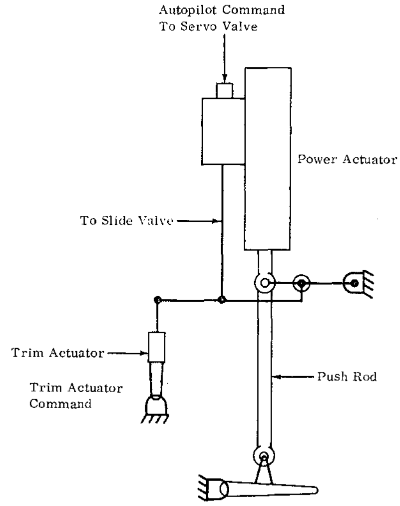

Fig. 4 Foil controls.

Foilborne control system: Foilborne control of attitudes and dynamics is obtained by flaps on the main foils and incidence control of the aft foil (see Fig. 4). The controls are similar on all three foils so that the operation of one foil is considered. A power actuator supplies the muscle to a push rod, causing the control surface to move. Commands to the actuator may be delivered either through the servovalve from the Hamilton Standard autopilot or through the trim actuator to the slide valve. The latter supplies backup control in the event of autopilot failure.

II. Operational Considerations

The Vessel

The HS Denison is a system comprised of a set of lifting surfaces (foils), a c.g., and respective moment arms, mass, and moments of inertia. As such, it is similar to its aircraft counterpart. It is, for example, stable in pitch if the response to a disturbance is in opposition to the disturbance. The Denison for any trim condition at foilborne speed is stable on all axes in translation and rotation. Unaugmented by control, it is inherently stable and capable of operation in a seaway without additional control.

Foils

The design of the foil system is responsible for the vessel's inherent operating capabilities. Area stabilization is a fundamental feature of this system, which may be briefly explained as follows. Assume that the hydrofoil craft is at trim equilibrium. It is then characterized by a specific pitch, altitude, and resulting foil-wetted area. A single wave is encountered. As the forward foils enter the wave, their immersion becomes greater, and the wetted area is increased over its smooth-water value. An excess lifting force is generated and the craft is accelerated upward. On coming through the backside of the wave, the reverse procedure is commenced, a net downward acceleration results, the craft drops back down, and returns to its original trim. If the craft is caused to enter a wave train, the dynamic process is now clear, and one can see how the vessel is able to maintain its foilborne operation without the aid of control. Furthermore, it is clear that the vessel is self-regulating in altitude, pitch, and roll.

Normal flying altitude, measured from the water surface to the keel, ranges from 4 to 5 ft. Flying altitude is controllable from the pilothouse.

The main foils have been designed to provide maximum sea-state capabilities (see Fig. 3a). It will be recalled that the foil is a three-element foil consisting of a lower foot, a dihedral element, and an upper diagonal. The lower foot is usually immersed and is the basic lifting element. The dihedral element provides the basic area stabilization in heave and in roll. The upper diagonal is a high lift section that aids in keeping the hull clear of waves and is primarily responsible for maintaining foilborne operation when exceptionally large, steep waves are encountered. The upper diagonal also provides the high lift coefficient that is required at takeoff.

There is one additional important feature. In short-crested, high-amplitude seas, it is not uncommon to broach the forward foils to the extent that both foils come clear of the water. In such circumstances it is essential that lift recovery be rapid if the craft is to remain foilborne. The ability of these foils to recover their lift has been dramatically proven in several instances when the forward foils have come clear of the water; the craft has recovered and remained foilborne.

Sea State and Control

The Denison utilizes automatic control to extend its sea-keeping ability. The control-system design requirements are dictated by the nature of the sea surface. The sea and its relation to control are now considered from two points of view: one relating to the individual wave, the other to the problem of the over-all sea.

There are two basic mathematical models that describe the mechanics of a surface wave.[1,2] The first is the irrotational model of Stokes, Rayleigh, and others. The second is the Gerstner wave, which is rotational. The Rayleigh-Stokes model forms the basis of the characteristics of the Gaussian sea† and is applicable to the statistical descriptions of the sea. The Gerstner wave aptly describes the wave orbital motions and focuses attention on the dynamic problem of the hydrofoil vessel.

The Individual Wave

The Gerstner wave (see Fig. 5a) is a two-dimensional rotational wave in which the net spatial displacement of a water particle over one cycle is zero. Assume that the wave crest velocity (or celerity) is to the left as shown. Then the particles define orbital trajectories such that all particles in the same vertical plane have the same time phase, the same vector direction, and a magnitude proportional to exp $(-2\pi\xi/\lambda)$ where λ is the wavelength and ξ is the depth with respect to the mean free surface. All orbits horizontally displaced have different phases. If a point of observation is selected on the front side of the wave, it will be seen that the vertical orbital velocity components are upward and spatially lead the wave profile by 90°. The horizontal orbital velocities are in phase with the wave profile, and are in the direction of the wave at the crest while they oppose the wave direction in the trough. The wave celerity is proportional to the square root of the wavelength, whereas the orbital velocity is proportional to the wave amplitude for a given wavelength and depth, being a maximum at the surface.

Clearly these matters affect seaway performance. The orbital velocities appear to the foil system as wave-induced increments in sensed angle of attack. Thus, on the front side of a wave there is a positive increment tending to lift the vessel out of the water, whereas on the following side the net angle of attack change is negative. The major problem confronting all hydrofoil craft may be attributed to the presence of these wave-induced angle-of-attack changes. For example, a craft flying into a head seaway does so with facility, whereas a craft negotiating a following sea does so with some difficulty. The reasons are evident (see Fig. 5b). A craft approaching a wave head-on first senses a positive angle of attack change due to the positive vertical orbital components. The tail foil senses either a negative component or a lesser positive component. The effect is twofold. The vessel is lifted upward over the wave and simultaneously experiences a bow-upward pitching moment. If the pattern is traced through, it will be seen that a head sea aids the flight of the craft. In this sense, head-sea control requirements are limited, and it will be found that until the waves become of too great proportion, stable fixed-foil craft will have little difficulty in negotiating head seas.

† Gaussian sea means that, for the period of observation, the sea may be considered to be a stationary random process.

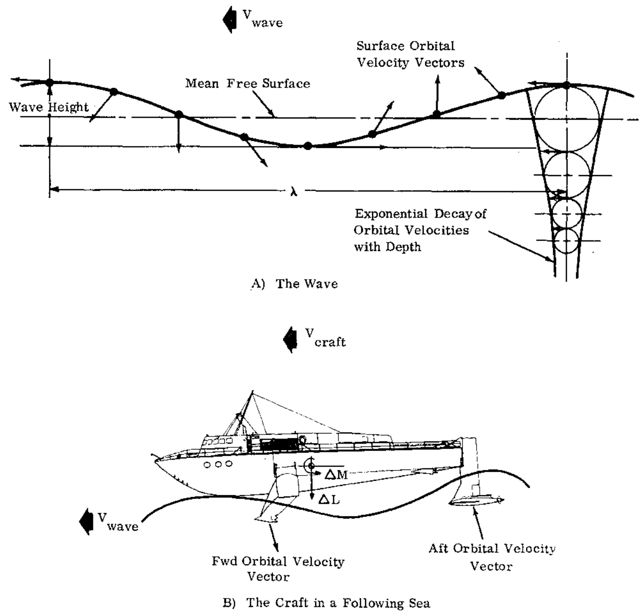

Fig. 5 Relationship between craft and wave.

In a following sea, everything is reversed. A craft approaching the backside of the wave encounters first a downward orbital component that tends to pull it into the water. Second, since the stern foil senses either a positive orbital angle or a lesser negative one, a bow-down moment is developed which would try to pitch the craft into the water. This adverse dynamic pattern persists throughout the wave, rendering following-sea operation more difficult than head-sea operation. This problem generates the need for automatic control in surface piercing craft.

Wavelength is an important parameter because it affects wave celerity and relative frequency of wave encounter, offering in combination with wave amplitude a geometrical contouring constraint. Celerity and frequency of wave encounter are closely related. A long wave is a fast wave; e.g., a 1000-ft wave would travel at approximately 42 knots. Thus if a hydrofoil craft were traveling at 50 knots, the following-sea frequency of wave encounter would be 0.013 cps. This would mean that the craft would experience a protracted period of downward orbital velocity on the backside of the wave. On the other hand, the shorter the wave, the easier it is to scale the following sea.

Wave amplitude has a direct bearing on orbital velocity and hence on induced angle-of-attack change. The larger the wave, the greater the orbital angle at a given speed. From the control viewpoint, the most significant downward lift increments are found in large-amplitude, long-wavelength following seas.

The next problem is kinematic. If a wave is of high amplitude, the limiting constraints become the hull, foil, and strut geometry. This establishes the need to contour. Contouring can only be executed to the point at which the

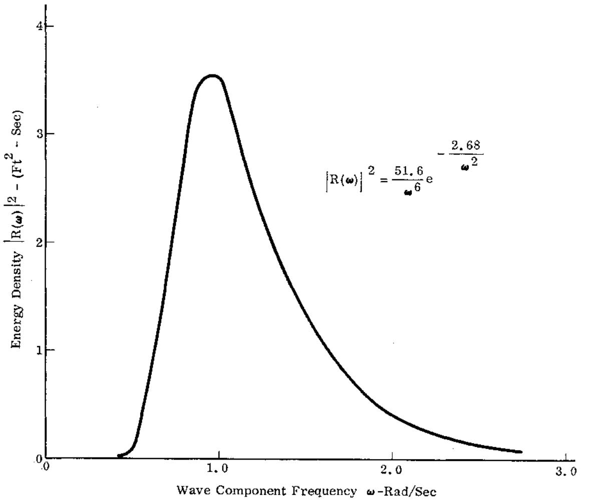

Fig. 6 Pierson-Neumann energy spectrum for a sea generated by a 16-knot wind (upper bound of sea-state 3).

craft geometry and high-amplitude short-crestedness of some seas conspire to make contouring pointless. At this juncture the craft knifes through the crest, and, providing sufficient horsepower is available, remains foilborne. One additional contingency generated by short-crested waves is the piercing of wave backsides, or broaching. This requires recovery and remaining foilborne.

The Over-All Sea

A sea state is generated by the interaction of the water with air at their boundary interface through the mechanism of viscous friction. A water surface will remain smooth up to a wind velocity of $\frac{3}{4}$ to 1 knot, at which point surface instability induces the generation of wavelets called capillary waves. Once the wave action is initiated, wave growth is perpetuated by the development of high pressure on the windward or backside of the wave, and low pressure due to air eddies and turbulence on the downwind or front side. Thus a pressure gradient is established across the wave which serves to increase and maintain the wave velocity and simultaneously causes the waves to rise. When the wind speed becomes sufficiently high, the wave departs from the trochoidal form as a result of the cropping of the crest. The wave becomes long on the backside and short on the front. This is a limiting process originating from the fact that the velocity gradient between wind and water becomes sufficiently high that the viscous shear forces overcome the gravitational constraints resulting in the cresting of the wave. Another effect is the shortening of the crests in a high wind. In the limit, a sea will rise until the energy of the sea state equals the energy delivered by the wind. The relationship is not simple, since the energy that the air is capable of delivering is somewhat modified by the turbulence existing in the wave depressions and since there is a fair amount of local interaction between sea and air.

Considering a rising wind, it is evident that many waves are generated randomly and simultaneously. Each of these waves must travel and decay. The net effect is that these randomly directed and phased waves cross each other, run into each other, catch up with each other, etc. Therefore, some waves tend to mutually cancel, whereas others add to make longer waves. Since the waves are traveling randomly, the sea-state pattern is constantly shifting. Thus a random pattern exists on the surface, the energy and characteristic amplitudes of which depend on the wind. For a given wind and fetch, a sea state will come to corresponding equilibrium. Where this state of affairs is achieved, the seaway may be characterized as a stationary random process normally described by the Pierson-Neumann spectrum (see Fig. 6). When a wind is freshening the sea is in a state of flux, and the process is not stationary. In this case, the changing spectrum tends to start at the high-frequency end, and it spreads toward the low frequencies until, when fully developed, the entire spectrum is present in the sea. This is because rising sea waves are primarily friction waves, by nature short and steep.

On the other hand, when the wind drops, the reverse takes place. The high end of the spectrum is deleted until those frequencies that contain most of the sea-state energy remain. This is, of course, the swell. Two statements may now be made. A fully developed sea contains a chop and a swell. A sea in development contains chop, but its swell exists to a lesser extent. The chop is characterized by the high-frequency end of the spectrum and the swell by the low-frequency end. The chop is a friction type of wave, and when the wind lets up, subsides very rapidly due to viscous damping. The swell once developed is a gravity type of wave with very low damping and therefore persists for a long time, traveling a long distance. This leads to two significant observations. First, a swell present in a storm will travel from one storm area to another and in its course will superpose itself on other waves to produce high-crested waves. Secondly, the swell will travel long distances from the storm area, resulting in the peripheral and more distant ground swell. These waves may travel thousands of miles. When a storm subsides, the chop rapidly subsides, leaving the swell. These swells tend to phase themselves with other swells to produce either reduced crests or augmented crests. The wave crests become longer, and as the waves radiate from the cyclonic area, become more characteristic of regular wave trains. These are the so-called regular seas.

One other property should be noted, i.e., the directional property. The energy of a short-crested sea tends to be widely dispersed in direction, whereas the swell tends to be quite directional. Thus, where traveling in an active sea, waves would appear to come from many directions, whereas in a swell the direction of propagation is more readily discernible. For example,[1] wave directions in a developed sea can range as much as $\pm 65°$ with respect to the wind vectors, whereas that of a swell may be in the order of $\pm 8°$. The picture becomes somewhat disturbed in a restricted cyclonic disturbance where the wind is constantly shifting. It should be pointed out that seldom does a hydrofoil operating in 30–35-knot wind fly in a fully developed sea, since a sustained period of 23–33 hr is required for the sea to reach equilibrium. Such a sea might result from a mild two-day northeaster over a 280–450-mile fetch.

The HS Denison has operated in somewhat restricted coastal waters, and due to lack of fetch and generally rapidly changing wind conditions has not normally encountered a fully developed sea.

It is now clear that sea state imposes the following hydrofoil design requirements: 1) the craft must be capable of operating in a chop; 2) the craft must be capable of operating in a swell; 3) the vehicle should recover after broaching; 4) it should be capable of knifing through an extreme short-crested high amplitude; 5) it should be able to compensate orbital effects adequately; 6) it should be capable of contouring swells; and 7) through the operating range the personnel's dynamic environment should be tolerable.

Control System

A hydrofoil craft operating with foils fixed will have its trim attitudes changed whenever its weight and center of gravity change. Such circumstances may arise when cargoes vary or when fuel is consumed. Furthermore, it was seen in the discussion of sea states that the condition of the water surface and the heading of the craft with respect to the prevailing wind will limit fixed-foil operation. To alleviate these problems, the Denison has been equipped with a control system (see Fig. 7). Two modes of control, trim and automatic feedback control, handle, respectively, the attitude command problem and the sea-state requirements outlined previously in items 1–7.

Trims

Variable craft trims are obtained by means of flaps on the forward foils and incidence controlling the aft foil. For any desired angle settings of these control surfaces the craft will seek that pitch angle and depth for which angle of attack and resulting immersed forward foil area render the summation of forces and moments zero. Trim equilibrium is obtained in this manner. The advantage of the foil-trim capability is that the pilot may set a desired pitch, altitude, or roll at any speed, weight, and weight distribution within his operating range. This means, furthermore, that in a seaway, craft pitch angle and altitude may be adjusted to facilitate negotiating the waves. These trim commands originate at the pilot control panel.

In general, the automatic portion consists of transducers for sensing craft motions and a simple computer for transmitting commands to the electrohydraulic actuators. The transducers sense the craft motions and send their information to the computer. The computer processes the information and sums it with the trim commands. The net signal is issued to the actuator. The following dynamic signals are utilized: heave rate is fed symmetrically to the forward flaps; roll and roll rate are fed differentially to the forward flaps; and pitch rate is fed to the stern foil.

The longitudinal motions are extremely important from the seakeeping standpoint. Both the pitch and heave channels are rate channels. Thus the magnitude of their signal outputs depends on frequency of wave encounter and on forcing function-input amplitude, i.e., sea-state amplitude. This means that at high frequencies of wave encounter, control inputs are large and effectively attenuate the wave inputs. Furthermore, the craft's mass, hydrodynamic mass, velocity, and viscous damping will cause the craft to act as a mechanical filter, thereby supplementing the control system. Thus the high-frequency compensating characteristics of the control system, coupled with the craft mechanical-filter characteristics, make an important contribution toward reducing the acceleration level in a chop at high frequencies of wave encounter. On the other hand, when the frequencies of wave encounter drop off for a given amplitude, the acceleration level drops and orbital velocity decreases. The upshot of this is that as frequencies drop off the craft contours. This is a very desirable characteristic, because in heavy seas, where the craft geometrical constraints come into play, contouring is essential. The system therefore contributes to flight in two vital areas. It should be pointed out that the situation is not so clear cut as this. For example, orbital angle is proportional to frequency of wave encounter, wave amplitude, and wave length, the point being that system performance is trended to provide appropriate compensation as the situation requires it.

III. Performance

The performance of the vessel is now considered. It will be discussed in three phases: hullborne operation; foilborne speed, range, and maneuverability; and foilborne dynamics.

Hullborne Operations in a Seaway

Hullborne operation has been demonstrated in severe, steep seas where foilborne operation has been precluded. In encountering sharp successive wave contours, bow-up moments resulting from the bow geometry provide a strong override to the after-hull generated bow-down moments. As a result, the bow exhibits no tendency to get buried in extreme waves. In addition to shape, the light hull weight, low foils-down center of gravity, and the strong foil rotational-velocity damping render the hullborne craft a highly stable and buoyant platform in a rough sea. Experience has confirmed this in short seas ranging to 12 ft in amplitude.

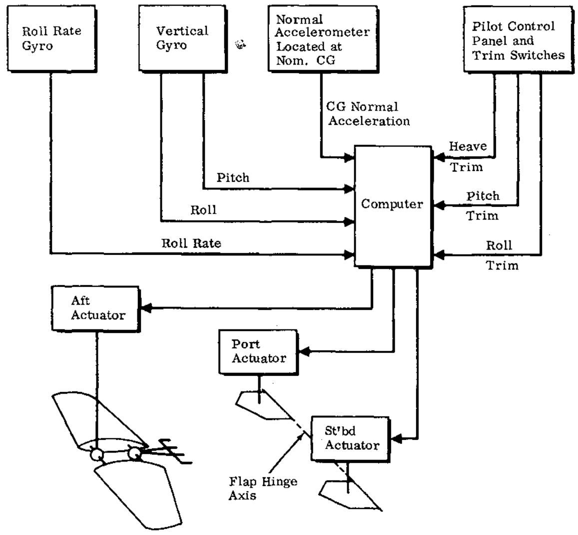

Fig. 7 Control system schematic.

Foilborne Speed, Range, and Maneuverability

The design maximum speed of the Denison in calm water is 60 knots. This maximum has been exceeded. Cruise speed is between 50 and 55 knots, normally being 53 knots. This speed may be maintained in seas ranging from 3 to 4 ft in amplitude with no appreciable increase in power. After this, an increased throttle setting is required to maintain speed.

The present foilborne range for an 80-ton craft traveling at 50 knots in relatively calm water is 450 naut miles. This reduces to 390 naut miles at 60 knots. This assumes a 5% fuel reserve. Wave-impact drag becomes significant in the higher sea states, and, because of the required increase in specific fuel consumption to overcome the additional drag, both speed and range fall. The specific relationships between sea state and range are not now known. It is only clear that sea state imposes a reduction of range.

One of the appealing aspects of the Denison is its turning performance in a variety of seaways. Its maneuverability is superior to its ship counterparts, particularly regarding the speeds at which tight turns may be executed. Again, increasing sea state imposes some degradation on turning radius so that maximum foilborne maneuverability is attained in calm water. Figure 8 provides an envelope of turning radius as a function of rudder deflection over a full range of seas in which the Denison has successfully operated. The operating speeds varied from 47–53 knots so that the envelope is charac-

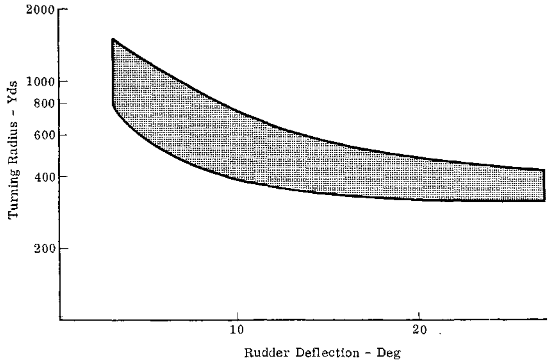

Fig. 8 HS Denison turning capability at speeds varying from 47–53 knots.

teristic of cruise. It is noteworthy that banking the vessel in a turn decreases the turning radius. The maximum amount of bank in calm water is greater than that which may be used in a substantial seaway.

Foilborne Dynamics

To demonstrate the stable nature of the craft, a transient response to a 1-ma pulse to the stern actuator servovalve is shown in Fig. 9. This is compared with the predicted transient. The actual craft tends to be somewhat less oscillatory than the theory would tend to indicate. The craft uncontrolled resonant frequency occurs at about $\frac{1}{10}$ cps. The transient response with automatic control was much tighter for the same craft operating conditions and of much lower amplitude.

The Denison will sustain foilborne operation in most head seas up to 6-ft waves. Where a following sea must be negotiated, short 4-ft waves are no problem. Operation becomes marginal in 4-ft waves of length in excess of 100 ft. In our experience, utilization of automatic control channels becomes essential in following seas exceeding 4 ft. Following-sea operation then becomes comparable to head-sea operation.

An estimate of HS Denison operating boundaries is shown in Fig. 10. This curve should be considered an estimate of maximum constraint in which craft seakeeping ability is not expected to exceed the boundary. Maximum negotiable amplitude is plotted as a function of wavelength. The curve is valid for all headings irrespective of speed. The curve may be divided into four areas of influence.

Area 1: 0 × 0 ft to 4 × 24 ft

The greater height-to-length ratio for waves is about 1:6. Steeper waves are not hydrodynamically possible. Within the confines of 4-ft, short waves, the vessel is capable of handling all seas.

Area 2: 4 × 24 ft to 7 × 90 ft

Within this area craft frequency response is the governing factor. Thus, response amplitude and phase relative to input limit the ability of the craft for handling greater amplitude waves.

Area 3: 7 × 90 ft to 8 × 200 ft

Here the foil spacing, keel clearance, and foil immersion relative to wave dimensions conspire to cast geometric constraints on operating capability.

Area 4: 8 × 200 ft and up

As the waves become larger, wave-induced orbital angle becomes a restraining factor. Recall that as the wave becomes longer, its celerity increases with the square root of its length. There exists a limit in following seas for which the smooth water angle of attack is reduced by the wave-generated orbital angle, such that the produced lift is inadequate for supporting the weight of the craft. In addition, the longer waves travel rapidly, resulting in low following-sea frequencies of wave encounter and long persistance of the adverse orbital angle. Thus, the final constraint of the curve results.

The line drawn at 150-ft wavelength characterizes the longer waves that the Denison has handled. The absence of experience in longer waves is a result of the areas of operation and the weather. Operation has been confined primarily to state-III seas or less. On those occasions where limited operations have been achieved in 30–35 knot breezes, the wind has been fresh, and the water shoal and the high-amplitude waves have been very steep. In such circumstances 7-ft waves have been handled successfully. A 100- to 150-ft ground swell was negotiated on one occasion. This swell resulted from the previous passage of a summer storm in the vicinity of Newport, R. I. This was a low-amplitude swell running 3–5 ft.

In a heavy seaway, substantial incremental lifts result from the variation of main foil immersion. As expected, these forces result in significant accelerations, which are greater in a head sea than in a following sea.

Acceleration curves based on accumulated data for all seas and all headings are shown in Fig. 11. Predicted vertical accelerations in 5-ft seas were in the order of 0.3 g. Test experience shows the mean value to be somewhat less. This originates from the dynamic studies having been based on a sine wave analysis, thereby concentrating the energy at one frequency. Since the sea-state energy spectra define waves of all frequencies and amplitudes, it follows that the driving energy per encountered wave will generally be somewhat lower. Thus over a finite record the rms value of acceleration will be somewhat lower.

There is a decrease in speed associated with the additional drag developed in heavy seas. This is reflected in the longitudinal acceleration increase with increased wave amplitude. It has been found that holding a steady throttle corresponding to 50 knots in calm water results in a speed reduction in the order of 5 knots in a 5-ft seaway and 7–8 knots in heavier seas.

Lateral accelerations are in the same order of magnitude as the normal accelerations. This is due to the large lateral lifting surface. It will be remembered that horizontal orbital velocity components are of the same order of magnitude as the vertical, at a given depth. The horizontal orbital velocities act regardless of the heading of the vessel, owing to the three-dimensional character of the seaway. Lateral lifting areas are approximately the same as the vertical areas, and moments of inertia are similar. Everything being equal, it is not surprising that the lateral accelerations should be similar to the normal accelerations. Because of the directional nature of energy propagation in a seaway, the omnidirectional horizontal orbital velocity effects combine with the adverse vertical orbital velocity components to make following-sea lateral responses large.

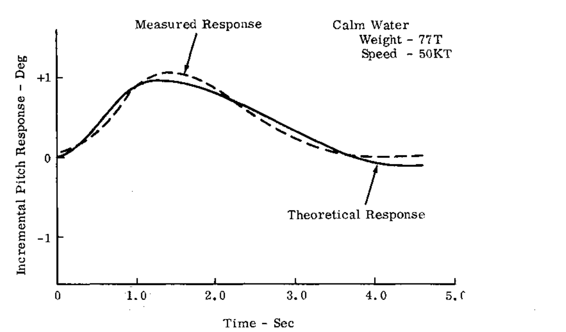

Fig. 9 Comparison of predicted and measured pitch response to 1 ma-0.85 sec pulse to stern foil servovalve HS Denison.

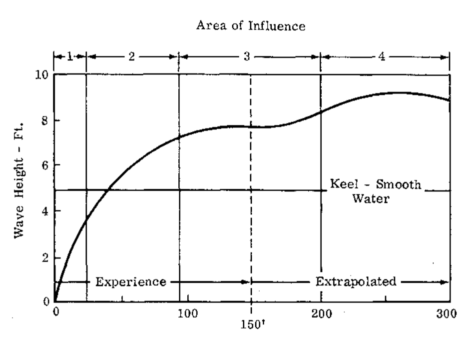

Fig. 10 Sea-state operating boundaries.

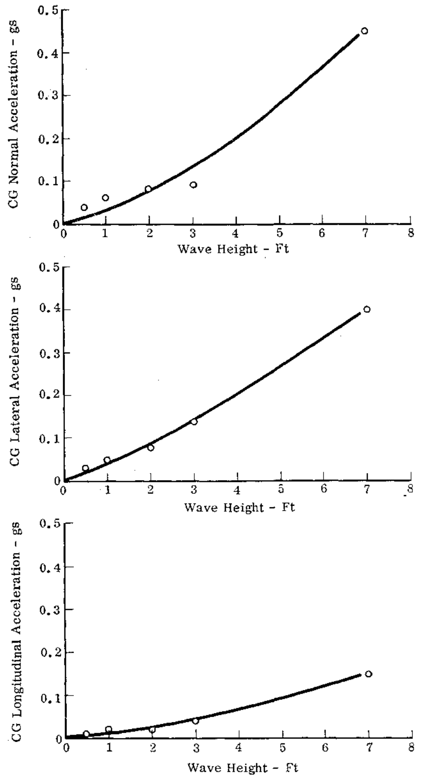

Fig. 11 HS Denison response in seaway 45–50 knots average speed.

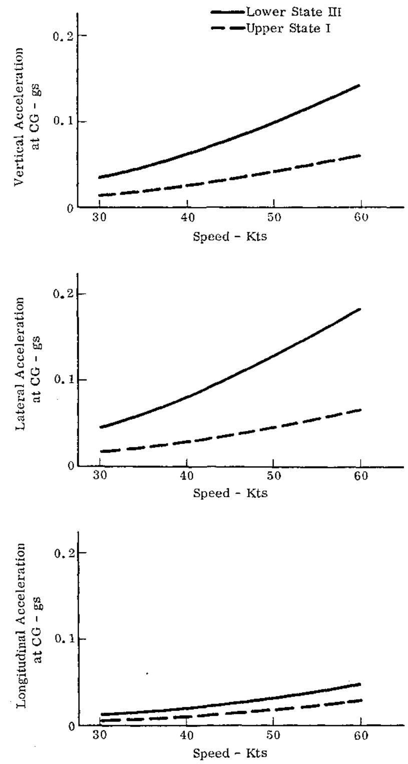

Fig. 12 Variation of accelerations with speed for sea ranging from upper state I to lower state III.

The final consideration is speed, which might be expected to have a bearing on response. The effect of speed is demonstrated in Fig. 12, in which data for various known sea states have been correlated by means of a least squares approximation. The two curves shown in each figure actually define an acceleration environment envelope ranging from an upper sea-state I to a lower sea-state III. This corresponds to generating winds ranging from 7–16 knots and average $\frac{1}{10}$ highest waves from 0.4 to 5.8 ft. As can be seen, a square law relationship is involved. Curves are based on points taken between 40–58 knots.

Conclusions

The results discussed in this paper represent the culmination of the three-phase development program which involved the engineering design, construction, and evaluation of a fully operating, manned, scale model, and the construction and evaluation of the full-scale prototype. It is felt that the model phase was worthy and significant, for it confirmed the design at scale speed and solved some important control problems at great cost saving. As a result, the vessel took off and achieved 59 knots on its first attempt and was able to exceed its rough-water design objective of sustained oilborne operation in 5-ft seas.

The entire sequence has proved to be sound and has led to a confirmation of design procedures. The extended operation of the Denison has provided much background concerning the problems peculiar to large hydrofoil craft. Considering the capabilities developed and the experience gained, effective future designs may be guaranteed.

References

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