Marine Systems Supplement

Operational and Developmental Experience on the U.S. Navy Hydrofoil "High Point"

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Developmental trials on the U.S. Navy's first hydrofoil ship have determined operational capabilities and evaluated a number of problem areas. Takeoff speed is 27 knots at a gross weight of 262,000 lb. At a cruise speed of 40 knots, 4400 hp are required with propellers turning at 1270 rpm. Accelerations in Sea State 4 of 0.35 *g* rms, while hullborne at 8 knots, are to be compared with 0.07 *g* rms while foilborne at full power speed. Ventilation of the forward foil and hull furrowing occurred 2 to 3 times/min in the occasionally larger short-crested waves, thus indicating a need to lengthen the forward strut to give the craft increased capability in the higher seas. A turning radius of 3000 ft was reduced to 1100 ft by increasing the size of the spade rudder. An unstable cavity at the forward foil-strut juncture, causing a roughness in the ride at high speeds, will be corrected with a fillet pod around this juncture. The original neoprene coating on the foils and struts failed below the waterline because of adhesion difficulties. Salt water leaking into the transmission oil sumps was the principle reason for frequent drydockings, thus limiting foilborne operation to approximately 2200 miles, to date.

Introduction

CONSTRUCTION of the PC(H)-1, named "High Point," was begun in January 1961, under a Navy contract awarded to The Boeing Company in June 1960. General design of the craft was specified by the Bureau of Ships under a set of contract guidance plans, with responsibility for detail design being assigned to Boeing.

During the builder's trials, a number of areas requiring improvement became evident. Failure of the neoprene coating on the foils and struts, cavitation damage to the aft propellers, and inconsistent turning capability at high speed were the more notable of these early developmental problems.

The ship was accepted by the Navy in August 1963 and based at the Puget Sound Naval Shipyard at Bremerton, Washington. After initial training runs were made with the Navy crew, the craft was drydocked, at which time Stellite (a hard, brittle, nonferrous material) overlays were fastened to the struts and foils in the tip wake area of the forward propellers. This work was done from October through December 1963.

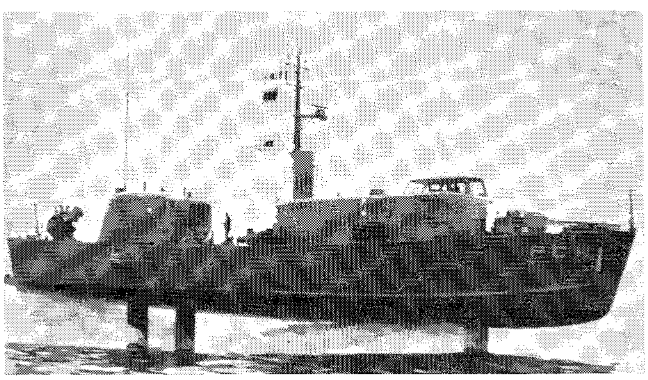

Fig. 1 PC(H)-1, foilborne.

Received March 22, 1965; also presented as Preprint 65-244 at the AIAA/USN Marine Systems & ASW Conference, San Diego, Calif., March 8–10, 1965.

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Subsequent tests made in January 1964 in inclement weather, revealed additional problems. Among these were height sensor difficulties in head winds, control porpoising, poor capability to turn into the wind, failure of the Stellite overlay attachments, and corrosion with resultant leaks in strut plumbing.

Although the height sensor and porpoising difficulties were corrected by late March 1964, it became evident that an extended period of developmental trials should be performed. With Boeing providing engineering assistance, the Puget Sound Naval Shipyard providing industrial support and a Navy crew operating the ship; a determination and evaluation of design problems are being made. Follow-up work, in progress, is emphasizing correction of these problem areas.

Craft Description

A picture of the craft while foilborne is shown in Fig. 1. The general arrangement of the craft is shown in Fig. 2 along with other dimensional data. Hullborne propulsion is

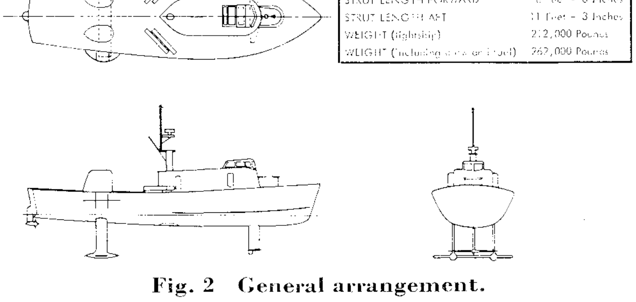

Fig. 2 General arrangement.

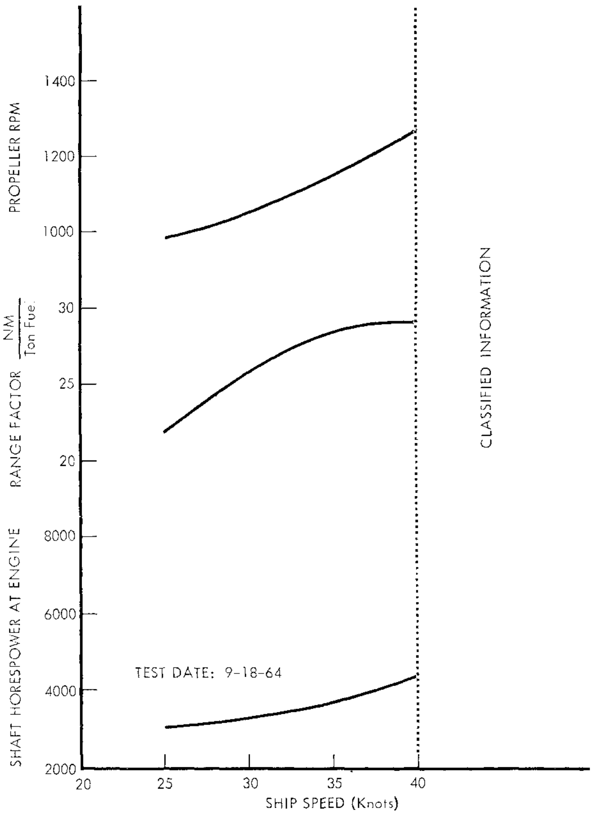

Fig. 3 Speed and power summary.

provided by a single Packard diesel, Model ID-700, rated at 600 shp. The unit is coupled to a 43-in.-diam propeller through a retractable outdrive unit that can be rotated 360°. Foilborne propulsion is provided by two Proteus turbines, Model 1273, each rated at 3200 shp. Each unit is coupled to a pair of contrarotating, subcavitating propellers, 29 in. in diameter, through two right-angle gear boxes: one at the top of each aft strut and the other in each of the underwater nacelles. The hull and interior structure are of welded construction employing 5456 aluminum alloy. The foils and struts are of built-up construction of HY-80 steel. Further details on the construction of the craft can be found in Ref. 1.

Capabilities and Limitations

Speed and Powering

At a gross weight of 262,000 lb, takeoff occurs at 27 knots with 3880 total hp delivered to the transmission system, with speed stabilizing at 36.6 knots at that power setting. Minimum foilborne speed is 24 knots.

The product of lift-to-drag ratio and propulsion efficiency $L/D\ \eta$, being easier to measure accurately than the constituents, was found by tests to agree closely with the results of model work done by the David Taylor Model Basin. At two representative speeds, 30 and 40 knots, the $L/D\eta$ product of the full-scale craft was found to be 7.44 and 7.25, respectively. These values of $L/D\eta$, being a good index of vehicular efficiency, show that the PC(H)-1 speed and powering performance is commendable. The constituents of the $L/D\eta$ product of 7.25 at 40 knots are, based on model data, approximately 11.2 and 0.65, respectively.

Maximum range factor is 29.2 naut miles/ton of fuel and occurs at a speed of 40 knots. Foilborne range at that speed, based on fuel consumption rates and assuming 95% full fuel tanks, exceeds the design specification by 27%. Foilborne speed and powering data are summarized in Fig. 3. In Sea State 4, range is reduced and an increase in power required, at a given speed, by 8%.

Hullborne speed is 10.9 knots with the outdrive propeller turning at 776 rpm. There is no discernible speed difference with foils extended or retracted.

Rough-Water Performance

Rough-water tests have been conducted in an area just north of the northwesternmost tip of the United States (Cape Flattery). Large ground-swells are characteristic of the area with frequent periods of high winds occurring throughout the year. Although being 130 miles from the Seattle-Bremerton area where the High Point is based, the area is well suited to hydrofoil testing because of the ready availability of chal-

Table 1 Rough-water performance (September 22, 1964)

Relative Heading of Sea	Craft Speed, Knots	Length of Data (Minutes)	Average Wave Height Trough to Crest (Feet)	Average Height of 1/3 Highest Waves (Feet)	RMS Acceleration: Forward (Approximately 1/4 L From Bow) g's	RMS Acceleration: Aft (6 Feet Aft of Center of Gravity) g's	Forward Foil Broach: Number	Forward Foil Broach: RMS Acceleration Forward — g's	Hull Contact, Due to Forward Foil Broach: Number	Hull Contact, Due to Forward Foil Broach: RMS Acceleration Forward — g's	Hull Contact, No Foil Broach: Number	Hull Contact, No Foil Broach: RMS Acceleration Forward — g's	Data Section Number
Bow	36	3.8	3.5	5.6	0.024	0.031	0	-	0	-	0	-	1
Head	36	3.7	4.9	7.9	0.095	-	10	0.83	6	0.84	5	0.61	2
Following	36	6.2	[1]	[1]	0.034	0.023	4	0.36	0	-	0	-	3
Bow	36	4.3	3.3	5.2	0.056	-	5	0.46	3	0.70	3	0.38	5
Beam	36	4.0	[1]	[1]	0.041	0.028	2	0.51	1	0.91	2	0.46	6
Head	36	3.4	3.7	5.9	0.065	-	2	0.81	1	0.74	4	0.42	7

[1] Wave height data not available for Data Sections 3 and 6. Data Sections 1 through 7 were taken in sequence in the same general area. Wave heights for Sections 3 and 6 may thus be assumed consistent with wave heights for Sections 1, 2, 5, and 7.

lenging conditions. Adjacent land masses also provide some variety in water conditions in a given hour.

The first tests in a significant seaway occurred on June 30, 1964. Prior to foilborne tests, hullborne tests at 10 knots were made at all headings relative to the advance vector of the waves with the foils first retracted and then extended. The purpose of these tests was to ascertain the damping effect of the foils in a seaway. Although little difference in craft motion was measured between the retracted and extended modes, conclusions on the damping effect of the foils should be cautioned by the fact that the foil retraction system on the PC(H)-1 does not permit a removal of the foils from the water. Accelerations due to hullborne slamming were, however, found to be much more severe than that resulting from wave furrowing while foilborne in one test in a significant seaway. Accelerations at the steering station were 0.35 g rms while hullborne at 8 knots. This is to be compared with accelerations of 0.07 g rms at full power speed in a foilborne run made in the same seaway immediately after the hullborne test.

Heave accelerations, when operating at all headings in another seaway, were 0.095 g rms at the steering station for the head sea case, 0.041 g in a beam sea, and 0.034 g in a following sea. Table 1 is a summary of the rough-water performance experienced on one particular test day.

Subjectively speaking, the foilborne riding qualities in a seaway are much like those experienced in a jet aircraft when flying through mild turbulence. The sound level in the steering station is similar to that in a closed automobile on an open highway.

In the stronger seas, particularly when heading into the waves, broaching or ventilation of the forward foil and related furrowing of the hull occurred 2 to 3 times/min. The foil and hull loads transiently applied at these times are in contrast to the relatively smooth performance when negotiating wave heights that are less than the length of the forward strut, which is 8 ft 8 in. Figure 4 shows a typical time history of craft motion that was recorded while negotiating a large wave.

Because the statistics of a random sea[2] indicate that every 23rd wave is twice the average wave height and every 1075th wave is three times the average wave height, foil broaching must be expected occasionally for a craft with struts of practical length. However, it is desirable that the frequency of this occurrence be minimized.

Contouring over the larger, long-crested waves, particularly at the low wave encounter rates when in a following sea, is relatively easy to do; however, the limited availability of hydrodynamic lift, control phase lags, and the geometric limitation formed by the strut-to-hull length ratio of the PC(H)-1 generally precludes any useful contouring of the higher, short-crested waves encountered when heading into a random sea. Because the forward strut of the PC(H)-1 is presently 31 in. shorter than the aft struts, a lengthening of the forward strut by some 2 ft or more is possible and would extend the craft's capability to operate in head seas, at the higher sea states, with some contouring being possible to negotiate beam, quartering, and following seas up into even higher states.

The instrumentation system used to obtain the rough-water data, as well as the calm-water data, consists of a 32-channel direct-reading oscillograph employing light-sensitive paper and a 14-channel magnetic-tape recorder. Craft motions, control flap positions, and other sensor outputs, as needed for a particular test, were recorded. Because of the roominess of the craft and the use of a direct-reading oscillograph, technical specialists can observe test data as they are recorded and thus provide consulting advice and direction to the operating crew as a test progresses. Wave height data were determined from the height sensor when the craft was platforming over the waves, and statistical data on wave heights and craft accelerations were determined by processing the magnetic-tape data at a playback speed of 60 times real time.

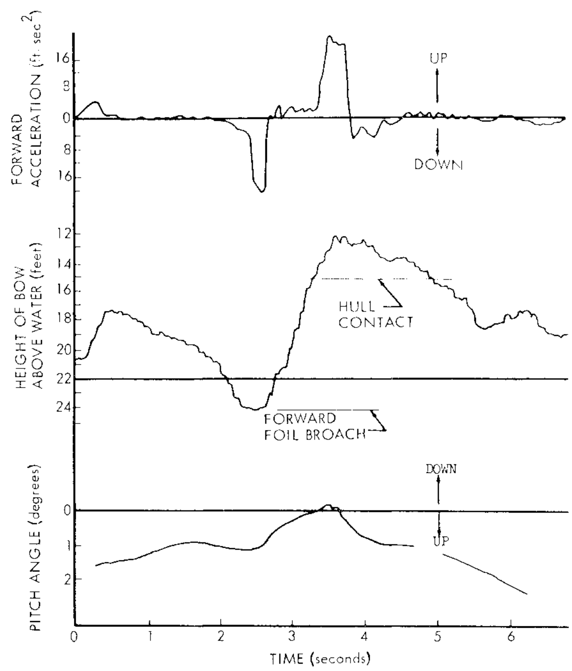

Fig. 4 Foil broach and hull slam in a large wave.

Developmental Experience

Cavitation at Forward Strut

The juncture of the forward foil and strut is very abrupt or square. As a result, the pressure distribution along the side of the strut at the bottom and over the top of the foil causes a low-pressure field, or cavitation, at this juncture. At speeds below 40 knots, this wedge-shaped cavity is only about 10 in. long, is quite stable, and does not have any effect on the behavior of the craft. At speeds above 40 knots, this cavity extends forward some 3 ft, extends laterally along the foil, and up the aft portion of the strut, enveloping the lower third of the flap rudder. The cavity also becomes unstable at a semi-periodic frequency of approximately 12 cps, causing buffeting loads on rudder mechanisms and a slight roughness in the ride of the craft. Proposed modification plans include installation of a fillet pod around this juncture to correct this problem.

Leaks and Coatings

The slipstream velocity over the transmission nacelles, due to the forward propellers, is some 5 knots greater than the freestream velocity at the higher craft speeds and is given a twist by the propeller action. The tips of the forward propellers also shed high-energy vortices. The resulting flow conditions in the vicinity of the strut/nacelle/foil juncture are conducive to the formation of multiple unstable cavities on the struts and foils.

Early in the builder's trials, the neoprene coating that had been specified for protection of the foils and struts, peeled off below the waterline (Fig. 5). After only a few hours of foilborne running time without any such protection against cavitation erosion, it became evident that the HY-80 skin on the foils and struts was being eroded along lines fore and aft generally coinciding with the tip wake of the forward propellers.

As a means to prevent this erosion, bands of Stellite 12 in. wide and $\frac{1}{8}$ in. thick were fastened around the struts and foils in the tip wake area of the forward propellers. The original method of fastening these overlays used nylon screws. Failure of this method of attachment to endure led to the use of metal screws with a peripheral weld around the overlays and, finally, to the use of plug welds to replace the metal screws.

The Stellite overlays have been reasonably successful in resisting cavitation erosion; however, the cavitation implo-

Fig. 5 Neoprene peeling from nacelle.

sions and other fluctuating loads have caused recurring fatigue cracks in the HY-80 base metal because of stress concentrations at fastening points, thus admitting salt water directly into the transmission oil sumps. This problem has been the major cause of drydockings during this developmental period, as indicated in the drydocking history (Table 2). The use of more malleable materials than Stellite for protective overlays, such as Inconel, stress relieving of welds at attachment points, and the use of improved elastomer coatings are all expected to contribute to a successful solution to this problem.

Propeller Drive Transmissions

Related to the problem of cracks and leaks in the transmission nacelles is the propeller drive arrangement, which can be discussed from that point of view. Although the forward propellers appear to have contributed to the damage to the struts and foils in the vicinity of the nacelles, the fore and aft propeller arrangement permits a narrower nacelle than with a single propeller because of the lower gear tooth loads and near-balanced side loads on the vertical shaft pinion bearing. The over-all propulsion efficiency times lift-to-drag ratio product is high and is due, in part, to the propeller transmission arrangement and the use of subcavitating propellers. With the exception of potential difficulties arising from the salt water leaks into the oil sumps, transmission system operation has been trouble-free.

Propellers

Cavitation erosion on the aft propeller blades has limited their operating life to about 20 hr between repairs. The largest cavities, which are some $\frac{3}{8}$ in. deep before repair, are located on the suction side of the blades, at midspan and midchord; whereas the cavities on the pressure side, which are very small, are more randomly distributed over the face of the blade. The use of stainless steel or titanium propellers, as replacements for the present cast bronze units, and, possibly, local protection with neoprene coatings, are expected to increase propeller life considerably.

Unlike the aft propellers, the forward propellers have suffered no erosion damage in 54 hr of foilborne operation to date, due largely to the even flow field into which they advance. However, because of the strut and foil erosion believed to be due to the forward propellers, current plans include replacing these three-bladed units with a five-bladed version, with unloaded tips, as a means to reduce the strength of the tip vortices. Model tests of this propeller design change indicate a reduction in efficiency from 70 to 64%; however, the power margin in the craft makes this loss acceptable.

Rudder Effectiveness

Inadequate and inconsistent turning capability was one of the most serious operational defects encountered during the early stages of the test and evaluation work. Although a turning radius of 1000 ft was usually available at speeds less than approximately 37 knots and in light winds, the turning radius at speeds above 40 knots, or in high winds, was frequently as high as 3000 ft. On occasion, the turning rate was of opposite polarity to that commanded from the helm, thus creating a hazard to navigation.

Test observations indicated that ventilation of the suction side of the upper flap rudder and inconsistent flow around the lower spade rudder were responsible for this behavior. Tests with a temporary fence, to stop ventilation of the upper rudder, were not successful, evidently because of the air source being far aft in the wake of the strut. A drydocking inspection of the paint damage pattern on the spade rudder revealed that this rudder, which had a blunt leading edge, was apparently operating in a cavity starting near the leading edge with flow reattachment occurring near the trailing edge.

Table 2 Drydocking history and causes

Drydocking number	Reason for drydocking	Drydocked period
1	Cavitation erosion of struts and foils in tip wake area of forward propellers; Stellite cladding installed with nylon screws.	October 25, 1963 to January 10, 1964
2	There were 30 gal lube oil "lost" in starboard strut voids; oil scavenger pump replaced	January 20 to January 24
3	Stellite cladding broke loose; refastened with peripheral weld, and nylon screws replaced with metal screws; $\frac{1}{8}$-in. corrosion hole found in starboard lube oil line.	February 4 to March 18
4	There were 3 gal salt water found in starboard nacelle from cracks in Stellite and HY-80 skin at fastening points; corrosion hole in salt water inlet and another in lube oil line found and repaired; temporary rudder fence and pitot tube installed on forward strut.	March 27 to April 24
5	Frayed neoprene cleaned off forward strut to correct erratic steering; salt water found in strut voids because of loosening of bolts at strut/foil production breaks; craft was weighed.	May 22 to June 18
6	Replaced eroded aft propellers with Superston units; removed damaged neoprene from aft struts in attempt to correct skidding problem.	July 15 to July 24
7	Salt water found in starboard transmission because of cracks in Stellite and HY-80 between plug welds; installed new spade rudder.	August 4 to August 28
8	Spade rudder attachment bolts failed because of cavitation buffet on upper rudder; shaft keyways installed; differential pressure instrumentation across rudder actuator installed.	September 3 to September 11
9	There were 15 gal salt water found in starboard transmission nacelle; major overhaul begun to improve strut watertight integrity.	September 25, 1964 to December, 1965

Correction of this turning problem was effected by replacing the original spade rudder, which had an area of 1.1 ft and an 18%-thickness ratio, with one that has an area of 3.4 ft^2 and a thickness ratio of 12%. Turning radii as low as 1100 ft at the higher speeds are consistently available in calm weather, with turning capability when turning into a wind yet to be evaluated.

Erratic Turning

An interesting turn anomaly occurred when a pitot tube was installed down the leading edge of the forward strut. This was done because the electromagnetic speed log had a history of inaccurate operation, up to that time.

Subsequent tests revealed an erratic turning characteristic that was unrelated to the position of the helm. Turn rates up to 8°/sec were recorded that were essentially unaffected by rudder control action. The onset of the turns, occurring in either direction, was sudden, with the force clearly emanating from the vicinity of the forward strut. These turns could be arrested either by landing the craft or by manually adjusting the roll trim of the craft outward from the turn, the latter action evidently causing the rewetting of a ventilated area formed on the side of the strut facing the outside of the turn.

Removal of the pitot tube and grinding smooth the leading edge did not correct the problem. The evidence at this stage of the investigation implicated the frayed neoprene around the pitot tube attachment points (Fig. 6). Accordingly, all the remaining neoprene on the forward strut was removed. This corrected the problem. Recordings made during these erratic maneuvers revealed that a side force in excess of 10,000 lb was triggered by these discontinuities. The electromagnetic speed log was eventually modified so that dependable speed readings could be obtained.

Yawing Skid-Outs

Occasionally divergent skid-outs of the stern, particularly in a seaway, have been experienced, apparently due to a combination of asymmetrical ventilation of the aft struts and transient differences in strut immersion. Yawing rates up to 13°/sec were recorded during these skids. Ventilation fences on the aft struts and the use of yaw rate feedback to the rudder are considered to be the most promising fixes for this problem.

Control System

An analog simulation was maintained throughout the developmental trials to aid in explaining anomalous behavior and to guide changes made to the control system. Some examples are cited.

Banked turns produced a sagging in height because of the heave velocity and pitch rate components of the turning motion being coupled into the height control loop. This was corrected by feeding the absolute value of roll angle into the height loop as a means of compensation. The exact transfer characteristics were first derived analytically and then tested on the simulation before installation in the craft.

In another instance, a disturbing roll "jiggle" was experienced in rough-water tests that was not physically sensed, and thus not detected, in the environment of the analog simulation facility. This was determined to be due to short-period yaw motion, as sensed by the yaw-rate gyro, feeding through the turn coordination circuit into the roll control flaps. Through use of the analog dynamic simulation, a filter in the turn coordination circuit was tested that attenuated the higher frequency yaw-rate gyro input to the aileron servos without adding excessive lag to the roll bank function.

In another developmental phase, the basic incompatibility of a controller adjusted for head seas with that of one adjusted for beam seas was reconciled to the maximum possible extent. The problems experienced in actually negotiating certain seas and the analog simulation studies of this problem were of mutual assistance in reaching the best possible solution. To help insure reality to this work on foilborne dynamic behavior, the engineers conducting the analog simulation studies and those operating the instrumentation system aboard the craft were the same people.

Fig. 6 Frayed neoprene on strut leading edge.

The most satisfactory takeoff procedure has been determined to be simply to set the desired flying height and then advance the throttles. No manual adjustments as a function of speed or sea state have been found necessary, with the latter conclusion subject to change as a result of further developmental trials in an expanded variety of sea conditions.

Developmental adjustments to the control electronic hardware have been found difficult to set accurately, particularly while at sea. Insulation degradation in the flap position pickoff wiring, because of salt water contamination in the struts, has contributed to this difficulty.

Hull and Foil Configuration

The hull form has permitted good takeoff performance and has exhibited good wave-furrowing characteristics at foilborne speeds. Also, during evaluation tests on the yaw skid-out problem, in which near-equilibrium outward roll angles up to 32° were recorded, the strong righting moment provided by the hull gives evidence that the craft will strongly oppose any upsetting roll moments that may derive from hydrodynamic, structural, or control failure.

Maintenance and repair of the foils, nacelles, and propellers were complicated by the foil retraction scheme that does not permit removal of the underwater running gear from the water without a drydocking. However, the wet stowage arrangement permits a weather deck relatively free of encumbrance, provides a good metacentric height while hullborne with foils retracted, and permits a high-aspect-ratio single-span foil. The narrow over-all foil span thus availed has also permitted exclusive use of the fully banked turn in all sea conditions, resulting in turn behavior in which the possibility of hydrodynamic collapse of roll control is essentially eliminated, because of the zero steady-state aileron deflection while turning.

Conclusions

The PC(H)-1 program has yielded and is continuing to yield much data on the capabilities and problems in the design and development of ocean-going hydrofoil ships. With the exception of having demonstrated full design capability in rough water, the craft has met or exceeded all of her design goals, including a verification of the concept of the turbine-powered, fully submerged foil ship being routinely operated by the "white hat" Navy.

Sporadic leakage of salt water into the transmission oil sumps has been the principal reason for limited reliability to date. This and other problems evaluated during the test program can be corrected, as presently envisioned, without major alteration of the craft. In contrast, much operational experience and test data have been obtained that commend many of the more gross aspects of the craft design. Seakeeping characteristics while hullborne, takeoff performance foilborne comfort, and safety have been found to be most satisfactory. The high vehicular efficiency of the full-scale craft was accurately predicted by model work done prior to construction of the ship.

References

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JAN.-FEB. 1966 J. AIRCRAFT VOL. 3, NO. 1

Selection of a Propulsor for a Submersible System

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The problem of propulsor selection is discussed as it might arise when conducting a preliminary performance estimate on an underwater vehicle. To this end, the methods of determining the performance characteristics of a single open propeller and a single rotor pumpjet for operation on a given vehicle are presented. Included are propulsor efficiency, cavitation, and noise produced as affected by propulsor size, rotational shaft speed, and vehicle forward velocity. A comparison of these characteristics is made to allow the selection of the best suited propulsor configuration. The predicted performance is obtained employing average velocity ratios and actuator disk theory. Although this approach is not as accurate as the more detailed design procedures, it is sufficient when employed as a preliminary design tool for predicting over-all performance characteristics. An example is presented to illustrate the use of the procedure.

Nomenclature

A_B = frontal area of body, ft^2
A_D = disk area, ft^2
A_i = inlet flow area [defined by Eq. (2)], ft^2
C_b = blade pressure coefficient [defined by Eq. (22)]
C_D = drag coefficient (drag/$1/2\rho V_\infty{}^2 A_B$)
C_T = thrust coefficient (thrust/$1/2\rho V_\infty{}^2 A_B$)
D_m = maximum body diameter, ft
d_t = blade tip diameter, ft
F = force, lb
h_s = submergence depth, ft
J_m = advance ratio, V_∞/nD_m
k = energy loss coefficient [defined by Eq. (13)]
L = body length, ft
m = mass flow, slugs/sec
n = shaft speed, rev/sec
P_∞ = freestream static pressure, psf
P_D = static pressure immediately upstream of blade leading edge, psf
$P_{\min}$ = minimum pressure on blade surface, psf
P_v = vapor pressure of fluid, psf
ΔP = pressure rise across propeller, psf
Q = volumetric rate of flow, cfs
r_h = body radius at any specific station, ft
r_t = blade tip radius, ft
R_L = Reynolds number, $V_\infty L/\nu$
shp = shaft horsepower
t = time, sec
U = average rotor velocity, $U_t/2^{1/2}$
U_t = rotor tip velocity, fps
V_∞ = freestream velocity, fps
$\bar{V}_D$ = average fluid velocity at disk, fps
V_i = velocity upstream of inlet, fps
$\bar{V}_i$ = average velocity upstream of inlet, fps
$\bar{V}_e$ = average propulsor exit velocity, fps
ΔV = change in average fluid velocity between the inlet and discharge of propulsion unit in the direction of thrust, fps
V_θ = average fluid peripherial velocity, fps
W = relative fluid velocity at blade leading edge, fps
W_t = relative fluid velocity at blade tip leading edge, fps
y = normal distance from body, ft
β = angle between relative inlet velocity to blade and axial direction, deg
δ = boundary-layer thickness, ft
η_t = over-all efficiency [defined by Eq. (11)]
η_p = propulsive efficiency [defined by Eq. (12)]
η_h = hydraulic efficiency [defined by Eq. (11)]
$\eta_p{}'$ = propeller propulsive efficiency [defined by Eq. (14)]
$\eta_p{}''$ = pumpjet propulsive efficiency [defined by Eq. (15)]
θ = convergence angle of hull, deg
ρ = mass density, slugs/cf
σ_{cr} = critical cavitation index, $P_\infty - P_{\min}/1/2\rho V_\infty{}^2$
ν = kinematic viscosity, ft^2/sec

Presented as Preprint 65-232 at the AIAA/USN Marine Systems and ASW Conference, San Diego, Calif., March 8–10, 1965; revision received July 23, 1965.

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Introduction

WITH the advent of more sophisticated and diversified submersible vehicle systems, it is becoming increasingly important to be able to understand the general performance of individual system components and how each affects the over-all performance of the vehicle. Depending upon the