U.S. Navy Hydrofoil Craft

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Background information, characteristics, operational experience, and future plans for U. S. Navy hydrofoil craft are summarized. Included are the 120-ton hydrofoil patrol craft HIGHPOINT (PCH-1); the 320-ton experimental hydrofoil ship PLAINVIEW (AGEH-1), largest in the world; the high-speed foil test platform FRESH I; and the hydrofoil gunboats FLAGSTAFF (PGH-1) and TUCUMCARI (PGH-2). The two gunboats, destined for early fleet deployment, represent the first product of this development program, whose objective is to provide the Navy with a significantly improved capability to achieve high, sustained speed in rough water.

Introduction

DURING almost the entire first half of the 20th century, the flickering flame of enthusiasm for the development of hydrofoil craft waxed and waned with only sporadic interest and very limited financial support. Excellent summaries of activities during this period of history are given by Crewe[1] and Hayward,[2] as well as by many other authors; and it is not the intent of this paper to deal with these earlier historical aspects of hydrofoil development. It is interesting to note, however, that only within the current decade has there been a concentrated effort to develop such craft for either military or commercial purposes. This has led many to express the opinion that hydrofoil development, in contrast to that of the aircraft, now falls into the category of "too little, too late" except for specialized situations. Certainly, it is true that progress has been painfully slow; however, the substantial growth in the employment of commercial hydrofoils for passenger service during the last several years strongly suggests a contrary view of the future. Further, it is the conviction of the author that there is a real future for hydrofoil craft in military applications, and that this future is coming to full realization in the current U. S. Navy Hydrofoil Development Program.

Background

The U.S. Navy's interest in the potential of hydrofoils dates from the late 1940's. In the period 1947 to 1960 the Office of Naval Research, with support by the Bureau of Ships, sponsored a number of research and development projects directed toward the establishment of feasibility and fundamental criteria for the design of hydrofoil craft. Theoretical analyses and model experiments were made and tests were conducted on a variety of small craft. Of the small hydrofoil craft, the SEALEGS, Fig. 1, is perhaps the most notable. SEALEGS, through the joint efforts of Gibbs and Cox and the Massachusetts Institute of Technology Flight Control Laboratory, provided the first real demonstration of the feasibility and advantages of a fully submerged, automatically controlled foil system. The many hours of foilborne operation of SEALEGS produced much valuable data and only within the past year has it been retired and donated to the Smithsonian Institution.

The year 1960 was a significant milestone in the Navy Hydrofoil Program. At that time it was decided that sufficient data had been accumulated to demonstrate that large, submerged-foil craft are feasible and that such craft could provide the Navy with a significantly advanced high-speed mission capability. As a result, an accelerated program of development was initiated and funds were made available to support an expanded research and development effort. Also, fiscal year 1960 ship construction funds were allocated for the design and building of the PCH-1, a 120-ton hydrofoil patrol boat. Later, in FY 1962, funds were allocated for the design and construction of the AGEH-1, a 320-ton experimental antisubmarine warfare (ASW) hydrofoil ship. Finally, in early 1966, contracts were let for the construction of two patrol gunboat hydrofoils (PGH), one by the Grumman Aircraft Engineering Corporation and the other by the Boeing Company. The characteristics of each of these craft and their status are discussed in detail in the sections that follow.

During the period from 1960 to the present there has been a continuing program of supporting research and development directed toward solution of problems and the generation of criteria for the design of hydrofoil craft subsystems, including hull, struts and foils, propulsion, ship control, and auxiliary machinery. The results of much of this work have been incorporated in the design of present craft; however, much remains to be done toward the achievement of higher performance and increased reliability. Excellent summaries of the state-of-the-art in Navy hydrofoil craft design were presented by Oakley[3] in 1962 and Lacy[4] in 1964. These papers provide the foundation for this review and up-dating of the status of U.S. Navy hydrofoil craft.

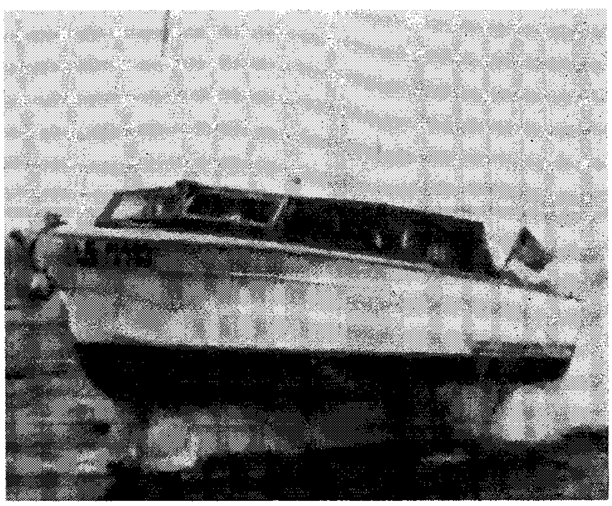

Fig. 1 SEALEGS.

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Table 1 Craft characteristics

Characteristics	PCH-1 (Mod-0)	AGEH-1	FRESH-1[a]	PGH-1	PGH-2
Configuration	Canard	Airplane	Various	Airplane	Canard
Length over-all, ft	115.7	212	53.1	74.5	71.8
Beam, extreme—foils down, ft	33.3	70.8	22.5	21.5	19.5
Full load hullborne draft—foils up, ft	6.5	6.4	...	4.2	4.5
Full load hullborne draft—foils down, ft	17	25	10.4	13.5	13.9
Full load displacement, long tons	120	320	16.7	57	58
Hullborne propulsion				...	
Engine	1) Packard diesel	2) GM diesels	...	2) GM diesels	1) GM diesel
Shaft horsepower	600	1200	...	320	160
Thrust producer	1) 3-bladed Subcav. prop	2) 5-bladed Subcav. props	...	Waterjet	Waterjet ... ...
Foilborne propulsion					
Engine	2) Bristol Proteus G.T.	2) GM LM-1500 G.T.	1) P&W JT-3D Fan jet[b]	1) Rolls-Royce Tyne G.T.	1) Bristol Proteus G.T.
Shaft horsepower (continuous)	6,200	28,000	...	3,150	3,100
Thrust producer	4) 3-bladed Subcav. props	2) 4-bladed Supcav. props	Turbo fan	1) Supcav. prop ...	Waterjet ... ...
Max. hullborne speed, knots	12	15	4.5	7+	7+
Calm water takeoff speed, knots	27	33	45	...	...
Max. foilborne speed, knots	40+	45+	80–100	40+	40+
Foil and strut material	HY 80 steel	HY 80/100 steel	17-4PH	Cast Alum/HY80 4130	17-4PH
Hull material	5456 Al	5456 Al	5456/2014Al	5456 Al	5456 Al
Type of control	Flaps	Incidence	Flaps	Incidence	Flaps

[a] Demonstration foil configuration.
[b] 18,000 lb static thrust.

Craft Status

Although a substantial part of the foundation for design of operational craft can be, and has been, established by development of theory, analyses, model tests, and experiments with small vehicles, there must ultimately be verification by construction and test of full-scale prototypes. At present there are three experimental craft encompassed by the U.S. Navy Hydrofoil Development Program. These are the HIGHPOINT (PCH-1), the PLAINVIEW (AGEH-1), and the FRESH-I (a high-speed platform for tests of new high-speed foil systems). In addition, there are two hydrofoil gunboats, FLAGSTAFF (PGH-1) and TUCUMCARI (PGH-2), under construction at Grumman and Boeing, respectively. These two craft, being of smaller size and within the state-of-the-art, are not considered developmental and, upon completion of final acceptance tests, they are scheduled to be delivered to an operational unit of the fleet.

Before proceeding to a detailed discussion of the characteristics and status of each craft, it is important to make note of the special provisions that have been made to conduct an extensive special trials program. For some time the Navy has recognized the need for a special facility to conduct technical trials of advanced surface craft. The first step toward provision of such a capability was taken in November 1966. At that time, the Naval Ship Research and Development Center, upon request of the Naval Ship Systems Command, established a Hydrofoil Special Trials Unit at Bremerton, Wash. This Unit is a tenant activity of the Puget Sound Naval Shipyard and the officer-in-charge is responsible for the conduct of all special trials of assigned craft.

HIGHPOINT (PCH-1)

General

The guidance design of the PCH-1 was performed by the Bureau of Ships and a contract for detailed design and construction was awarded to the Boeing Company in June 1960. The keel was laid at J. M. Martinac Shipyard in February 1961 and the hull was launched in August 1962. Construction was completed and the craft began operations in September 1963.

The principal characteristics of PCH-1 are given in Table 1 and are graphically illustrated in Figs. 2 through 6. As shown, the craft is a canard configuration similar to SEA-LEGS with 70% of the load being borne on the after inverted π foil. Foil lift is controlled through trailing-edge flaps. The flying height is controlled by the flaps on the forward foil by comparison between the signal from two bow-mounted ultrasonic height sensors and a manually positioned altitude-set device. Pitch is controlled by differential operation of the flaps on the aft outboard foil sections. Foilborne steering is accomplished by means of a small strut-flap above the forward foil and a spade rudder, on the same shaft, positioned below the forward foil. Hullborne steering is accomplished by rotation of the hullborne propulsion unit about a vertical axis. This unit can also be rotated upward 87° about a longitudinal axis to eliminate its drag during foilborne operation. Further information on the control system and its evaluation is given in Refs. 5 and 6.

Foilborne propulsion consists of two 3100-hp Bristol Proteus gas turbines, each driving two propellers, one on each end of pods at the aft strut-foil intersections. Power is transmitted through an upper gear box and a single vertical

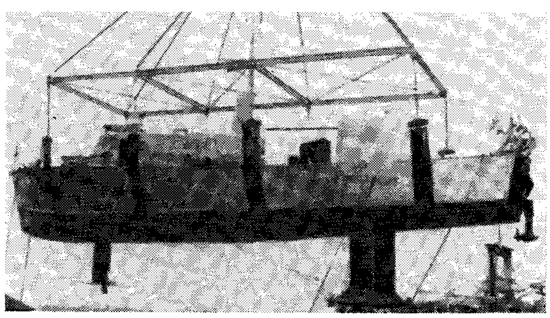

Fig. 2 PCH-1 suspended from crane.

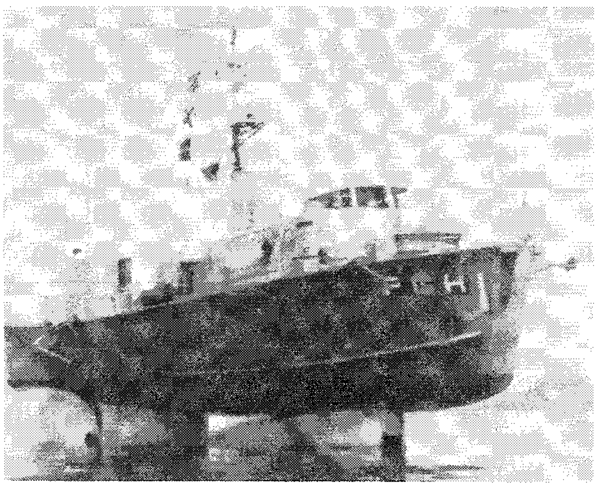

Fig. 3 PCH-1 foilborne.

shaft in each strut which terminates in a single bevel gear in the pod. The pod itself comprises the watertight lower transmission housing.

Provision is made for vertical "wet" retraction of both the forward and aft struts in order to reduce navigational draft during hullborne operation. The aft struts retract into the trunks seen on the afterdeck, and these also house the air intakes for the gas turbines.

Operational Experience

Before proceeding to a discussion of operation experience with PCH-1, it is important to establish the proper context in which to evaluate this experience. PCH-1 was originally conceived as a state-of-the-art craft and, therefore, upon delivery and completion of special performance trials it was planned that it be assigned to an operational fleet unit. As a result, only limited provisions were made for installation of instrumentation with which to make detailed assessment of subsystem operation and craft performance, and acquire the more extensive data needed to correct design deficiencies. This reflected the traditional view that conventional new ships usually incorporate only modest evolutionary changes in design and, thus, do not require an extensive period of testing and major modification in order to achieve the desired performance and reliability. Hydrofoil craft such as PCH-1, however, represent a revolutionary change in design concept and, in contrast to conventional displacement ships, are more akin to aircraft. In retrospect, therefore, the difficulties that have been experienced with PCH-1 should have not come as a surprise and should not reflect adversely on the potential of such craft for considerably enhancing naval capabilities.

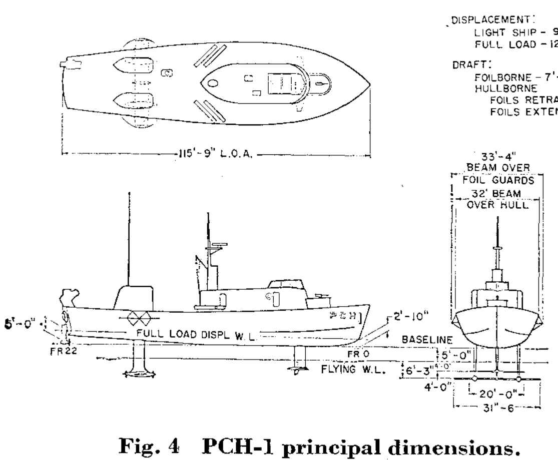

Fig. 4 PCH-1 principal dimensions.

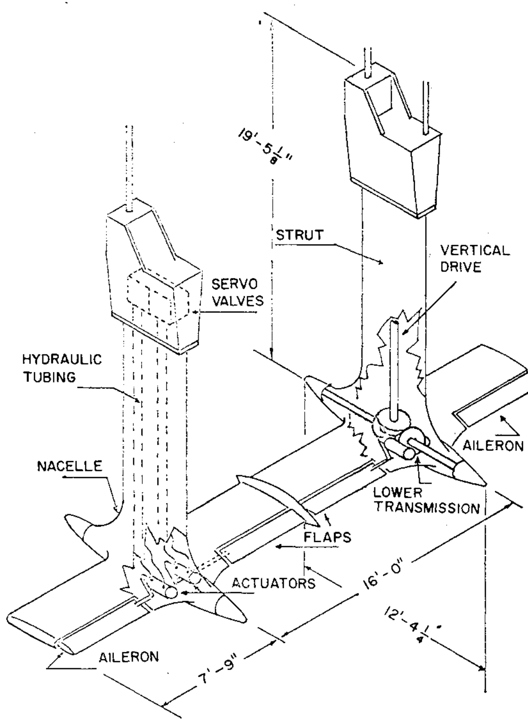

Fig. 5 PCH-1 main aft foil configuration.

The operational problems that have been encountered stem, in great part, from failure of conventional hardware components. The major problem areas stem from the not unexpected difficulties of operating at cavitation inception speeds. In the latter case, the step from commercial surface-piercing hydrofoils to the PCH-1 might be compared to that of advancing from the DC-3 to near-sonic aircraft such as the DC-8 and 707. Viewed in this context, and considering that PCH-1 represents the first and only craft of its kind, the performance that has been achieved is considered remarkable.

PCH-1 was delivered to the U.S. Navy on August 15, 1963 and was manned by a Navy crew. Support for the craft was provided by three large mobile shore vans containing spare parts, hydraulic and electronic test and repair equipment, and a small administrative office.

During the period from delivery until September 1964 the craft operated foilborne for a total of 54 hr of which about 2 hr was in rough water of sea-state 4. Numerous problems

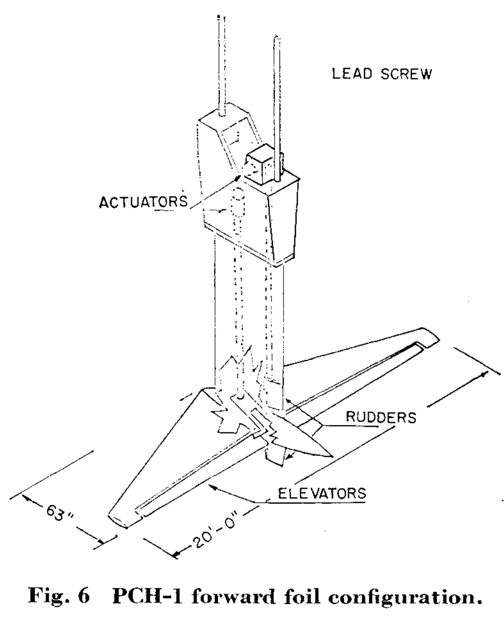

Fig. 6 PCH-1 forward foil configuration.

were encountered including erratic steering, cavitation damage and failure of coatings applied to the HY-80 struts and foils, and saltwater contamination of the lube oil in the transmission. This period of operation is described in detail in Ref. 7, and results thereof led to a decision in September 1964 to refurbish completely and repair the craft. It remained out of water until June 1966 and underwent a complete overhaul of the strut-foil and transmission systems. Modifications were made to the automatic control system, a larger spade rudder was installed, and several different types of elastomeric coatings and test patches were applied to the struts and foils. Additional instrumentation and recording equipment was also installed, including 63 bonded strain gages in the struts and foils, and adaptation was made to the height-sensor output to permit recording of actual wave heights during rough water operations.

Operational testing in calm water was resumed on June 22, 1966 and continued until the middle of October, with the exception of a short drydocking period to replace one of the experimental coatings that proved defective in bonding. During this period, 26 hr of foilborne calm-water operations were carried out successfully and extensive data were obtained. On October 19, the craft made a foilborne transit from Bremerton, Washington to Neah Bay, a distance of more than 100 miles, in an elapsed time of 3 hr and 19 min. During this transit, weather conditions were severe and swells were encountered which averaged 6 ft, with the highest being as much as 10 ft in amplitude. Subsequently, further rough water operations were conducted in the Neah Bay area for a total of 11 hr of foilborne time. During this period, the craft was operated at speeds up to 40 knots in seas in excess of sea-state 4. Forward foil broaching was periodically experienced primarily due to shorter length of the forward strut. This was attendant with some hull slamming that produced occasional bow accelerations as much as 2 g. However, foilborne operation was maintained without difficulty and rms vertical accelerations at the steering station did not exceed 0.2 g. Furthermore, no difficulty was experienced in rough water takeoff at any heading even in winds up to 30 knots. The only significant mechanical failure occurred at the beginning of the return transit to Bremerton, after completion of the trials. Immediately after takeoff both transmission disconnect couplings failed and necessitated making the return trip in the hullborne condition. Although this was a disappointing conclusion to an otherwise successful operation, it did serve to demonstrate the significant benefits of foilborne operation from the standpoint of human factors. Foilborne comfort was reflected in the relative absence of seasickness when operating on the foils. Only four cases of mild foilborne seasickness were acknowledged during the entire trials period. In contrast, after the transit up to Neah Bay, only 3 min elapsed before the first hullborne seasickness occurred, and on the return hullborne transit, a large percentage of the crew and trials personnel were sick.

Although PCH-1 has now demonstrated that the achievement of the original design goals is entirely feasible, there remain a number of design problems still to be resolved. Experience with the present coatings, described in detail in Ref. 8, shows considerable promise in that no significant deterioration was found after nearly 40 hr of foilborne operation. Speeds during these trials were, however, restricted to a maximum of 40 knots, which considerably alleviated cavitation effects. More data at higher sustained speeds must be obtained before a complete evaluation of coatings can be made.

Previous difficulties with saltwater leakage into the transmission lube oil appear to have been corrected by internal pressurization of the system. It is clear, however, that future designs should provide for containment of the lower gear box in a completely separate watertight housing within the pod.

Although the three-bladed forward propellers have not shown evidence of cavitation damage, their wake seriously affects flow conditions over the pod and strut-foil function. The increased velocity in the wake and the cavitating tip vortices which are generated considerably degrades the cavitation characteristics of the pod assembly and a change to eliminate the forward propellers is indicated. As for the after propellers, they have proved completely inadequate in their resistance to cavitation damage. The present bronze aft propellers are seriously eroded by cavitation on both faces of each blade, and require replacement or repair after about 40 hr of foilborne operation at cruise speeds. A three-blade configuration is particularly poor due to the harmonic content of the wake, and a wake-adapted design is required to alleviate the problem. Even so, it is not likely that aft propeller cavitation can be avoided at the desired speeds and other design techniques must be employed; these include recourse to partially cavitating or supercavitating designs, or provision for forced air injection.

The transmission disconnect couplings that are required for strut retraction have proven to be a continual source of trouble. The primary problem occurs in the difficulty of maintaining alignment with three essentially independent structural support points. Ultimate solution can be effected only by a complete redesign, and this is currently underway.

Future Plans

Operational experience with PCH-1 has demonstrated that a second iteration in the design of the strut-foil-propulsion system is required in order to achieve an acceptable level of performance and reliability. As a result, a contract was awarded to the Boeing Company in May 1966 to make a detailed study of candidate strut-foil-propulsion systems reflecting current advances in technology and incorporating changes necessary to overcome deficiencies in the present PCH-1 design configuration. In this study, a detailed comparison was made between improved propeller propulsion concepts and waterjet propulsion systems. This design study was completed in September 1966 and after extensive consideration and review by the Navy, the following conclusions were reached regarding the configuration of PCH-Mod-1.

1) Steering will be provided by a rotatable forward strut in lieu of the present strut flap and spade rudder.

2) Propeller propulsion will be retained. However, the Mod-1 configuration will consist of two pusher propellers, of new design, mounted on the aft end of the pods. Provision will be made for future addition of air injection to the propeller blades.

3) Watertight housing will be provided for the lower gear boxes, separate from the pods.

4) Wet retraction of the struts will be retained to minimize navigational draft.

5) Struts and foils will be constructed of higher-strength material. This will permit utilization of sections of smaller thickness, thus improving cavitation inception characteristics.

6) Flap control will be retained. However, consideration will be given to the use of an elevon system on the main foils so that all flaps will provide both roll and pitch control. (In the present Mod-0 system, the center-span flaps provide only pitch control and the outboard flaps provide only roll control.)

Based on these conclusions, the contractor is currently proceeding with the detailed design of the PCH-Mod-1 configuration. Upon completion of the detailed design in early 1968, construction will be initiated and the new strut-foil-propulsion system is scheduled to be completed and ready for installation in the summer of 1969. At that time, the PCH will enter drydock and undergo conversion that is expected to be completed in approximately six months.

Prior to installation of the Mod-1 strut-foil-propulsion system, the PCH will continue to undergo extensive test and evaluation by the Hydrofoil Special Trials Unit. During 1967, preliminary investigations will be made of the interfaces

Fig. 7 AGEH-1 afloat.

between the craft and potential mission equipment, such as weapons; and detection, navigation, and communication equipment. Here, it is not the intent to develop new mission equipment, but rather to explore the potential for utilization of existing hardware with this new high-speed platform. From such tests, requirements and specifications will be developed for mission equipment tailored to realize maximum benefit from the advanced performance capabilities of hydrofoil craft.

This period of mission interface testing will afford an opportunity to acquire limited additional craft performance data and permit more thorough analyses of extensive data that have already been acquired. During this period, also, a more complete documentation will be made of the existing craft system and subsystem configuration. Based on this analysis and documentation, performance areas requiring further definition will be delineated. Then, additional calm water and rough water performance trials will be carried out to establish fully the performance envelope of the Mod-0 configuration.

During 1968, emphasis in the trials program will shift again to more detailed investigation of mission capabilities. Experimental towing equipment, simulating a high-speed towed sonar system, will be installed and towing capabilities of the craft will be evaluated. Upon conclusion of this phase of the planned trials program, the craft will be drydocked for installation of the Mod-1 strut-foil-propulsion system.

PLAINVIEW (AGEH-1)

General

Funds for construction of the AGEH-1 were authorized in the fiscal year 1962 ship construction program and the guidance

Fig. 8 AGEH-1 stern view.

Fig. 9 AGEH-1 supercavitating propeller.

design was completed by Grumman in May 1963. A contract for detailed design and construction was awarded to Lockheed Shipbuilding and Construction Company in June 1963 and the hull was launched in June 1965. As of this writing, construction is nearly complete; however, due to problems that have arisen in the design of the hydraulic system and other construction delays, delivery to the Navy is not expected before the end of 1967.

The major characteristics of AGEH-1 are given in Table 1, and further illustrated in Figs. 7 through 10. It is the largest hydrofoil ship in the world and will offer the first opportunity to evaluate the potential of such craft for full ocean-going naval service. In addition to its large size, it is substantially different in design concept from PCH-1. Foil-lift variation is effected by change in incidence angle of both the main foils and the tail foil, which are arranged in an airplane or conventional configuration rather than a canard. Ultrasonic height sensors are mounted both at the bow and at the stern. Foilborne propulsion is by two 62-in.-diam, four-bladed, supercavitating propellers, one on the end of each gear pod. The hydrodynamic design of these propellers were performed by Hydronautics Inc. They were built by Hamilton Standard and are made of titanium alloy with blades bolted to the hubs. The initially installed power plant consists of two General Electric LM-1500 gas turbines, each driving one propeller through a right-angle bevel-gear transmission. Provision has been made, however, for adding two more engines, ultimately, to achieve much higher speeds using a ventilated or supercavitating foil system. The hull, which is constructed of welded 5456 aluminum, has been designed to meet the structural load requirements of higher speed operation.

Future Plans

Upon delivery to the Navy, AGEH-1 will be assigned to the Hydrofoil Special Trials Unit and will undergo extensive evaluation for a period of several years. This will undoubtedly include at least one major modification to correct design deficiencies and enhance performance capabilities.

Since this ship was conceived and built as an experimental tool for acquiring data to establish a firm foundation for design of large submerged-foil craft, it is being outfitted with an extensive instrumentation suit. More than 200 strain gages have been installed and calibrated in the struts and foils. Additional strain gages are being installed throughout the hull structure along with hull pressure sensors. Velocity transducers, accelerometers, and other measuring equipment are also located throughout the ship, and provision is made for accurate measurement of thrust and torque. To facilitate

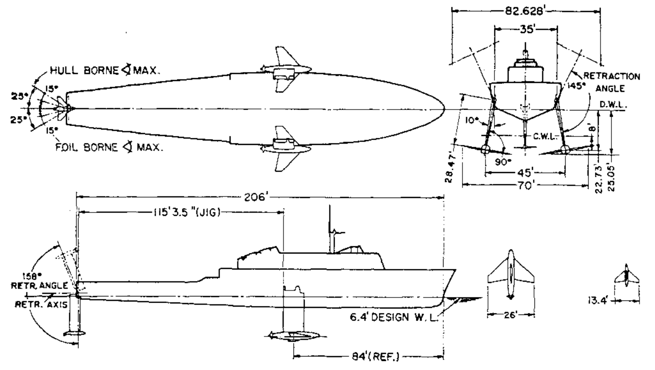

Fig. 10 AGEH-1 principal dimensions.

analysis of data obtained from the many sensors, provision has also been made for continuous and simultaneous recording of the more than 200 data channels on a single magnetic tape.

Based on experience with PCH-1, it is to be expected that early operations with the AGEH-1 will be characterized by a host of minor and major problems that will severely restrict its availability for test. Furthermore, in view of its unique nature and aspects of safety, advancement to full rough-water operation must proceed in careful steps. This process will involve detailed analysis of data as they are acquired and continual refinement of analog computer predictions of performance to be expected. The planned special trials program is tailored to this situation and will permit the acquisition of full-scale data necessary to correct deficiencies in design and establish firm criteria for design of future operational craft.

FRESH-1

General

As previously noted, the attainment of foilborne speeds considerably greater than 50 knots requires recourse to ventilated or supercavitating foils. Limitations on maximum speeds of available model test facilities seriously limit the acquisition of data needed for the design of such systems. Furthermore, scale effects associated with two-phase flow phenomena significantly affect the accuracy of predictions of full-scale behavior based on model studies. As a result, the need for a flexible, large-scale, high-speed foil test craft was recognized early in the Navy Hydrofoil Program. A competition for design and construction of a 100-knot, fully instrumented test vehicle, designated FRESH-1, was held by the Bureau of Ships in early 1961. On the basis of this competition, a contract was awarded to the Boeing Company in June 1961.

FRESH-1 was launched in February 1963 and began its performance trials in the spring of that year. The characteristics of the craft are listed in Table 1 and illustrated in Figs. 11 and 12. The initial foil configuration, referred to as the demonstration foil system, consists of three struts that can be attached in either a canard or an airplane arrangement.

Provision is also made for use of a fourth strut to permit tests of a tandem arrangement. The demonstration foils are of equal area with base-vented cambered parabolic sections. The struts are also blunt, base-vented, with parabolic section.

Propulsion is provided by a large turbo-fan engine that, although inefficient, permits investigations of foils and foil control systems without interference. The catamaran hull also permits considerable flexibility in strut-foil arrangement.

Operational Experience

Experiences and data acquired in operating the FRESH-1 are reported in detail in Ref. 9, and will be summarized only briefly here. Extensive hullborne and foilborne trials were conducted by the builder during the first half of 1963. During most of this shakedown period, the demonstration foil system was arranged in a canard configuration. A change was made to an airplane configuration and the craft first flew with this arrangement on June 6, 1963. No significant problems were encountered during these tests and demonstrations at speeds up to 80 knots were conducted for a Navy Trials Board on July 10, 1963. During the following week, a change was made back to the canard arrangement and demonstrations for the Trials Board were resumed on July 18. During this series of runs, the craft went out of control at a speed of 70 knots and turned over. Fortunately, the two-man crew and a member of the Trials Board, who were on the craft at that time, sustained only minor injuries. Damage to the craft was also light except for considerable deformation of the first-stage blading in the jet engine and later extensive corrosion of other metal parts of the engine.

Analysis of data tapes, which were recovered undamaged, made possible a complete reconstruction and analysis of the series of events leading up to the accident. In brief, a loss of flap effectiveness due to the formation of cavities in the flow permitted a gradual increase in flying height during the run and this was not detected until the foils were in the near broach condition. At the very shallow foil submergence, the craft lacked both lateral stability and rudder effectiveness, and went into a divergent yaw to starboard. Ultimately, the port foil completely overloaded and stalled with a resulting rapid roll to port causing the craft to capsize.

Following the accident, the FRESH-1 was completely refurnished and changes were made to prevent a recurrence of a loss of directional stability. A water brake system was also added and the JT-3D fan jet engine was replaced with a reconditioned YTF-33 jet engine acquired from the Air Force. Upon completion of the refurbishment, additional trials were successfully conducted by the builder. Delivery of FRESH-1 was accepted by the Navy in July 1964 and, after completion of final tests of the demonstration foil system in December 1964, the craft was placed in storage at the Boeing Company in Seattle.

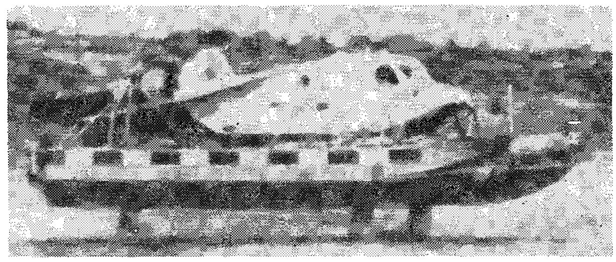

Fig. 11 FRESH-I foilborne.

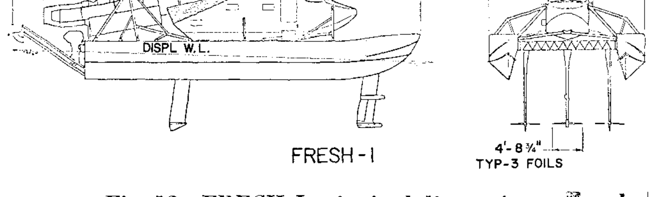

Fig. 12 FRESH-I principal dimensions.

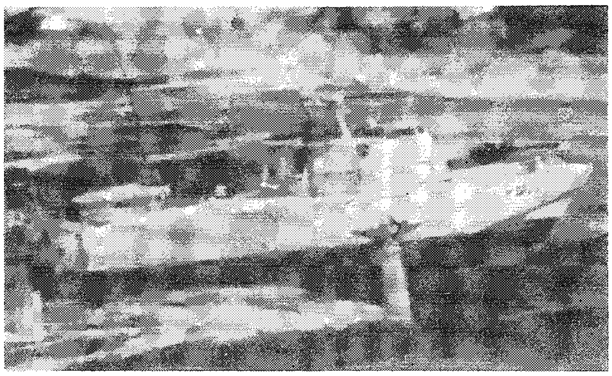

Fig. 13 PGH-1 (Grumman) artist concept.

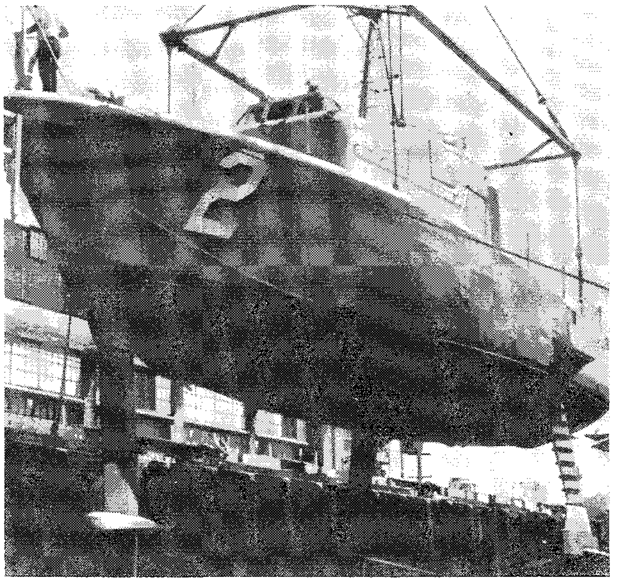

Fig. 15 PGH-2 suspended from crane.

Future Plans

At the present time there are no immediate plans for further tests with FRESH-1. A transit foil system has been designed and constructed by Grumman for installation on FRESH-1; however, plans for test of this system have been temporarily shelved. This results from a reappraisal of program goals which was made in early 1965 in light of difficulties incurred in operations of PCH-1. At that time, it was decided to concentrate efforts and limited funding on resolution of current design problems as evidenced in PCH-1 and as expected in AGEH-1. Upon successful demonstration of the performance capabilities of these large submerged-foil craft in the intermediate speed range, attention will again turn to the development of higher speed systems. In the interim, fundamental design studies and model tests of ventilated and supercavitating foils are being continued in the Navy's Exploratory Development Program. Some consideration is also being given to the feasibility of utilizing FRESH-1 as a platform for testing waterjet propulsion systems.

FLAGSTAFF (PGH-1) and TUCUMCARI (PGH-2)

In response to a requirement for a high-speed hydrofoil gunboat, established by the Chief of Naval Operations in 1963, two PGH's were authorized in the FY 1966 shipbuilding program. Based on design data generated by the Hydrofoil Development Program and further feasibility studies, conducted by the Ship Concept Design Division of the Naval Ship Engineering Center, final characteristics for the craft were approved in early 1965. In July 1965, a request for proposals was sent to a selected list of contractors known to have interest and experience in the design and construction of hydrofoil craft. Of the seven contractors solicited, only two responded. These were the Grumman Aircraft Engineering Corporation and the Boeing Company. Both proposals, although presenting substantially different design concepts, were considered technically sound and offered configurations adequate to meet the requirements. As a result, it was decided to procure one boat from each firm and, accordingly, contracts were awarded in April 1966. Builder's trials are expected to be conducted in the latter part of 1967 and delivery is planned for early 1968.

Principle characteristics of the two PGH's, described in Ref. 10, are listed in Table 1 and shown in Figs. 13 through 16. The Grumman PGH-1 has a conventional foil configuration similar to AGEH-1 with a 70/30 load distribution and incidence control. Foilborne propulsion is provided by a single supercavitating propeller located on the aft end of a pod at the juncture of the tail strut and foil. The prime mover is a Rolls-Royce Tyne gas turbine that drives through a right-angle bevel-gear transmission. Hullborne propulsion consists of two Buehler waterjets, each powered by a General Motors diesel engine. The foils are of subcavitating design and will be made of solid cast aluminum.

The Boeing PGH-2 is a canard configuration with a 31/69 load distribution and flap control system. The foils are of subcavitating design and the main foils are arranged in an anhedral configuration to reduce their tendency to ventilate in banked turns. Foilborne propulsion will be provided by a waterjet system consisting of a Byron-Jackson pump driven by a Bristol-Proteus gas turbine. Water inlets are located at the juncture of each main strut and foil. Hullborne propulsion consists of a single Buehler waterjet driven by a General Motors diesel engine.

As previously noted, these craft are considered within the state-of-the-art and are not a part of the RDT & E program.

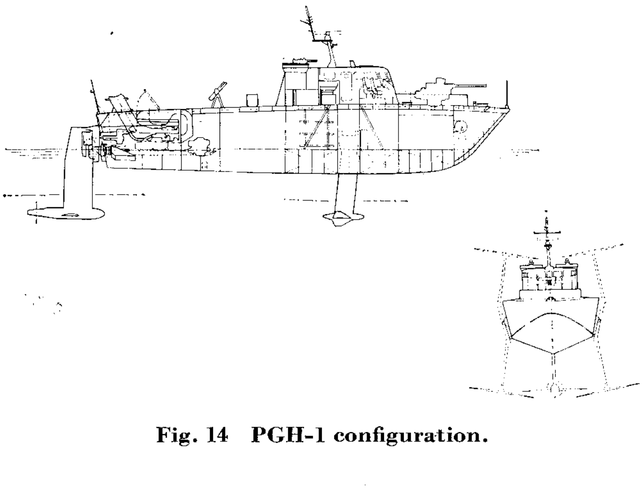

Fig. 14 PGH-1 configuration.

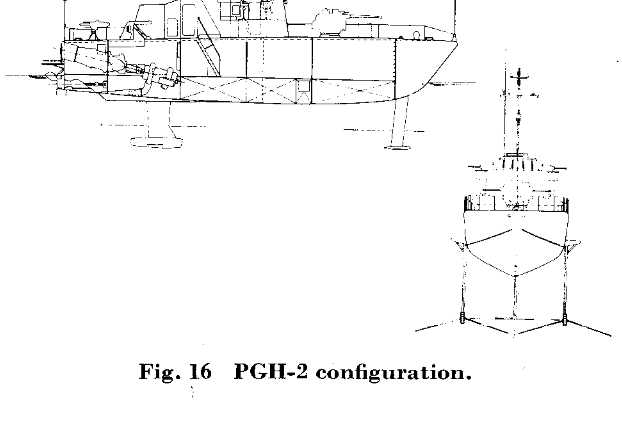

Fig. 16 PGH-2 configuration.

They will, however, undergo special trials before they are delivered to the fleet; the data obtained from these tests and future operations will be of considerable value in the design and development of present and future hydrofoils. Of even greater importance, the results of their operational evaluation and experience gained in their tactical deployment will provide the basis for quantity procurement of this new form of high-speed surface craft.

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Development of an Autopilot for the Dolphin Hydrofoil

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The Dolphin autopilot is the result of conceptual and hardware studies that were conducted on a number of hydrofoil craft in an effort to achieve successful open ocean performance. Such operation is characterized by the maintenance of low vertical accelerations in small, high-frequency waves and the avoidance of hull impact and foil broach in large ones. This has led to an autopilot design approach in which the hydrofoil craft is treated basically as a vehicle whose response must be tailored, by a control system, to each element of a set of random disturbances occurring in an incompressible medium. The paper presents a brief history of the analysis, design, construction, and test phases of such an autopilot for the Dolphin hydrofoil boat. Also described is the development of an automatic gainsetting procedure, based upon the integral of the absolute value of the error input to each autopilot control channel. Employment of this technique has aided the analytical work on the Dolphin autopilot and shows promise of being useful in the establishment of suitable gains during initial sea trials of future hydrofoil craft.

I. Introduction

The Dolphin, designed and produced by Grumman, is a 75-ft, 60-ton craft with conventionally placed, fully submerged hydrofoils, as shown in Fig. 1. The craft is capable of 50 knots in smooth water, carrying 88 passengers and a crew of four. It is also capable of open ocean operation in sea state 3.[1] Incidence-controlled foils, rather than trailing-edge flaps, provide optimum lift-to-drag ratios. The first Dolphin was constructed to Grumman specifications by Blohm and Voss in Hamburg, Germany.

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The Dolphin autopilot was built by the AiResearch Manufacturing Division of the Garrett Corporation, in accordance with a specification evolved from a series of studies performed on the HS Denison, the XCH-6, PC(H), AG(EH), and FRESH-1 hydrofoil craft.[2–5] During these studies considerable data on the effects of speed, size, weight, and sea state upon craft stability and performance were amassed. The data were used to establish the functional designs for the autopilots of these vehicles. Although differing in details, the designs all had a basic similarity to those for aircraft, in that heave (vertical) acceleration, pitch, and roll parameters were employed to operate control surface hydraulic actuators through a control computer.

II. Hydrofoil Control Problem and a Solution

In dealing with a design for which calm water instability is predicted, autopilot will certainly be required for stability augmentation. Moreover, our work has shown that submerged foil craft, whether stable or not, in calm water with fixed foils, tend to exhibit heave and pitch divergence in waves. Hydrofoil craft, therefore, operating in a relatively incompres-