PROTEUS—A Versatile Vehicle for Open-Water Hydrodynamics Research

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The design requirements and philosophy are described for a small, stable, high-powered craft for use as an experimental hydrodynamics research facility. The design concept evolved from requirements peculiar to the experience, environment, and resources of a small research laboratory and the result is a unique facility, tailored primarily for high-speed marine propulsion experiments, but with potential for much broader application. It is capable of operating at slow speeds as a displacement boat, at moderate speeds in a planing mode and at high speeds as a hydrofoil craft. Principal design characteristics, predicted performance, model tests, and instrumentation plans are reviewed. PROTEUS (Propulsion Research and Open-Water Testing of Experimental Underwater Systems) is currently under construction and is expected to be complete in 1971.

Introduction

IN hydrodynamics, the link between laboratory experiment employing water tanks and tunnels and actual in-service experience is often tenuous. Practical constraints on model size and speed are common and result in compromised representation of system geometry and flow state. This link may be strengthened by developing rational design techniques through experiments on large scale models run under realistic conditions in open water. Carefully planned, open-water research can be both scientifically significant and of direct use to the design engineer or naval architect, while the required facilities complement those in use in conventional laboratories.

The Defence Research Establishment Atlantic (DREA) is engaged in a long-term hydrodynamics research program aimed at improving performance and efficiency of naval ships, their components and equipment. Specific research topics include high-speed ship propulsion and optimum design of surface-piercing hydrofoil systems. DREA does not possess a towing tank, water channel or wind tunnel and must contract for conventional model tests elsewhere. However, DREA has considerable experience with open-water testing in hydrofoil and towed systems research, using the $3\frac{1}{2}$-ton "Rx"[1] and 20-ton "Baddeck"[2] hydrofoil craft.

DREA's location on Halifax Harbour permits boat trials in a wide spectrum of realistic environments. Measured distance courses are laid out in the harbour approaches, within the harbour confines, and in Bedford Basin. The latter is a large body of salt water, 200 ft or more deep over wide stretches and almost completely land-locked, being connected to the harbour by a narrow channel. An underwater acoustics range is available in the harbour approaches where water conditions vary from calm to over sea state 6, on occasion.

Ship propulsion is a field for which open-water test techniques are particularly appropriate. Conventional propellers are most efficient at ship speeds less than 25 knots and at relatively low rotational speeds corresponding to cavitation-free operation. Therefore, the operating range for conventional propellers is quite limited. Conversely, supercavitating propellers require high rotational and forward speeds for best efficiency. There is a region of partial cavitation conditions between the two in which neither conventional nor supercavitating types have best efficiency and propeller radiated noise reaches an objectionable level. Research could be profitably directed towards investigation of this "propulsor performance gap" and ventilating propellers which show promise of both good efficiency and noise characteristics in this intermediate zone. The injection of large volumes of air causes no problem in open water, and hydrodynamic performance tests can be combined with noise ranging without interference. Cavitation tunnels, while essential for certain basic studies, are not satisfactory for acoustic tests and have limited capability for testing fully ventilated propellers since air contained in the water tends to increase and is recirculated, thereby changing propeller inflow conditions. On the other hand, full-scale experiments in ships are costly and time consuming and seldom permit the variety or control of test conditions desired.

Design Requirements and Principal Characteristics

Efficient open-water propulsion research requires a small, high-speed craft, normally housed ashore. The design should permit rapid inspection, installation, and maintenance of propellers, variable ratio gear boxes, and other propulsion system components. A controllable, reversible, propeller pitch mechanism, and a source of air for propeller ventilation must be provided.

Performance requirements include the capability for testing over a wide range of marine screw rotational and inflow speeds extending from reverse through the subcavitating and partially cavitating (performance gap)[3] zones to supercavitating speeds. Speeds of up to 50 knots are required since this is a speed at which supercavitating and ventilated supercavitating propeller performance is clearly superior to conventional designs. It is also the speed at which contemporary water-jet technology approaches a practical limit and a speed at which meaningful research on cavitation of hydrofoil sections can be undertaken.

The boat must be sufficiently stable to permit operation as a steady test platform from slow speed displacement operation to high foilborne speeds. Maneuverability must be such as to permit safe operation at slow speed in confined spaces, rough water handling and utility as a working platform. Payload must include at least one test observer in

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Table 1 Principal characteristics

Dimensions		
Over-all length		33′ 0″
Maximum hull beam		9′ 0″
main foil span		24′ 4″
bow foil span		7′ 0″
Draught of hull (fully loaded)		1′ 3″
main foil		5′10″
bow foil		5′ 3″
Keel to airscrew centerline		7′ 0″
marine propeller centerline		4′ 6″
Foil base length-min-max		20′ 0″
		24′ 9″
Weights		
Planing boat (no foils or air propulsion)		7100 lb
Hydrofoil boat (maximum)		10,000 lb
Propulsion System		
Engines:	(2) United Aircraft of Canada Ltd. ST6 A-64	
Ratings: short	550 hp at 2200 rpm	
intermittent	445 hp at 2100 rpm	
continuous	390 hp at 2100 rpm	
Fuel: type	JP 5	
capacity	660 lb	
normal load	400 lb	
Marine propeller	3-blade, variable pitch	
Airscrew	Hamilton Standard, 3 blade, variable pitch, 8′0″ diameter	
Performance		
Speed: planing (no foils)		28 K
foilborne on either engine		35 K
foilborne on both engines		50 K

addition to the driver and a comprehensive research instrumentation system for propulsion experiments, hydrodynamic load measurements, boat motions, and flow monitoring.

An interesting additional requirement is the measurement of hydrodynamic loads on models suspended ahead of the craft in relatively undisturbed water. An instrumented test boom, mounted at the bow, would take advantage of the high-speed and extensive research instrumentation capabilities of the craft. Combined with flow visualization techniques, this added feature will permit fundamental studies of cavitation, ventilation, and hydrodynamic shapes.

Finally, the craft should permit good control over steady-state conditions for experiments on propulsion devices and test-boom mounted models and provide the versatility for wider application to possible future research on surface-piercing foil systems, ship control systems, and seakeeping research.

PROTEUS, the craft designed to meet the above combination of requirements, has a broad-beamed planing hull and a canard, surface-piercing foil system. Figure 1 illustrates general hull and foil system configuration and Fig. 2 is a three-view general arrangement sketch. The canard foil configuration is compatible with a hull form which is satisfactory for both planing and displacement operation when the foils are removed. It is also the system with which DREA has had most rough water experience and is the one in which Canada currently has most interest. The hydrofoil system will allow high-speed steady-state operation in the slight wind-lop often experienced in Bedford Basin. Alteration of foil parameters will allow a range of steady-state operating conditions for propulsion research and versatility in powering will be achieved by using two independent means of propulsion: a pusher airscrew and a marine propeller. Each is powered by a gas turbine engine. The two systems will be capable of use independently or in combination. Each will be completely removable to allow use of the stern space above or below the water level for research equipment. Conversion to a water-jet system, installed in the stern well, is possible when the marine outdrive unit is removed, and the airscrew system may be replaced by a small turbofan. The gas turbines, manufactured in Canada, have a high power-to-weight ratio, excellent growth potential and are available in a marinized version. Principal characteristics of the craft are summarized in Table 1. Fully-equipped all-up weight is 10,000 lb, broken down as shown in Table 2. Propulsion system weights include engine weights, and payload totals 1800 lb. Equipped as a planing craft without airscrew propulsion, all-up weight is 7100 lb.

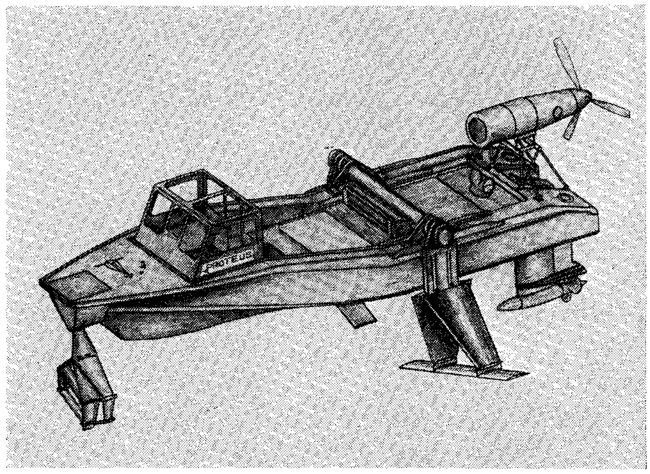

Fig. 1 PROTEUS.

Table 2 PROTEUS weights

Hull structure			2900 lb
Mechanical and electrical systems			900
Propulsion system:	marine	1500	
	air	900	
			2400
Foils:	bow	400	
	main	1600	
			2000
Research instrumentation			900
Crew (3)			500
Fuel (normal load)			400
All-up weight			10000 lb

Hull Design

The hull has fine lines forward to reduce wave impact loads, bow wavemaking and wetness. It has a low, full beam, and constant 15.0° bottom deadrise aft for good planing performance and stability. It is subdivided by four watertight bulkheads into five compartments, which comprise (from bow to stern) a small buoyancy chamber, wheelhouse, research instrumentation compartment, forward engine

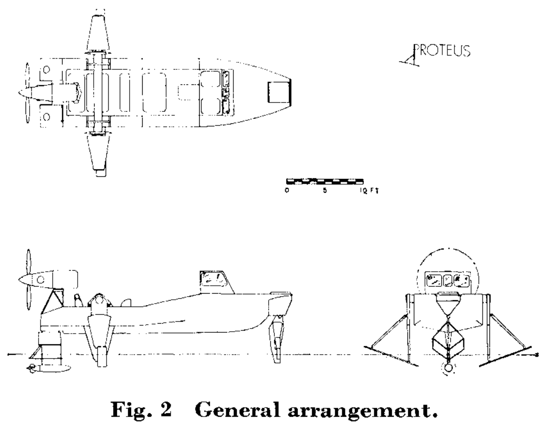

Fig. 2 General arrangement.

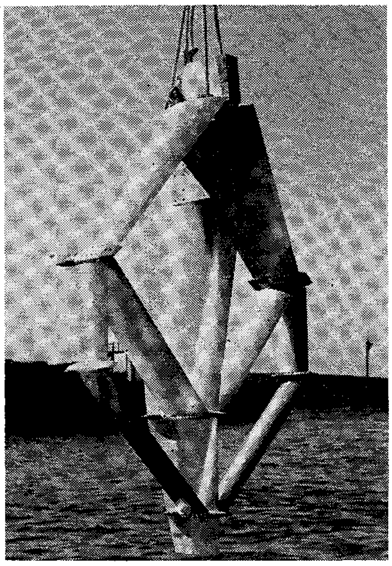

Fig. 3 Bow foil.

compartment which houses fuel tanks and systems, and aft engine compartment. A bollard stressed for towing at speeds to 35 knots is mounted on the forward deck. Sufficient strength has been provided in the stern to permit later installation of transom flaps.

Hull structure comprises a light, riveted aluminum shell over transverse frames and longitudinal stringers. The hull bottom structure has been designed to resist hullborne slamming and sudden loss of bow foil lift when foilborne. Peak pressures of 30 psi at 35 knots for slamming and 48 psi at 40 knots for foilborne crash cases were estimated. Consideration of permanent deformation and fatigue life criteria led to the selection of $\frac{3}{32}$ in. aluminum plate on frame and stringer spacings of 18 and 6 in., respectively.

Foil System

The nonretractable, surface-piercing, canard foil configuration for PROTEUS is shown in Fig. 2. It has been designed to provide a smooth, stable, high-speed test platform and incorporates variable geometry to permit research on surface-piercing hydrofoil hydrodynamics and sea-keeping. Satisfactory steady running conditions cannot be easily achieved at speeds much beyond 20 knots without using hydrofoils, and higher speeds will be needed in most of the work envisaged for the craft.

The bow foil shown in Fig. 3 consists of a double V ladder arrangement with central strut and anhedral upper foil. Pin-jointed connections permit ready replacement of individual foils with others of different geometry and section. Alternative locations of the anhedral apex permit the lower foil dihedral to be varied from 25° to 45°. The bow foil unit is attached to the hull through a dynamometer assembly capable of measuring lift, drag and side force. The entire foil assembly may be raked forward and aft by an electric actuator, and hydraulic power steering is incorporated.

The main foil is split with the single dihedral and anhedral foils on each side supported on a single strut which is, in turn, attached at its upper end to an athwartship beam. This main foil beam is connected to the hull through a three-axis dynamometer and the main foil assembly can be moved fore and aft on deck rails. This fore and aft movement permits bow foil loadings up to approximately 20% of all-up weight. The entire main foil assembly may also be manually adjusted through a vertical distance of 6 in., and raked forward and aft. The main dihedral foil can be easily changed and its dihedral angle varied from 10° to 27°. Main anhedral foil structure incorporates provisions for ailerons or flaps. Both main and bow foil strut trailing edges are removable to permit their use as base-ventilated sections.

First fit bow and main dihedral foils are of unswept, constant chord planform with 7.5% thickness-chord ratio, flat faced ogival (plano-convex) sections. Anhedral foils are symmetrically tapered and employ 10% thick, flat faced, ogival sections. Struts are tapered and have 10% thick biogival sections. Foil and strut section shapes were chosen for their ease of manufacture and relatively high cavitation inception speed.

Although a foil system research program is not currently planned, initial trials of PROTEUS will provide data for comparison with predictions and permit evaluation of both foilborne performance and stability and DREA simulation methods.

Variable foil system geometry is needed for control of propulsor draft and trim as well as to provide good stability over a wide range of loadings and speed. This feature also makes it possible to use the craft for meaningful foil system research and permits further development of the Canadian, canard, surface-piercing system.

Propulsion System

The underwater propulsion unit consists of a hull-mounted ST6 A gas turbine, driving a marine screw through a Z drive contained in a single strut and pod. Primary design requirements for the outdrive unit are lightness, underwater streamlining and ease of maintenance commensurate with the required durability and power capacity. The unit will weigh approximately 960 lb and caters for an engine growth to 650 hp normal rating at 2200 rpm.

The marine drive unit, supplied by Hydro Drive Corporation of Seattle to DREA specifications, is attached to the transom in the stern well and is steered by a hydraulic actuator through an angle of ±20°. The complete unit may be easily detached for ease of maintenance or use of the stern well for other marine propulsion devices. Special provisions include a shaft brake, which prevents turbine motoring, and interchangeable upper gear sets for ratios of 1:1, 1.46:1 reduction, and 1.48:1 stepup.

The lower, biogival, strut section is cast integrally with the pod in aluminum. The removable, hollow strut leading edge permits installation of depth-of-immersion transducers. There is sufficient internal space aft of the leading edge for propeller ventilating air piping (50 ft^3/min at 100 psi), instrumentation cabling and the variable pitch propeller control rod. A propeller antiventilation plate is fitted externally to the lower strut. Clearance between the propeller tip and antiventilation plate may be easily adjusted to accommodate different propeller diameters. The propeller shaft is hollow and may be ported through the hub to permit propeller blade ventilation, but for constant pitch only. Hub design allows easy replacement of individual blades and the hydraulic, reversible-pitch mechanism permits a wide range of blade angles to be tested. This mechanism, the lower gear set, propeller thrust and torque transducers and a Pitot static tube with transducer are all housed in the lower pod.

The initial propeller fitted to the Hydro Drive unit will be a Newton-Rader, 3-bladed design fabricated from 17-4 PH steel. Methodical series data are available from Vosper Cavitation Tunnel tests of 10.0-in.-diam models with varying pitch and area ratio.[4] These propellers obtain good efficiencies under cavitation conditions without significant penalty in noncavitating operation. It is planned to test the first PROTEUS marine screw in a cavitation tunnel for comparison with the Vosper data and measurements of torque and thrust using PROTEUS instrumentation.

As a marine propulsion research vehicle, PROTEUS requires an auxiliary thrust capability to permit control of marine propeller inflow or slip conditions, windmilling and locked shaft performance experiments and measurements of

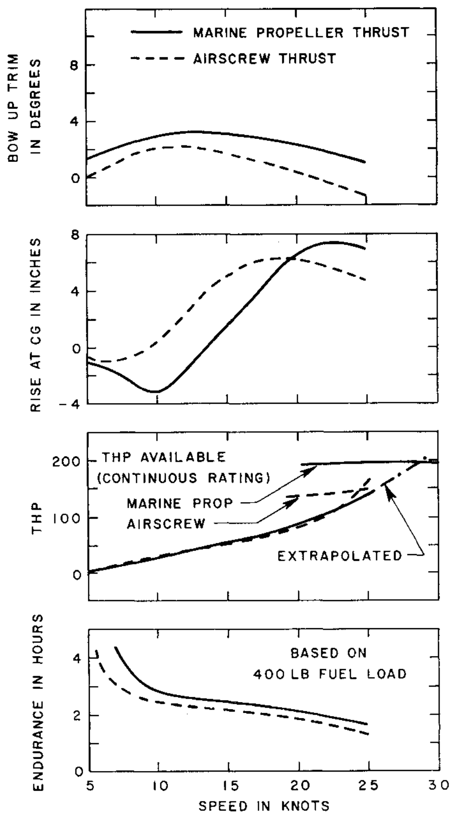

Fig. 4 Planing performance.

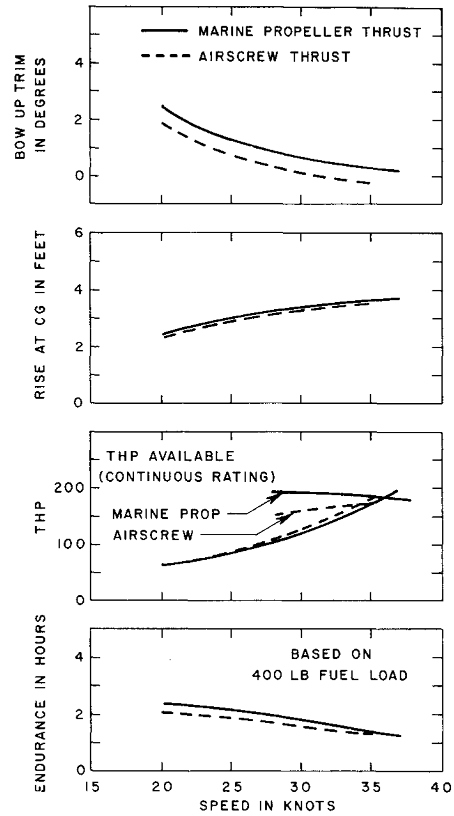

Fig. 5 Foilborne performance.

underwater radiated noise at speeds to 35 knots with marine screw removed.

The air propeller system is relatively simple and inexpensive and its engine and systems are similar to that for the marine drive gas turbine. It consists of an ST6 A gas turbine engine mounted in a nacelle supported by a pin-jointed truss attached to the stern. Thrust is measured by a four pillar dynamometer, similar in design to that used at the bow foil, fitted between the nacelle and the supporting truss.

The engine drives a Hamilton Standard, aluminum, pusher propeller. The propeller has automatically controlled, constant RPM operation at low-power settings, for slow speed forward and reverse thrust, and provision for manual feathering. The propeller system combines good control for maneuvering and docking at slow speeds with efficient engine and propeller performance matching at higher speeds.

Predicted Performance

Rise, trim and resistance characteristics are presented in Fig. 4 for representative conditions in the planing mode and are based on model test data. Endurance estimates are also presented for the normal 400-lb fuel load. Internal tank capacity allows a fuel overload of 260 lb when required. Maximum predicted planing speeds of 24 knots using airscrew propulsion alone and 28 knots using a marine propeller are based on conservative estimates of propeller efficiency at continuous engine rating.

The selected initial foil configuration offers the predicted single engine performance shown in Fig. 5. Characteristic low resistance, hence high maximum speed and good endurance, and little change of trim and draft with variation in power configurations are indicated. The latter result is particularly significant for propulsion tests since marine propeller draft and inflow angle will remain substantially unaltered over a wide range of air and marine propulsion system thrust combinations. Estimated maximum speed is 36 knots using the marine screw and 34 knots using the air propeller alone. Endurance is about 1.5 hr, assuming continuous running at 35 knots and normal 400-lb fuel load, although 3 hr or more can be obtained on maximum internal fuel under more realistic conditions.

Predicted Stability

Conventional hydrostatic calculations for the craft in the displacement mode have indicated good stability margins in pitch and roll. PROTEUS should have very good tolerance to a wide range of loading conditions at low speed and should therefore provide good working platform characteristics. There may be a tendency to porpoise when powered by marine screw alone when the c.g. is at an extreme aft location but this tendency should be easily overcome by either providing transom flaps or operating with the bow foil unit attached.

Computer studies of dynamic stability in calm water have shown that the variable foil geometry gives good control over natural frequency and damping of the boat's characteristic modes of motion, thus permitting meaningful sea-keeping research. These studies are based on a linear mathematical model and the assumption of subcavitating, nonventilating flow over the foils at speeds from takeoff to approximately 40 knots.

Root loci for the craft with the initial foil configuration, as foilborne speed is varied from 20 to 40 knots, are shown in Fig. 6. DREA computer studies and experience with small, canard, surface-piercing craft indicate that excellent longitudinal response in a seaway can be obtained with a combination of bow foil lift slope and high stiffness or rate-of-change of lift with draft. This combination leads to the characteristic lightly damped, relatively high natural frequency pitch mode shown in the figure. The heave mode is generally better damped and of lower natural frequency than the pitch mode and is primarily dependent on main foil characteristics. Both lateral-directional modes demonstrate ample stability over the foilborne speed range. Good roll mode damping is due to the wide track of the main foils.

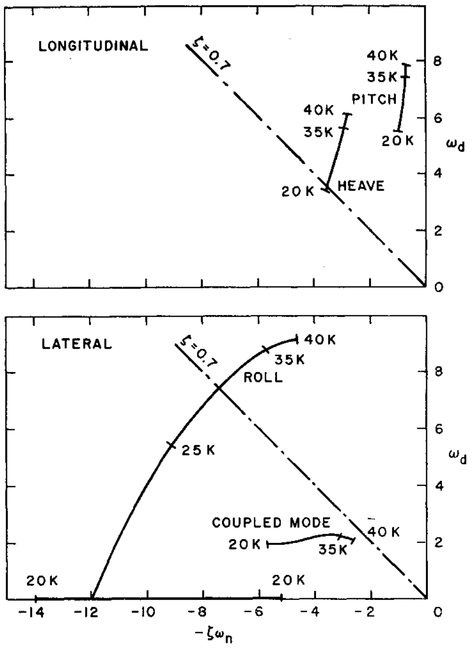

Fig. 6 Characteristic root loci.

Free-to-rise-and-trim towing tank tests have demonstrated that, with fences fitted to the lower bow dihedral foil, longitudinal dynamic behaviour is satisfactory. Removal of the fences leads to porpoising due to cyclic inception and suppression of ventilation at the higher bow foil rake angle settings. This cyclic pitching phenomenon was also encountered on DREA's Rx hydrofoil craft when fitted with a subcavitating bow foil.

Model Tests

Tests were conducted at the National Research Council (NRC) towing tank in Ottawa using a three-eighths scale model with and without foils. The initial hullborne experiments consisted of free-to-rise-and-trim tests at full-scale speeds to 25 knots with the model constrained laterally. Craft weights from 6000 to 10,000 lb were simulated and results are reported in Ref. 5. Performance was generally satisfactory at planing speeds except for extreme combinations of powering configuration and c.g. location. The craft trimmed excessively bow down when ballasted to simulate airscrew thrust alone with the c.g. at its forward limit. There was also a tendency for the craft to porpoise when powered only by the marine propeller simulated thrust with the c.g. at its aft limit. The vertical c.g. location was incorrectly modelled and this may have aggravated the porpoising tendency but the possibility remains that transom

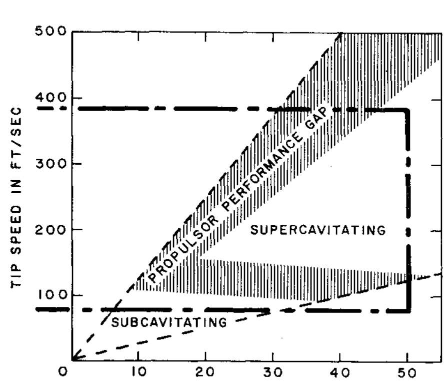

Fig. 7 PROTEUS propeller research envelope.

flaps may prove necessary when operating without foils in some circumstances. Further tests were conducted at a series of fixed drafts and trim angles to determine resistance with and without the propulsion strut.

An extensive series of foilborne tests has also been carried out at NRC. Initial free-to-rise-and-trim tests were conducted at a main foil loading of 90% of all-up weight for marine propeller simulated thrust. The effects of independent variations in bow and main foil rake angles were examined. Resistance was found to be lower than predicted, and variation in trim and rise with speed followed predicted trends.

A series of fixed draft tests was conducted on the model main foil at various drafts and trim angles, and these demonstrated that the ogival section possessed excellent ventilation- and cavitation-delaying properties.

Research Instrumentation

PROTEUS is intended as a versatile test craft and requires a flexible recording system with a high data capacity, particularly for so small a vehicle. Typical recording requirements are outlined in Table 3. The system will probably be based on frequency division multiplexing since this should give adequate accuracy and should be lighter and more flexible than a direct digital system.

A small oscillograph recorder will be fitted to permit monitoring of essential data during trial runs and a signal patchboard will be employed for flexibility and convenient interchange between transducer signals, tape amplifiers, and multiplexing and monitoring equipment.

Torque and thrust are measured in the marine drive pod. These measurements are fundamental to the success of marine screw performance experiments and high output and reliability are required. A load cell will measure thrust and a strain-gaged shaft with rotating transformer pickup will measure torque. Load cells in the transom attachments will provide a secondary or back-up thrust measurement capability. In addition, both gas turbines will be fitted with engine output torque transducers and tachometers. Air screw thrust will be measured by a strain gage system incorporated in the engine mounting structure.

Hydrodynamic forces generated by the bow foil or boom-mounted models will be measured on a three-axis bow dynamometer. The dynamometer comprises four vertical, strain-gaged pillars mounted between two 30-in. square, horizontal frames. The upper frame is rigidly attached to the hull and the lower frame to the bow foil assembly. Bow foil lift, side and drag force moments are obtained from the pillar strain gage bridges. Bow foil drag and side force are measured by differential transformers. Dynamometer requirements are particularly exacting since the dynamometer assembly must be small and light to avoid excessive weight. It must also be rigid enough to avoid cross coupling, to measure translational forces accurately in a high moment situation and to withstand foil impact loads.

Further development of the instrumentation system for propulsion research will include installation of an impeller type knotmeter for more accurate measurement of slow speeds. The possibility of photographing the marine screw through the antiventilation plate is being studied. Consideration is also being given to measurement of blade surface pressures, blade root strains, and shaft vibrations to provide some capability for research on unsteady load phenomena. Provisions for recording ventilating airflow rate, temperature and pressure will be required for superventilated propeller tests.

Propulsion Research

Figure 7 is a diagram outlining the practical operating regimes for various types of marine propellers. Tip speed

Table 3 Typical recording requirements

Measurement type	Frequency range, hz.	Over-all accuracy	Number
Propulsion data	0–5	1%	8
Motional data	0–5	2%	9
Loads and pressures	0–100	5%	9
Systems monitoring	0–25	5%	6
Vibrations and acoustic	25–8000	10%	4
Voice	0–5000	...	1

in fps is plotted vs ship speed in knots. Data for this figure have been derived from Morgan and Tachmindji.[1] The "subcavitating" zone is the most efficient region for subcavitating, conventional propellers and its upper boundary is an approximate practical limit on tip speed for relatively cavitation-free operation. The "supercavitating" zone is an area of high forward and high tip speeds in which supercavitating propellers have best efficiency. Perhaps the most important zone for propulsion research is the zone labelled "propulsor performance gap." This is the region in which neither conventional nor supercavitating propellers have best efficiency. Operation in the lower leg of this zone, in particular, usually results in partial cavitation. Ventilated propellers, pump jets, water jets, and "noise reduced" propellers are propulsor devices which have the potential for improved efficiency and reduced cavitation noise in this region.

The PROTEUS marine propeller operating envelope made possible by the provision of special features such as variable gear ratio and auxiliary thrust is shown as a heavy chain-dotted line on Fig. 7. The envelope encloses the whole of the "performance gap" to high tip speeds and significant portions of the regions for best conventional and supercavitating propeller operation. It also indicates that meaningful research could be conducted outside of these zones where considerations such as bollard pull or reverse thrust rather than efficiency determine design. In addition, PROTEUS is configured to permit installation of propulsion devices other than propellers which may also have important application in the performance gap.

Conclusion

In this paper, the design philosophy for a unique and versatile hydrodynamics research vehicle, currently under construction, has been presented. The small size of this manned vehicle gives many advantages in maintenance, modification, and cost. The foil system is designed to provide a stable experimental platform at high speeds but is sufficiently versatile to permit meaningful research into fundamental problems of canard, surface-piercing configurations. The craft may also be used without foils in displacement or planing modes and an instrumented boom attached to the bow dynamometer will allow testing of isolated hydrodynamic shapes in relatively undisturbed water ahead of the boat. Marine propulsion system qualification trials will be carried out in early 1970 and first trials of the complete craft are expected in 1971.

Primary initial use of the facility will be propulsion research, particularly in the field of super-ventilating propellers, but provisions have been made for other forms of propulsion as well. The variable geometry hydrofoil system permits control of draft and trim angle for a given speed while the air propeller allows control over boat speed for a given RPM and pitch while conducting marine propeller tests. Tests covering a wide range of primary marine screw performance parameters such as advance ratio, cavitation number, and pitch can thus be carried out. PROTEUS is a logical outgrowth of the experience, resources and natural environment of DREA and is expected to considerably enhance the potential of the establishment for further contributions to hydrodynamics knowledge.

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