HYDROFOIL OVERVIEW - A BRIEF TUTORIAL

By

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INTRODUCTION

The basic principle of the hydrofoil concept is simply to lift a ship's hull out of the water and dynamically support it on wing-like lifting surfaces, i.e, hydrofoils, in order to reduce the effect of waves on the ship and to reduce the power required to attain modestly high speeds. Engineers and naval architects have been intrigued with the possibilities envisioned by this concept for many years. A United States patent for a hydrofoil was defined in the late 1880's, about the same time as the early airplane and airfoil patents. The earliest record of a successful hydrofoil flight is 1894 when the Meacham brothers demonstrated their 14 foot test craft at Chicago, Illinois. This compares with the Wright brother's first airplane flight in 1903. The early attempts to exploit the hydrofoil concept were frustrated by lack of suitable structural materials and power plants. However, advancement in these areas, much of it stemming from aircraft developments, have permitted development over the past 30 to 40 years of the technology necessary to achieve and demonstrate reliable and effective hydrofoil ships for both military and commercial applications, see Reference [1]. History of early developments and later U.S. Navy programs is detailed in References [2] to [5].

HYDROFOIL CONFIGURATIONS

Hydrofoil configurations can be divided into two general classifications, surface piercing and fully submerged, which describe how the lifting surfaces are arranged and operate (see Figure 1). In the surface piercing concept, portions of the foils are designed to extend through the air/sea interface when foilborne. Struts connect the foils to the hull of the ship with sufficient length to support the hull free of the water surface when operating at design speeds. As speed is increased, the lifting force generated by the water flow over the submerged portion of the foils increases causing the ship to rise and the submerged area of the foils to decrease. For a given speed the ship will rise until the lifting force equals the weight carried by the foils. As indicated by the terminology, the foils of the fully-submerged concept

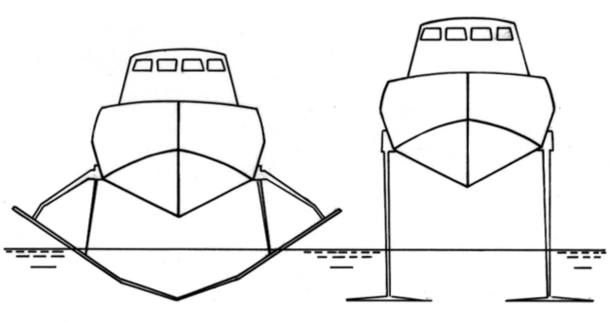

Figure 1-Surface-Piercing & Fully-Submerged Foil Configurations

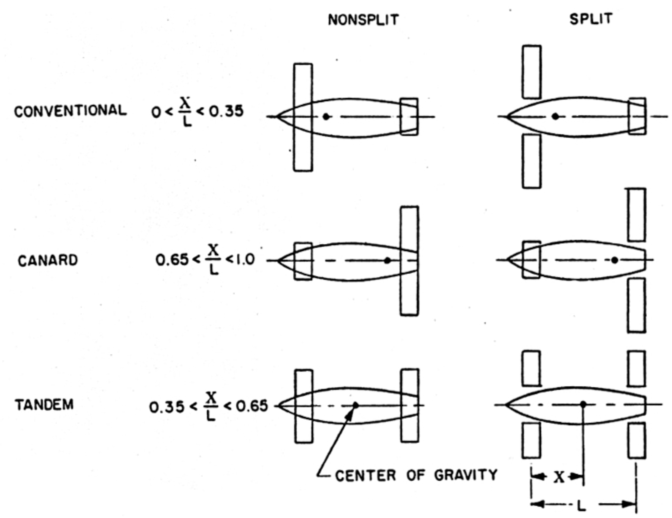

Figure 2-Foil/Strut Arrangements

are designed to operate at all times under the water surface. The struts which connect the foils to hull and support it when the ship is foilborne generally do not contribute to the total hydrofoil system lifting force. In this configuration, the hydrofoil system is not self-stabilizing. Means must be provided to vary the effective angle of attack of the foils to change the lifting force in response to changing conditions of ship speed, weight and sea conditions. The principal and unique operational capability of hydrofoils with fully-submerged foils is the ability to uncouple the ship to a substantial degree from the effect of waves. This permits a relatively small hydrofoil ship to operate foilborne at high speed in sea conditions normally encountered while maintaining a comfortable motion environment for the crew and passengers and permitting effective employment of military equipment. It is this desirable characteristic which has caused the hydrofoil ship development in the United States to concentrate on the fully-submerged foil concept. The basic choices in foil and strut arrangement are canard, conventional or tandem as shown in Figure 2. Generally ships are considered conventional or canard if 65% or more of the weight is supported on the front or aft foil respectively. If the weight were distributed relatively evenly on the fore and aft foils, the configuration would be described as tandem.

HYDROFOIL CHARACTERISTICS

Resistance and Powering

Although the major reason for the employment of hydrofoils is to lift the hull out of the water to reduce the effect of waves and to reduce the drag at high speed, a naval hydrofoil ship spends a considerable portion of its life hullborne and must have an efficient hull form to keep the drag low at low speed and through takeoff. Total drag just prior to takeoff is a significant factor in establishing the power requirement. Careful attention must be paid to the hull design to minimize this effect. Figure 3 shows a generalized smooth water drag curve for a hydrofoil craft with its significant "hump" prior to takeoff. Comparison is also made with a typical planing craft to illustrate the high-speed advantage of the hydrofoil even in smooth water. In order to overcome additional takeoff drag which results from rough water, a power margin over the smooth-water takeoff drag is required. Since the magnitude of this margin is a prime factor in the sizing of the propulsion system, it is essential that it not be arbitrarily overspecified. Tests in design sea states on well-instrumented U.S. Navy hydrofoils show that 20 to 25 percent margin is ample to permit takeoff in rough water in any direction.

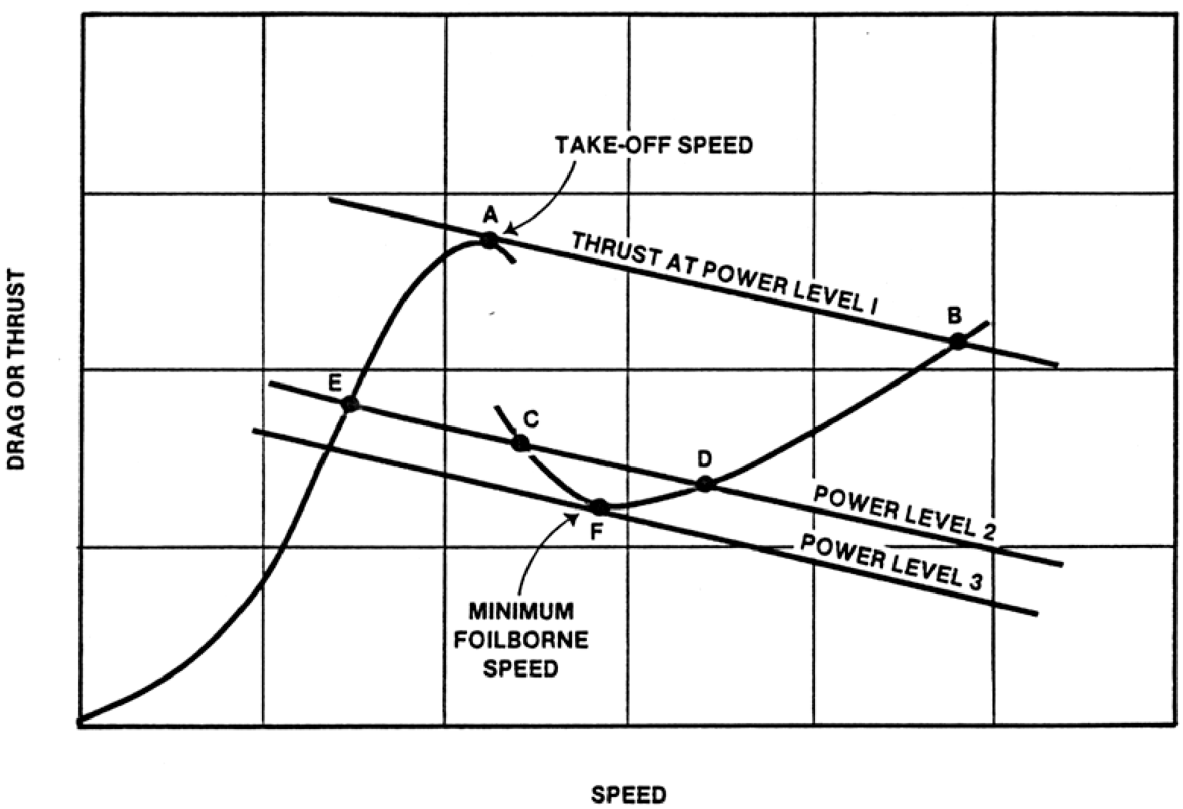

Figure 3-Typical Calm Water Thrust and Drag Curves

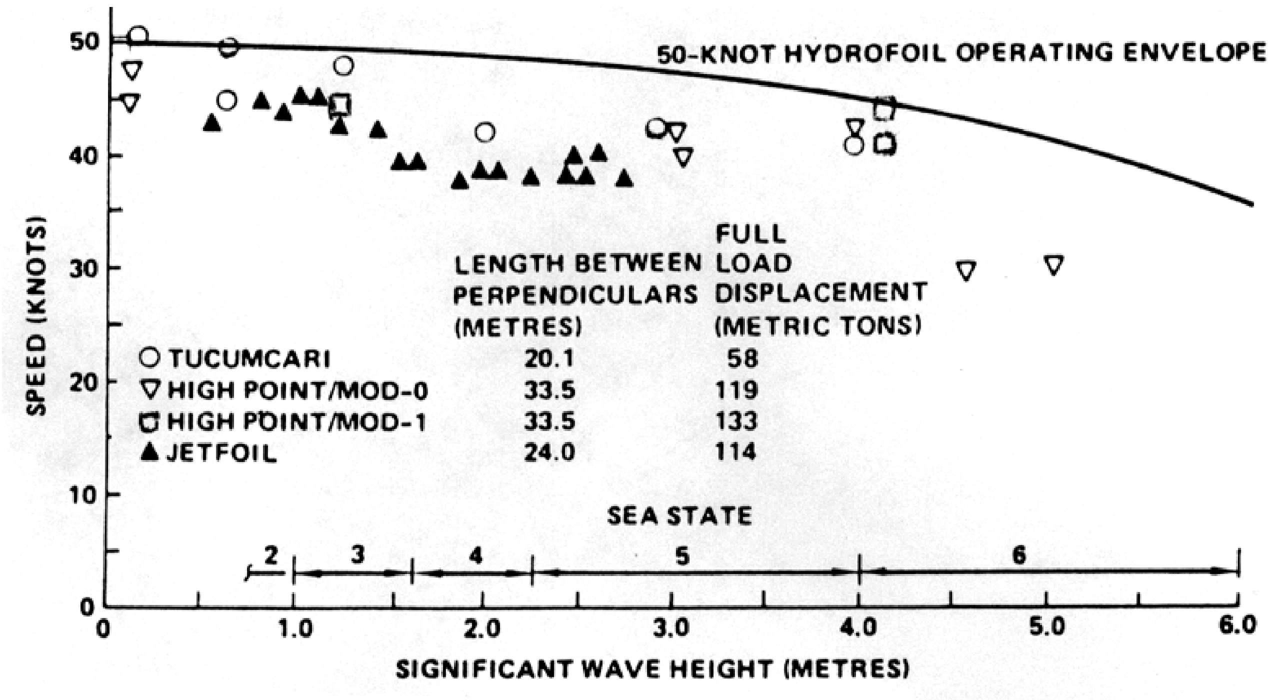

Figure 4-Effect Of Sea State On Hydrofoil Speed

Seakeeping

Some of the principle advantages of hydrofoil ships, over all other monohull or alternative ship types are: (1) the ability of a ship, which is small by conventional ship standards, to operate effectively in nearly all sea environments, and (2) an improved ratio of power to displacement in the 30 to 50 knot speed range permitting economical operation at these higher speeds. The submerged-foil ship can maintain its speed and maneuverability in heavy seas while simul- taneously providing a comfortable working environment for the crew. The ship's automatic control system (ACS) provides continuous dynamic control of the ship during takeoff, landing, and all foilborne operation. In addition to providing ship roll and pitch stability, the ACS controls the hull height above the water surface, provides the proper amount of banking in turns and all but eliminates ship motions caused by the orbital particle motion of waves. Foilborne operations only become limited as wave height exceeds the hydrofoil's strut length. Figure 4 shows operating data points for three submerged-foil hydrofoil ships in actual sea conditions. The data clearly show only a modest reduction in speed as wave heights increase. A hypothetical operating envelope is drawn to represent hydrofoils designed to have a 50-knot speed capability in calm water.

Maneuvering

Besides a significant speed advantage, hydrofoils are more maneuverable and provide a more stable platform than conventional ships. Foilborne turns are accomplished in a banked (coordinated) fashion. This causes the centrifugal force required in turns to be provided predominantly by the reliable lift capability of the submerged foils rather than by the unpredictable side forces from the struts. Turn coordination enhances crew comfort during high-rate turns because the accelerations due to turning are felt primarily as slightly greater vertical forces rather than lateral forces. For example, a 0.4g turn is felt as only 0.08g vertical acceleration increase while the lateral acceleration is zero. Therefore, hydrofoil ships have design turn rates of 6 to 12 degrees per second, two to four times those of conventional ships, and they can maintain these rates in both calm and rough seas. This makes the hydrofoil ship a more difficult target for enemy missiles, guns, or torpedoes. The exceptional stability of the hydrofoil ship makes it a superior platform in which to mount surveillance equipment and weapons while maintaining crew comfort and proficiency.

HYDROFOIL FEATURES

Weight Limitations

Like the airplane designer, the hydrofoil designer must, at all times, be extremely conscious of weight. The hydrofoil type of craft is weight critical and every pound of weight saved in structure, outfit, or machinery means weight available for payload and fuel.

The structural engineer, in designing hydrofoils to conserve weight, uses aircraft techniques. Relative to conventional ships, hydrofoil craft are subject to very high loadings, as caused by high operating speeds. Likewise, lightweight, high strength materials are used. He also must contend with fatigue and problems of hydroelasiticity, including both divergence and flutter.

Hull Considerations

The development of a satisfactory hull form for hydrofoil application represents a significant challenge to the designer. The hull should perform well in the hullborne mode but also during takeoff and during foilborne operation where impacts with waves are involved. In addition, the hull configuration of a hydrofoil ship must satisfy all of the requirements for strength, freeboard and intact and damaged stability for any other ship.

Relatively high power requirements for high-speed operation, in common with other high- performance systems, pay a high performance dividend for achieving a minimum weight structure. Therefore, hydrofoil ship hulls generally constructed using high-grade aluminum alloys, 5000 series weldable alloy being typical. Structurally, the hull must have the strength to resist wave impact at high speed as well as distribute the concentrated load at the strut attachment points. Although hydrofoil hulls may appear quite conventional, the required compromises are more complex than for a monohull because of the many operating modes of the ship. An efficient hull form for a lower speed operation requires a narrow beam. However, a righting moment large enough to satisfy the stability criteria of reference [6] with the foils retracted generally dictates a wide beam. Cresting the tops of waves while foilborne points toward the use of a deep vee forward and high deadrise.

Another major consideration in hydrofoil hull design is the requirement for good seakeeping characteristics in a heavy sea. If hydrofoil craft are to operate unrestricted in open ocean, they must be capable of surviving storm seas in the hullborne condition. Furthermore, in certain missions, it may be expected that the hydrofoil ship will spend the greater portion of its operating lifetime in the hullborne mode. Thus, it is essential that close attention be given to the hull seakeeping characteristics. With the foils extended during hullborne operation, which is normal operation at sea, there is a significant reduction of craft motion, in both the roll and pitch modes which is normally not heavily damped. Thus the strut/foil system gives hydrofoil craft hullborne motion characteristics of ships having much larger displacement.

Foil Systems

Foil variable lift is obtained by either trailing edge flaps or variable incidence of the entire foil as illustrated in Figure 5. A fundamental limitation is imposed by the so-called "square-cube" law, which impacts the growth potential of hydrofoil ships. The lift developed by the foils is proportional to their planform area (the square of a linear dimension), whereas the weight to be supported is proportional to a volume (the cube of a linear dimension). It follows that as size of the hydrofoil is increased, the foils tend to outgrow the hull. Aircraft solve this problem by increasing speed and wing loading as size is increased, but practical hydrofoil speeds are limited by cavitation. In the early period of hydrofoil development it was felt that an increase in the foil and strut weight fraction by direct application of the square-cube law would inherently limit hydrofoil size.

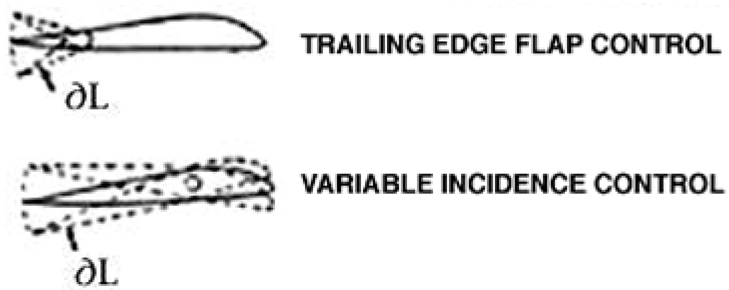

Figure 5 - Hydrodynamic Force Control

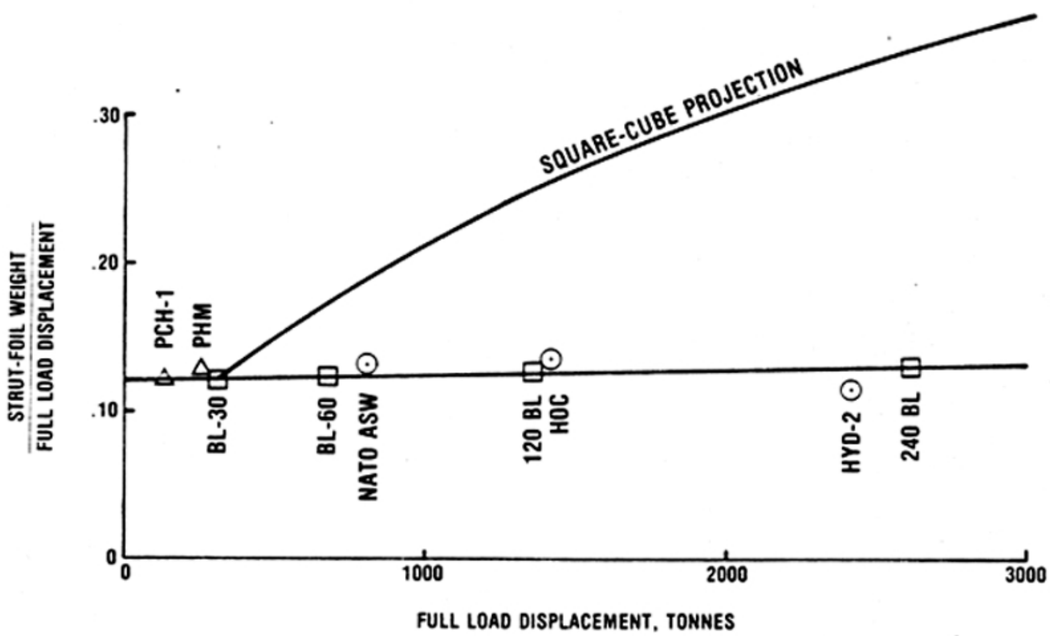

Figure 6 - Strut and Foil System Weight Trend

More detailed design studies show that foil system weight fractions increase only slightly with displacement, Figure 6. The principal reasons why the weight fraction does not increase as might be expected is that required strut length varies with design sea state, not ship size, and larger foils are structurally more efficient. For hydrodynamic efficiency, it is desirable to use as high a foil aspect ratio (span/chord) as possible. The PHM aft foil extends almost 10 feet on either side of the hull. Thus, a camel is normally used to hold the ship away from the pier for mooring. When no camel is available the ship must be moored across the end of a pier or the transom of a larger ship with the stern overhanging. PHMs have occasionally nested bow to stern. As ship size increases and foils grow relative to the hull and in actual dimension, practical considerations dictate efforts to limit the span. The trend will be to move toward tandem foil configurations to divide the weight more evenly between the forward and aft foils.

Propulsion Systems

Modern hydrofoil ships have been made possible by the development of lightweight diesel engines and marinized gas turbine engines. Most of the European commercial ships using fixed surface-piercing foil systems have used lightweight diesel engines driving subcavitating propellers by means of an angled transmission system. This combination provides simplified construction, relative ease of maintenance and low cost. However, the comparatively high specific weight (6-8 pounds per horsepower) of the diesel engines and higher overall drag have resulted in practical design speeds of these ships of about 35 to 40 knots.
Existing aircraft gas turbine engines slightly modified and coupled with specially designed free powered turbines are available in sizes with power ratings up to about 30,000 horsepower and specific weights of around 0.5 pounds per horsepower. The newer large engines employing blade cooling techniques have specific fuel consumption rates at their design power about equal to diesel engines. Gas turbine engines have been used in all major U.S. military and commercial hydrofoil ships permitting practical design speeds greater than 40 knots. Propellers are the most

efficient propulsion device available for operating over the subcavitating speed range of current hydrofoil ships. The power transmission systems required when using fully submerged foil systems consist of right angle bevel gears, flexible shafts and possibly a speed reduction gearbox in the propeller transmission pod. See Figure 7 as an example.

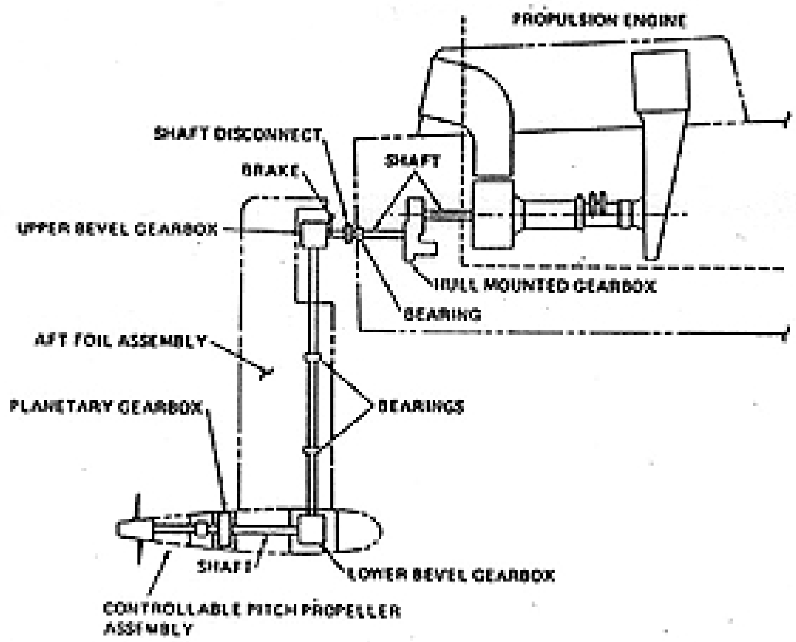

Figure 7 - PHG-2 FLAGSTAFF Propulsion System

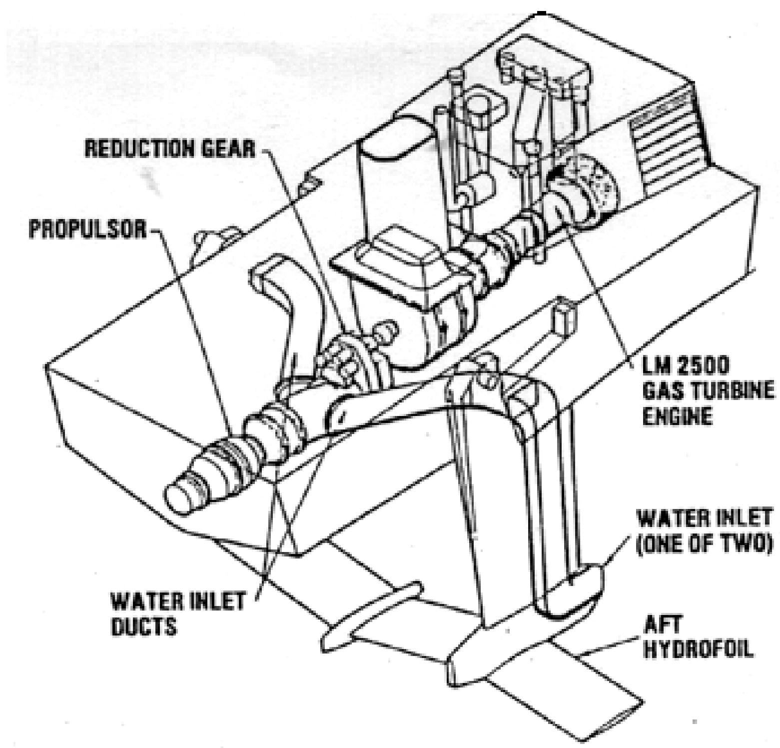

Figure 8 - PHM Waterjet System

Problems encountered with gear transmission systems in early hydrofoil ships led to interest in waterjet propulsion systems. While not entirely eliminating the need for gearboxes, these systems consist of underwater inlets, water ducts in the struts, a pump located in the machinery spaces and an above-water exhaust nozzle. The U.S. Navy's PHM waterjet system is shown on Figure 8. The price paid to achieve these less complex waterjet systems is a decrease in propulsive efficiency of about 20% at 45-50 knots and considerably more at takeoff speeds along with an increase in propulsion system weight due to the water carried in the system.

Automatic Control System

As noted earlier, surface-piercing hydrofoil configurations are self-stabilizing in both pitch and roll and thus do not require an automatic control system. However, to reduce the inherent reaction to rough seas, a number of ships have added trailing-edge flaps to the surface-piercing foils and have used autopilots for ride improvement.

In the United States, full automatic control of submerged foils has been deemed necessary to attain the seaway performance desired for ocean-going hydrofoil ships. Typically, control is accomplished by positioning trailing-edge flaps on the forward and after foils and by rotating the swiveled forward strut (rudder), or by moving the entire foil surface and by using the power driven aft strut as a rudder. See Figures 9 and 10 for schematic and pictoral diagrams of a control system. The control surfaces are positioned by means of conventional electrohydraulic servos. The control system motion sensors consist of: 1) a vertical gyro which measures craft pitch and roll angular motion, 2) a rate gyro which measures craft yaw rate, 3) three vertical accelerometers, one accelerometer being located approximately on top of each strut (the two aft accelerations work differentially to provide roll angular acceleration feedback, and they work in unison to provide pitch and heave acceleration feedback), and 4) a height sensor which measures the height of the bow above the water surface. The manual inputs consist of a foil depth command, which the helmsman uses to select any desired foil depth (or flying height), and the helm, which introduces the craft turning commands.

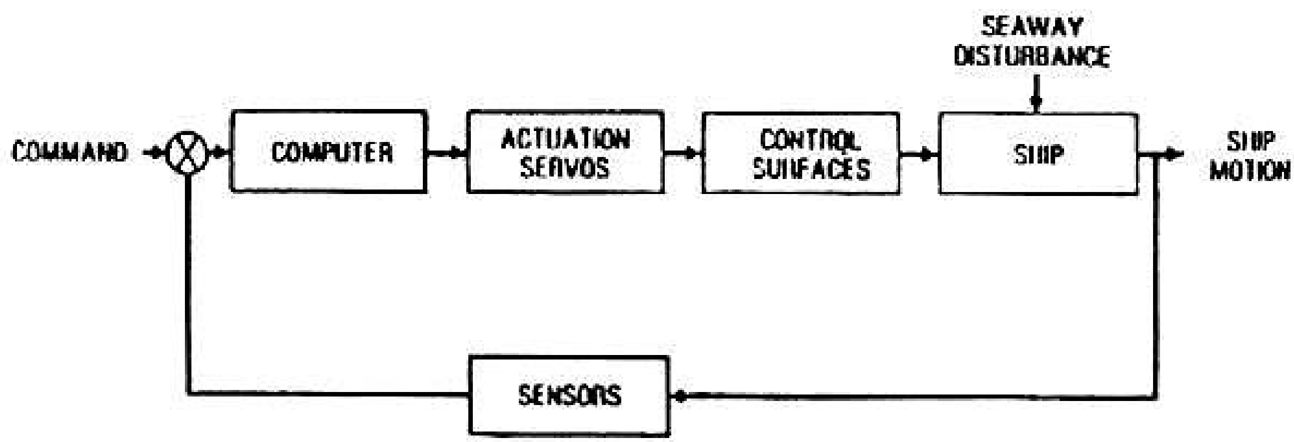

Figure 9 – Simplified Hydrofoil ACS Schematic

The ACS provides continuous control during takeoff, landing, and all foilborne operations. The pitch, roll, and height feedback loops provide automatic stabilization of the craft. The craft is automatically trimmed in pitch by the pitch feedback, and roll trim is accomplished by helm inputs. To steer the ship, the helmsman simply turns the helm, and the ACS automatically maintains a coordinated turn, with turn rate being proportional to helm deflection. ACS system requirements and operation are discussed in detail in References (7), (8), and (9).

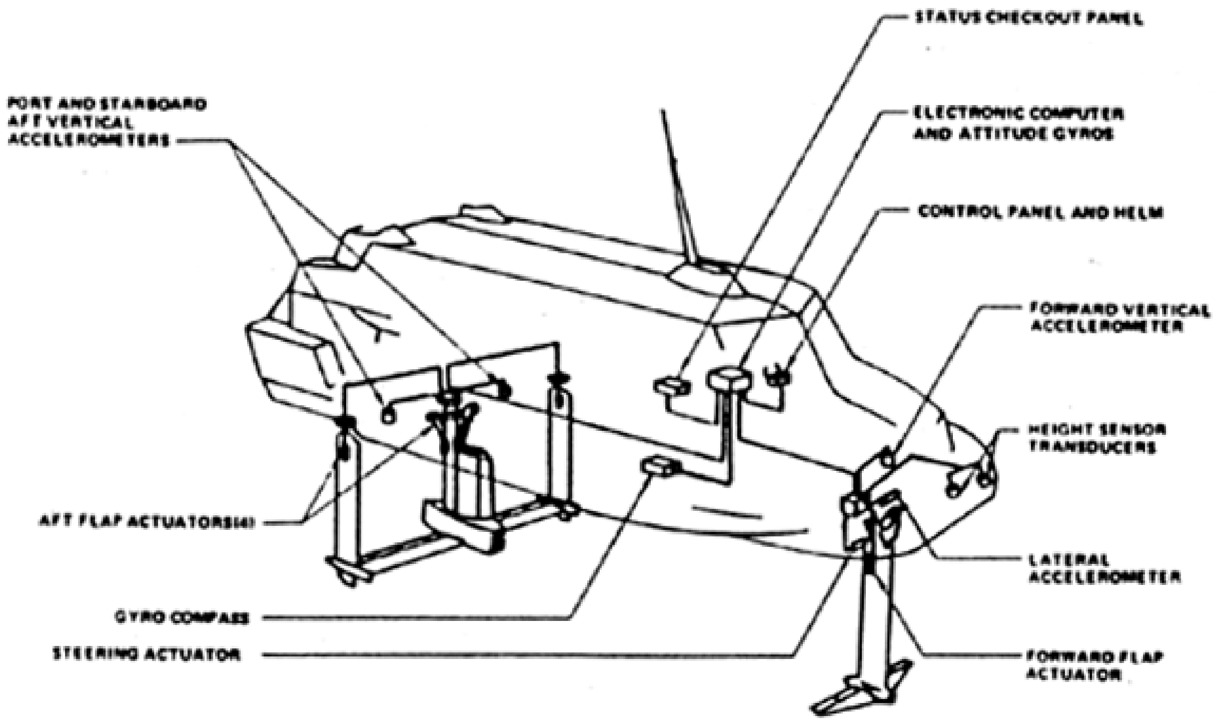

Figure 10 - Typical Hydrofoil ACS

Hydraulic System

The hydraulic and automatic control systems are worthy of mention because: 1) they have proven reliable and functionally well suited for a hydrofoil ship, 2) they combine proven aircraft system equipment applications, and 3) they are essential to all operations: foilborne, hullborne, and docking. Because the hydraulic systems are crucial to both foilborne and hullborne operation the design should employ multiple levels of redundancy to assure continued operation in the event of system failures.

On the PHM, for instance, four separate systems supply the required power to the various hydraulic equipment users which include the foilborne and hullborne control actuators, strut retraction and lock actuators, bow thruster, anchor windlass, and emergency fuel pump. Systems No. 1 and No. 2 supply hydraulics to the forward part of the ship while systems No. 3 and No. 4 supply the aft part. Two separate supply systems feed each user with provisions included to transfer (shuttle) the user from its primary supply to its alternate supply in the event of loss of primary supply pressure. The hydraulic systems of the PHM operate at a standard 3,000psi (20.68 MN/m^2) constant pressure. Proven aircraft hardware, mostly from the Boeing 747 aircraft, was used where possible. The hydraulic pumps, tube fittings, tubing material, and filters were all taken directly from the 747. In the case of the foilborne and hullborne steering actuators, an automatic shuttle valve was specifically developed for the hydrofoil program which rapidly transfers the user actuator from a failed supply to the alternate, thus assuring continued safe foilborne operation. The hydraulic actuators on the PHM were for the most part specifically designed and developed for this program. The four foilborne control actuators, the hullborne steering actuator, two hullborne thrust reverser actuators and the strut retraction actuators all were designed, manufactured and qualified to military specifications including rigorous environmental and life testing.

The hydrofoil program pioneered the use of a new hydraulic fluid, a synthetic hydrocarbon. This new fluid provides a much greater resistance to fire and explosion than its predecessor. At the same time it overcomes the serious shortcomings of phosphate ester base fluids which have proven to be incompatible with the saltwater environment.

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