The Development of Automatic Control Systems for Hydrofoil Craft

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SYNOPSIS

The modern hydrofoil has resulted from man's conviction that circumventing the Archimedes principle would help remedy some of the sea transportation problems. Attempts to develop lift and stabilise hydrofoils are fascinating examples of man's ingenuity coupled with his scientific and engineering skills. To the people whose insight now makes practicable naval ships and transportation systems using hydrofoils, this paper is dedicated.

The development of hydrofoil craft has been accomplished by two schools of endeavour. One school has pursued the surface-piercing principle whereby the craft is stabilised by a variable submerged area. The other school has been concerned with various means of controlling the incidence angle or lift on a fully-submerged foil. It is the progress of this latter school, from pitching the craft to change the foil angle of attack, through unique and innovative mecahnical means of controlling incidence, to the rather sophisticated electronic automatic control systems of today, that this paper intends to bring into perspective. Such a paper is not complete without discussing the methods employed to compute the proper control to tha foil surface. Finally, the paper concludes by describing what now appears to be a most promising future control system based on digital computer technology.

Introduction and background

The major reason for the employment of hydrofoils is, of course, the desire to lift the hull of a ship from the water and thus circumvent the constraints on high speed due to wave drag and frictional resistance of the hull. When the hull is lifted from the water and the weight of the ship is wholly supported by the foils, one can no longer depend on the hull to generate the restoring forces necessary to maintain the ship's attitude and stability. Such stabilising and control forces, therefore, must be generated by the foil system. These forces can be achieved either through active control of the lifting surfaces or through passive control by using a foil configuration which is inherently stable.

In order to review the history of hydrofoil control, it is essential that the fundamental differences of these two basic concepts of achieving stability and control of a hydrofoil are understood. This is perhaps best done by discussing the two basic foil system configurations used in hydrofoil ships. First, there is the surface-piercing foil system in which the lifting surfaces themselves penetrate the air-water interface as shown in Fig 1. Such systems are inherently stable in that the lift generated by the foils varies directly with the depth of foil submergence; in other words, as they go deeper in the water, more lifting surface becomes effective thus increasing the lift which tends to return the ship back to its equilibrium height. This phenomenon is called "area stabilisation." In the same manner, as the ship rolls, the outboard foil lift increases while inboard foil lift decreases, creating a moment to restore the ship to an unrolled condition. The degree of stability or stiffness can be altered by the nominal angle at which the lifting surfaces pierce the surface. As can be seen, the surface-piercing foil system is inherently stabie and closely coupled to the surface of the water. The degree of inherent stability is directly proportional to the degree of the coupling to the sea surface.

The other basic foil configuration is the fully-submerged foil system which places the lifting surface completely below the air-water interface as shown in Fig 2. in such a case, some type of control is needed to maintain flying height as the foil system has practically no sense of its position relative to the water surface *. In other words, with the fully-submerged foil system, the foils are essentially uncoupled from the surface. With the added complexity of the required control system, one may rightly ask why one would select a fully-sutmerged foil system. The reason is that with automatic control of the lift generated by fully-submerged foils, the foil system can be decoupled from the sea surface resulting in smoother Operation and greater flexibility in heavy seas.

Also, before reviewing the history of the development of hydrofoil control systems, identification of the areas which make up the control system is in order. The control system of a dynamic lift vehicle such as a hydrofoil can be divided

* There is a small stabilising effect which results from the variation of lift with depth on a fully-wetted foil operating near the free surface (less than one chord depth). This effect, however, is too small to assure stability in even modest seaways.

in five functional areas: sensors, computer, actuation, force producers. and the vehicle itself. The vehicle and control system react to two inputs: the command and external disturbances (ie, the seaway). These are shown in a typical block diagram in Fig 3.

Having established this brief background. a review of the history of the hydrofoil control system will follow; this review reflects the Ingenuity of the oioneers in this field who worked 'without many of the resources we now take for granted.

Mechanical control systems

In reviewing the history of automatic control systems, the first look is a! the initiations and developments of the early pioneers. In doing so. it would be easy to overlook or neglect some of those who contributed to the development of control systems for hydrofoils. If the authors in *the* following text fail to properly recognise any development, please attribute it to the author's lack of knowledge and not to intentional neglect.

We tend to look on the father of hydrofoils as Baron von Sthertel. Certainly he is the father of modern-day hydrofoils. It is recognised that he was preceded by such pioneers as Forlanini in 1905, Crocco in 1907, and Alexander Graham Bell in 1919. All three of these inventors essentially worked with various configurations of the surface-piercing foil system. We also basically know the successes of Baron von Schertel to be related to the surface-piercing foil system. However, his early work concerned fully-submerged foil systems. To quote the Baron from ref 1. "I decided for the fully-submerged type in order to get away as far as possible from the disturbing influence of the water surface in waves." Baron von Schertel's early work was aimed at taking advantage of the submergence depth stability by the surface effect which decreases lift with surface approach. In fact, the Baron relates that he used and studied this arrangement through five test boats. After several disappointing experiences, be became convinced that the only promising way to maintain the stability of fully-submerged hydrofoils would be through the us? of automatic lift control and a submergence depth sensing device. He, therefore, experimented with several types of mechanical depth feelers. This new idea seemed to work well in calm water, but was not particularly good in slight sea waves. The Baron's history indicates that he spent eight years and utilised six test boats in these trial efforts. He became impatient and in looking for a quicker solution, turned from the fully-submerged principle to the surface-piercing foil system for which he is so well known today.

Another type of mechanical control is known as the Grunberg system developed by Mr. W. A. Craig. His work was carried out mainly in France starting in the mid-thirties. Now, Mr. Craig lives in New Jersey, USA. The Grunberg scheme used a submerged foil aft as the major lifting surface. Forward, there were two skis, named frontal stabilisers, which essentially rode on the surface of the water. These skis not only provided forward lift and some lateral stabilisation, but were in effect a means of Sensing the oncoming wave profile. As the boat was pitched. it accordingly changed the angle of attack and control of the main hydrofoil. The aft submerged hydrofoil was also capable of using the principle of the reduction of lift with reduced submergence.

To further explain the Grunberg system. wc draw from some of Mr. Craig's personal notes. The system was conceived with the oblectivc of achieving lift control and associated static longitudinal stability by inherent angle of attack adjustment to operational conditions (variable speed, weight, cenire of gravity, longitudinal travel). Damping of oscillations about the transverse axis is very satisfactory so that dynamically the system is likewise longitudinally stabie.

On the other hand, unlike the surface-piercing hydrofoils, whose lateral stability and lift control are achieved by common inseparable means, the Grunberg system does not necessarily ensure, per se, lateral stability. Needless to say, in practical applications, the latter is necessary. Thus, lateral stabilisation and the method of obtaining it do not enter into the definition of the system. Far from limiting the scope of the concept, such potential mutual independence of the two functions liberates the configuration from certain constraints and makes the design more flexible.

In the original tests for lateral stability, the optional device of splitting was used; the frontal "stabiliser" was split into two units, one port and one starboard, spaced sufficiently far apart for lateral stability. This particular idea has been rather extensively tested, and was employed on a major commercial vehicle, Fig 4. The idea was also utilised in attempting to improve the landing capabilities of sea-based aircraft under rough water conditions. This early effort indicated many of the promises which were later achieved in electronically controlled hydrofoil systems.

One of the early inventors who successfully worked with submerged hydrofoil systems was the noteworthy English inventor, Mr. Christopher Hook. His development- date back to pre-World War II, and he continues to bring new thoughts and ideas to the hydrofoil world. In fact, Mr. Hook was probably the first submerged foil system designer to bring his ideas to the forefront in the United States. The first knowledge of Mr. Hook's invention occurred when he exhibited a small craft celled Red Bug at the New York Boat Show in 1951. The Red Bug was followed with a second version which Mr. Hook named the *Icarus*, Fig 5. The *Icarus* was demonstrated to the Navy in 1954 and was instrumental in the development of a hydrofoil landing craft programme. Mr. Hook's early ideas can be seen in some of today's electronically controlled submerged-foil configurations. The inventor ha: given his system the name "Hydrofin". The *Hydrofin* is characterised by a forward feeler system. This system provides spatial anticipation to sense oncoming waves with adequate time to change the angle of attack of the hydrofoils. The forward surface-riding portion of the feeler system consists of a float with a trailing heel, Generally, only the heel is in contact with the surface. The heel is a very clever spring device with the ability to attenuate small surface waves. The float is buoyant, responding to larger waves. Furthermore, the relationship between the movement of the feelers and the angle of attack of the controlled foils can be trimmed and adjusted. There are also dash-pots or dampers between the attachment of the feelers and their supporting struts to provide damping effect to the overall control motion of the feelers.

In addition to the Hook sensors which rode lightly on the water surface. there was also a mechanical biasing linkage. This linkage was connected to a joy stick so that the operator could control the height of the craft and also execute banked turns at high speed by using differentiai foil incidence. It had the unique feature of dipping the inboard foil ir a turn while keeptng the outboard foil at a constant submergence. Biasing linkage has the advantage of permitting a tight banked turn without tipping the outboard foil out of the water.

Mr. Hook continued his hydrofoil effort with the Miami Shipbuilding Corp. of Miami, Florida. Fig 6 depicts the utilisation of the Hook system on a scale model of a landing craft. This vehicle called "$d\alpha/dt$" was, in fact, a direct utilisation of the Hook system to demonstrate an incidence configuration for the US Navy. This craft gave the US Navy the confidence to go forward with the Miami Shipbuilding Corporation and build a full-scale model of an LCVP, *Halobates.* Fig 7 is a picture of *Halobates* underway employing the Hook principle to stabilise it in a seaway. While the craft was quite successful in handling sea states, it did show that as one scaled the feelers directly from smaller models, they became Quite large and rather clumsy for ship-type manwuvres. Mr. Hook has claimed that there were other systems of feelers still utilising his system which could have been employed on this application without the large scaled feelers shown in the photograph. In any event, these experiments with mechanical systems provided a basis of knowledge that permitted the designer to move toward the electronic control system. The equations of motion, the requirements of height sensing, the need for roll control, were all brought out in his early experiments and later applied directly to electronic control systems as the electronics became more reliable and more feasible for hydrofoil craft. Fig 8 is a picture of the conversion of *Halobates* to an electronic control system.

Mr. Hook has continued to actively pursue the development of hydrofoil craft. As recently as January 1973, Mr. Hook presented a paper on his latest thoughts regarding sailing hydrofoils (ref 2).

Let us next direct our attention to another clever designer who did considerable work in the field of mechanical control systems for hydroioil craft. We speak of Mr. Gordon Baker, a Wisconsin manufacturer who in the early 1950's conducted considerable experiments with various types of hydrofoil craft. His early vehicle which brought rather wide attention was a surface-piercing hydrofoil named *High Pockets.* This craft utilised the V-foil principle with a constant chord to stabilise its flight condition. Recognising the limitations of the surface-piercing configuration with its close coupling to the sea and poor following sea properties, Mr. Baker turned his attention to submerged incidence-control systems. Fig 9 shows the resulting craft *High Tail* in operation.

High Tail was a three-foil configuration with one foil forward and two foils aft. Each foil was independently incidence-controlled by hydraulic servo cylinders. The craft was 22 ft long and displaced 6,000 lb.

This craft has one forward extending mechanical sensor touching the water surfacr forward of the front hydrofoils. In addition, there were two aft-extending mechanical sensors, one touching the water surface forward of each aft hydrofoil. All were designed for near-optimum sensor lead of anticipation, the forward sensor for the forward foil and the aft sensors for the after foils. The forward sensor controls pitch and heave and the aft sensors control pitch, heave, and roll.

A mechanical computer was a basic part of *High Tail's* control. The computer was made up of adding and subtracting linkages, multiplying levers and function units. The inputs to the computer were:

Displacement of the three sensors
Steering angle of the forward hydrofoil
Servo pressure
Manual trim for elevation, pitch, roll, and sea conditions

The computer outputs were:

Control of retraction of the 5 sensors
Incidence angle control to the hydraulic *sensors*
Flying elevation

High Tail was successfully operated in waves up to 4-6 ft high. The craft was certainly the most sophisticated mechanically controlled hydrofoil that the US Navy evaluated. The evaluation was completed in 1960 and by this time the developn ent of the electronic control systems was well underway. In fact, the concluding report (ref 3) by the designer, recommended and suggested the use of some electronic components for *High Tail.* Time and events now directed the main effort toward the use of electronics.

Mr. Baker's exploitations must include his clever work with a mechanical control computer designed to calculate and change the angle of attack of a submerged foil on a sailing craft. Fig 10 shows his sailboat which achieved the remarkable speed of 40 [illegible]. This was One Of the first times that a computer of a v type was used aboard an incidence-controlled hydrofoil craft. The computing device received its input from the forces of the stays holding the mast. These forces were then used to calculate the proper angle adjustments to be applied to the after foil in order that the craft would not pitch-pole. The primary purpose was Therefore not stabilisation but to counteract by foil angle the tipping moment from the sail force.

A more recent mechanical system which is still in use is the "Savitsky Flap" invented by Dr. Daniel Savitsky of the Davidson Laboratory, and used hy Atlantic Hydrofoils on the *Flying Cloud* and the Korean Navy hydrofoil. The Savitsky Flap is a trailing edge flap, attached to the rear of the struts and nominally canted out at an angle. This flap is mechanically attached to trailing edge flaps on the foils as shown in Fig 12. At nominal flying height a portion of this flap is submerged. The hydrodynamic moment on the flap is reacted by a spring and the hydrodynamic moment on the trailing edge flap on the foil. If the craft goes deeper more of the Savitsky flap is submerged and the moment on this flap is increased. which deflects the foil flap to increase lift and thus restore craft to proper flying height. The mechanism has both a bob weight and a shock absorber (damping) attached to it so that if can be tuned to basically ignore high-frequency small waves and follow only the lower-frequency larger waves.

Manual control system

One cannot look at the background of the control of submerged foil systems without considering the possibility of manual control. Inherent lift control of submerged foils results from a reduction of lift as the foils approach the free surface. One is intrigued with the notion that by putting a man in the loop for lateral and pitch control, a hydrofoil can be flown. Several experimenters have used these principles to give the pilot "joy stick" control.

One of the first experimenters to study the technique of manual control was Captain H. C. Richardson, USN. He fitted a dinghy with submerged foils in 1908. In 1911 with collaboration from a Mr. N. White, manual controls were added (see Fig 11). The craft was towed by a motor boat and flew at a speed of about 6 knots. At that speed and in the Delaware River, the craft was man-controllable.

In the late 1940's and early 1950's, other expermienters carried the idea of the man-in-the-loop forward. Hazard Hydrofoils marketed a small runabout using submerged foils and manual control (Fig 13).

The Miami Shipbuilding Corporation built a small test craft which combined manual control with mechanised control (Fig 14). The forward feeler provided height and pitch control which could be biased by the pilot. The control stick in overriding the height input from the feeler could take off or land the craft in the same manner as an aircraft. For banked turns, the pedals provided differential control to the forward foils. Lateral control was assisted by the dihedral of the forward foils and struts. This craft was successfully demonstrated in moderate seas.

Probably the craft that provided the most answers for the use of manual control was the Gibbs and Cox Inc *BIW* (Fig 15). This versatrle vehicle is more fully described under the automatic control section of this paper. However, it had a feature in the electronic control system which permitted the lateral mode, or the pitch control mode, and/or the height control to be uncoupled from the system and controlled manually. The craft operated in the 25 knot speed *range* and could handle most of the seas of Long Island Sound. The interesting conclusions from these tests were that a man can sense and handle the lateral motions. However, when in a wave train, the height and pitch motion requirements very quickly exceeded man's response capabilities. As electronics became available to solve the control problem, there was no particular advantage in placing the man in the control loop. This control notion was dropped in later designs.

Pneumatic control system

Another most interesting means for controlling a fully-submerged hydrofoil is through controlled ventilation of the foil system. Tho Supramar A G, the leader in the development of this type of control system, refers to it as the "air-feed control system". This method'operates on the well-established principle that the lift of a hydrofbii , is. altered by introducing air along the lifting surface, usually through a span-wise row of holes. If the local pressure at the ventilation holes is low enough so that atmospheric pressure is sufficient to force the required quantity of air through the holes, the ventilation is said to be "natural". If pressurised air must be used, the ventilation is said to be "forced". Ventilation of the upper (low pressure) surface of a hydrofoil reduces the lift while ventilating the lower (high pressure) surface increases the lift. "Air-feed" is a substitute for other lift control devices such as trailing edge flaps or fully pivoted foils and does *not* perform the function of or replace the autopilot and its associated sensors.

To utilise this simple method of lift control, Schertel devised pneumatic and inertia sensing devices to operate the valves to control the amount of air flow to the foils.

The first full-scale demonstration of Supramar's new 'airfeed" system was on the *Flipper.* a PT-50 passenger craft on which the normal surface-piercing rear foils were replaced by a fully submerged rear foil system with air-feed stabilisation. The *Flipper's* control system is the essence of mechanical simplicity. Mechanical signals from a gyroscope (mounted in a plane in such a way that it senses components of both roll and pitch) are pneumatically amplitied, properly damped, and used to open the air valves in the foii through simple push-pull rods. From this observer's viewpoint, the motions of the *Flipper* in 3 ft waves are far less objectionable to a passenger than those of the PT-50 in 1 ft waves. A large part of this improvement in motion (particularly lateral motion) may be due to the replacement of the rear surface-piercing foils with fully-submerged foils, thrreby removing their close coupling to the sea surface. The stabilisation supplied by the air-feed control system is clearly demonstrated by the fact that the craft cannot remain foilborne with the air system turned off.

The US Navy entered into a contract with the Supramar AG to demonstrate the air-feed control system by placing a fully-submerged foil system on a PT-3 hull. redesignating the craft the ST-3A. Fig 16, a picture of the foil system, clearly shows not only the ventilation ports, but also the digital depth-sensor ports on the struts and the low-pressure ports near the strut-foil intersection which supplies the vacuum needed to bower the pneumatic amplifiers in the control system. A pneumatic-mechanical control system at each foil controls the air flow to the two sets of holes, located on the 50% and 70% chord line with the holes on the 50% chord line used only for large correction forces.

The ST.34 successfully demonstrated that a fully-submerged hydrofoil can be stabilised and controlled by an "air-feed" *system* tn both calm and rough water.

Using natural ventilation is a simple method to get lift control on a hydrofoil with very little control power. Two factors must be carefully assessed in a tradeoff study before selecting air-feed over mole conventional methods of lift control. They are the range of lift control available and the increase in drag associated with air-feed, which is essentially a lift spoiling device. Using natural ventilation alone. only about a 0.2 change in lift coefficient can be easily obtained, and an increase of about 5% in overall drag can be expected.

Supramar AG is still developing the "air-feed" concept in model tests which address these two problems and hopefully can improve their performance. Unfortunately, work has proceeded slowly as such tests are both expensive and push present test facilities to their limits.

For a large (1000 ton) hydrofoil. the foils and flaps become extremely large. For such applications "air-feed" lift control in conjunction with slow incidence trim may offer an alternative to trailing-edge flaps. This should be carefully assessed in system tradeoff studies.

Another application of the air-feed system which is of interest is its potential as a method of transiting from the subcavitating to the supercavitating regime in a smooth controlled manner. Test programmes in the 50 to 60 knot regime are currently underway in the basin at Wageningen, Netherlands.

Electronic control systems

As mentioned previously, *the* evolution for stabilised hydrofoil craft had been headed toward the use of electrohydraulic systems. At the time of the early studies of hydrofoils, electronic devices were in their infancy and were not very dependable. With the improvement of reliability, the use of electronics has broadened. In fact, the experience with US Navy hydrofoils has been that the auto-pilot system has been least troublesome in causing craft down-time.

One of the first craft to use an electronic autopilot for stabilisation was *Lantern,* Fig 17. built by the Hydrofoil Corporation circa 1953. This research organisation was founded by Dr. Vannevar Bush to study hydrofoil craft and provided much useful information to the early US Navy hydrofoil programme. *Lantern* employed a direct application of an aircraft autopilot, the Sperry A-12 Gyropilot built by the Sperry Corporation. This gyropilot controlled the craft in roll, pitch, and yaw. The turn control permitted bank turns. The craft employed a tandem submerged foil system with both forward and aft foils split at the centreline. A static pressure probe was used to maintain constant foil depth. Lantern made a number of demonstration runs out of Annapolis, Maryland. on the Chesapeake Bay. While making speeds of less than 20 knots, the craft gave an encouraging example of the feasibility of gyrostabilisation as a basic control philosophy.

As early as the mid-1950's several other US Navy programmes were underway to develop electrohydraulic systems. Miami Shipbuilding Corporation removed the Hook feeler *system* from *Halobates* and installed *an* enalogue computer and a step-resistance height sensor on the forward struts, Fig 7. This height sensor was a further development of Gibbs and Cox Inc's effort on a step-contact height sensor used on the BIW craft, Fig 15. A hydraulic servo actuator was used to accept the output from the computer and provide the muscle for incidence stabilisation. *On* this craft, the aft foil was fixed, with all the control authority in the two forward foils. The need for pitch control on the after foil was demonstrated during the sea experience of *Halobates*. A second version of Miami Shipbuilding Corporation's autopilot was demonstrated during the conduct of the Flying *DUKW* programme for the US Army. A picture of this craft is shown in Fig 18. Later, the AVCO Corporation built a 3,000 lb landing craft with wheels, the LVHX-1, which was an outgrowth of the *Flying DUKW* programme. The AVCO craft was *one* of the first vehicles to employ a sonic height sensor in lieu of the step-resistance type.

One of the transitional steps in the development of the electronic autopilot was an outgrowth of the US Maritime Administrations' *Denison* programme. The Grumman Aircraft Engineering Corporation, now known as the Grumman Corporation. contracted with the Maritime Administration through their subsidiary, Dynamic Developments Inc, for the design, construction, and test of a hybrid hydrofoil the *Denison, Fig* 19.

This 60-knot vehicle employed a submerged controlled tail foil and two flap-augmented surface-piercing forward foils. An electronic control system was provided for stability augmentation. This analogue computer incorporated one of the first electronically controlled steering modes. The steering mode was essentially a heading hold. Sea trials with and without the stability augmentation system on the tail foil engaged clearly demonstrated the improvement in the ride quality from an automatic system.

The outcome of the *Denison* experience was applied to the Grumman design effort on the US Navy's *Plainview* (AGEH-1) Fig 20. The *Plainview* is a totally submerged aircraft hydrofoil configuration using a complete automatic control system.

The Grumman Corporation, working with the Garrett Corporation, designed and built a series of electronically controlled autopilots for their commercial *Dolphin* craft and the US Navy's Flagstaff (PGH-1), Fig 21. The *Flagstaff's* computer is of modular construction using analogue techniques which, through electrohydraulic actuators, control the incidence of all three hydrofoils. Initially, the *Flagstaff* was delivered to the Navy with a sonic heighi sensor. Recently, the Navy has changed the height sensor to a Sundstrand Corporation radar-type to eliminate noise and heavy rain interference.

Also in the mid-1950's. Gibbs and Cox Inc, working with the Massachusetts Institute of Technology's Draper Laboratory, started work on an autopilot with an analogue computer and a sonic height sensor. This development led to the design and installation of an electronic control system on the craft *Sealegs*, Fig 22. This autoprlot was the basic system from which has been developed and perfected the modern day automatic control system for hydrofoil craft.

Sealegs' demonstration of the feasibility and advantages of a fully-submerged automatically-controlled foil system in the open sea provided the data which formed the foundation for the design of the *High Point* (PCH-1), Fig 23. The automatic control systems of all present US Navy hydrofoils functionally are very similar. The functional diagram shown in Fig 3 is basically applicable for all.

The components in each US Navy hydrofoil control system arc tabulated in Table 1 demonstrating the similarity even though designed by different organisations. The earlier major differences among the ships was the manner in which the ships' motions *were* controlled and they were manoeuvred; even those differences have tended to disappear as control philosophy evolved during sea trials. These evolutions will be briefly described for the PCH-1 from the original to the latest configuration since its control system is very representative of the control systems on all US Navy hydrofoils.

On PCH-1, as originally configured, height was controlled by the forward foil, pitch by the inboard flaps on the rear foil system, and roll by differential action of the

Table 1 US Navy Hydrofoils' Control System Components

	PCH-1 HIGHPOINT MOD 0	PCH-1 HIGHPOINT MOD 1	ACM-1 PLAINVIEW	PGH-1 FLAGSTAFF	PGH-2 TUCUMCARI
SENSORS					
Pitch	Vertical Gyro	Vertical Gyro	Vertical Gyro	Vertical Gyro	Vertical Gyro
Roll	Vertical Gyro	Vertical Gyro	Vertical Gyro	Vertical Gyro	Vertical Gyro
Height	Sonic	Sonic/ Radar	sonic	Radar	sonic
Heave Acceleration	Servoed Accel	Servoed Accel	Servoed Accel.	Servoed Accel.	Servoed Accel.
Roll Rate	Rate Gyro	Electronically Derived from Roll Angle	Rate Gyro	Rate Gyro	Electronically Derived from Roll Angle
Pitch Rate	Rate Gyro	Electronically Derived from Pitch Angle	Rate Gyro	Rate Gyro	Electronically Derived from pitch Angle
Yaw Rate	Rate Gyro	Rate Gyro	Rate Gyro	Rate Gyro	Rate Gyro
FORCE PRODUCERS					
Lift	Trailing Edge Flaps	Trailing Edge Flaps	Pivoted Foils	Pivoted Foils	Trailing Edge flaps
Rudder	Trailing Edge Flap plus Spade Rudder	Pivoted Forward Strut	Pivoted Rear Strut	Pivoted Rear Strut	Pivoted Forward Strut
COMPUTERS	Analog Solid State Electronic Plug-in Modules	Analog Solid State Electronic Cord-Wood Construction Plug-in Modules	Analog Solid State Electronic Rug-in Modules	Analog Solid State Electronic Plug-in Modules	Analog Solid State Electronic. Hard Wire Wrapped in Place Modules
ACTUATION	3000 psi Hydraulics pump redundancy with decreased capability	3000 psi Hydraulics pump redundancy with decreased capability	3000 psi Hydraulics 100% redundant system with tandem actuators	3000 psi Hydraulics pump redundancy with decreased capability	3000 psi Hydraulics pump redundancy with decreased capability
MANUFACTURER	Boeing	Boeing	Grumman	Grumman	Boeing

outboard flaps on the rear foil system. Steering was accomplished by a trailing edge flap on the forward strut. The pilot had the option of a flat turn or a coordinated or banked turn which was accomplished by scheduling roll angle as a function of yaw rate.

During trials. it was found that more steering control was needed. A spade rudder was placed below the forward foil to supply the additional side force required. Later, in rough water, it was found that the outtoard flaps which Supply roll control were bottoming quite frequently, indicating the need for more roll control authority. More roll force was achieved by modifying the autopilot to move both the inboard and outboard flaps on each side in unison, thereby using the complete rear lifting surface to generate controlling lift forces. Pitch was now controlled by moving each pair of starboard and port flaps in phase, and roll was controlled by moving them differentially. This was called "elevon" control. The PCH essentially remained so configured until the recent modification and overhaul, during which a new automatic control system was installed. This new control system functionally is almost identical to the *Tucumcari* (PGH-2). Fig 24, control which had performed so well. The simplest way to complete the evolution of the PCH-1 control system is to describe the *Tucumcari* control system.

On the *Tucumcari.* as *on* all US Navy hydrofoils, height is controlled by the forward foil, pitch by the rear foils. and roll by differential lift on the main foils. For steering, however, the *Tucumcari* employed what we call "roll-to-steer". That is, a helm command rolls the ship and the complete forward strut turns as a function of roll angle to approximately weathervane the forward strut. Turning force is thereby supplied by a component of the lift vector rather than by the struts or a rudder. This method of turning eliminates high angles of attack and possible ventilation of the struts and results in fully-coordinated turns. With this system, turn rates of 8°/sec are achieved routinely and more than 12°/sec have been demonstrated. Another feature incorporated in the *Tucumcari* after delivery was the replacement of the single central heave accelerometer with two, one directly over each toil. so that disturbing forces on each foil were corrected individually. This is particularly effective in ameliorating the annoying "roll jiggle" which occurred in steep bow seas where each foil is in a different portion of the wave. Roll-to-steer and placing separate accelerometers over each main strut proved so successful in the *Tucumcari* that these features were not only incorporated in the *High Point* but also in the *Plainview.*

The *Tucumcari* control system also eliminated the need for pitch rate and roll rate gyros by generating these functions electronically in the autopilot. The flat turn was eliminated, further simplifying the control system.

As mentioned earlier, the PCH recently went through an extensive overhaul and modification. Two major items in this modification were: replacing the fixed-forward strut with a fully steerable forward strut to improve manoeuvrability through use of the roll-to-steer mode, and the installation of a completely new auromatic control system essentially identical to that of the *Tucumcari.* The functional block diagram of the present PCH-1 auromatic control system is shown in Fig 25.

A discussion of electronic control systems would not be complete without mentioning the work done in the commercial area. An early passenger-carrying vehicle to use such a control system was the *Victoria* built by the Maryland Shipbuilding and Drydock Co and operated by the Northwest Hydrofoil Corporation. The design was done by Gibbs and Cox Inc, based on their successful Navy test craft *Sealegs.* The autopilot was built by the General Electric Defense Electronics Division. This craft has the significance of being one of the first hydrofoils certified by the US Coast Guard to carry passengers on Puget Sound.

Another early electronically controlled hydrofoil was the *Enterprise,* Fig 26. This craft was designed and built by Marine Systems Corporation and operated by North American Hydrofoils Inc. It was a canard configuration with each foil having flap control. Ref 4 gives a good description of the craft. The 40-ft 8-ton *Enterprise* was certified to carry 27 passengers in the New York Harbour area. The autopilot was built by the Sperry-Piedmont Co using an Arma sonic height sensor. The craft completed successful trials and was demonstrated in New York and on Lake Michigan. This small craft operated consistently with seas running 2½-3 ft.

The Grumman Aerospace Corporation built a Dolphin class hydrofoil at the Blohm and Voss Shipyard in Hamburg, Germany. The autopilot for this passenger hydrofoil was built by AiResearch Division of the Garrett Corporation. It used an Arma sonic height sensor. This craft was widely demonstrated in Germany, the Canary Islands, Straights of Florida, and in the Virgin Islands.

Currently under construction at The Boeing Co. is a new commercial class called the *Jetfoil.* This vehicle is a Boeing development using the company's own electronic control system and sonic height sensor. It can carry up to 250 passengers with the design based on the successful Navy hydrofoil *Tucumcari.*

The L. Rodriquez Shipyard. of Mescina, Italy, is currently marketing a second-generation hydrofoil stabilised with a Hamilton-Standard Automatic Control. Since the craft is basically a surface-piercing hydrofoil. the stabilisation system has the capability to augment and improve the ride quality. This system is offered on both the RHS 70 and the RHS 140 passenger hydrofoils.

Ongoing automatic control developments

At present, two areas of hydrofoil foil control are actively being pursued: lift control devices, and digital autopilots.

Lift control

In the area of lift control devices, emphasis has been placed on developing schemes which are simple and reduce the Power required to actuate them. Seven possible ways of achieving lift control are shown in Fig 27. Where known, the relative power required to actuate each of these relative to full incidence control is listed in the figure. When *choosing* the type of lift *control* device for a hydrofoil, one must make a balanced judgment amony mechanical Simplicity, reliability, actuation power. range of lift control, field experience, and cost. Incidence and flap control have been well documented and proved acceptable on existing hydrofoils. The bearings used ir these systems, however, have shown limited life. The Boeing Co is actively pursuing a programme to increase the service life of these bearings to at least 2.000 hours.

The other lift systems which show the greatest promise, particularly for large (≈ 1,000-ton) hydrofoil ships. are: (a) the trailing-edge tab in which the actuation forces required to pivot the complete foil are supplied by the hydrodynamic forces on a smell trailing-edge flap; (b) the extended flap in which a balanced flap is placed below the foil to put the flap in a high-pressure reyion to avoid hinge-line cavitation, and (c) the air-feed control which has been discussed previously.

Autopilot

As previously discussed, all US Navy hydrofoil control systems sense the same basic parameters, shown in Fig 25, and all have the four servo amplifiers which control through electrohydraulic servo valves rhe four control surfaces. one on each foil and one for the rudder. Only the shaping networks. logic and interconnections vary from ship to ship. This logically leads to the possibility of standardising all hydrofoil control.;. From a control engineer's viewpoint, this standardisation has essentially come into being as the block diagrams of the PCH, Mod-l, PGH-2, AGEH, and the new PHM have become almost indistinguishable. Although similar to a control engineer, the systems are anything but the same to the electronic technician who must maintain them. At present all hydrofoil autopilots are analogue hard-wired for a particular ship and use early-1960 plug-in modular construction techniques which, because of their ruggedness and success, have been perpetuated. This perpetuation has been brought about because all new procurements, and rightfully so, emphasised the use of proven state-of-the-art hardware.

In order to standardise hydrofoil autopilots and to bring them up to the latest technology, a programme was initiated in 1972 to develop a Hydrofoil Univer al Digital Autopilot (HUDAP). The goal of the HUDAP programme was to develop a highly reliable hydrofoil autopilot with enough flexibility to be used on all present and future hydrofoils and have sufficient growth capacity to integrate the automatic control with other ship functions.

Digital computers, with their high-density digital integrated circuits, extreme flexibility through the use of software, increasing reliability through multiple unit manufacture and fault-tolerant configuration, have been chosen as the major electronics assembly for this universal automatic control system. These computers have the speed to do the job, the flexibility to grow with the expansion requirement, the size and power to be economical in use, and the reliability to out-last the best analogue or mechanical assemblies.

The advantages of a HUDAP are numerous. They include the following:

Increased system reliability through standardisation and the use of digital components

Complete redundancy with multiple fault tolerance and a background programme which checks the health of every element of the system ten times a second with automatic switching to a back-up circuit when a fault is detected

Manageable growth potential with no sacrifice in reliability (a) for motion control related tasks (b) for additional tasks interfacing with other vital craft systems

Extreme flexibility in configuration without impairment of reliability through changes to software only

Improved maintainability

Substantial *savings* in logistics support of a growing fleet of Navy hydrofoils

Reduction in training costs for crew and support personnel. Standardised hardware not only reduces support and crew personnel training, but it also permits intership personnel transfer with no loss of expertise. Troubleshooting and maintenance needs would be decreased and/or facilitated. Maintainability will be enhanced because of the added assistance from the computer: a diagnostic programme may be resident to troubleshoot and fault-isolate problems to the level of single module replacement by a relatively inexperienced technician. Defective modules can be replaced by spare modules without additional tuning or calibration, and, finally, if digital circuitry is used extensively, there is no requirement for periodic adjustment or calibration often needed by analogue circuits.

The HUUAP is designed with sufficient memory, speed, and input/output circuitry over and above that required to perform the primary control tasks to accomplish additional tasks such as:

Navigation interfaces either for simple data transfer for use in automatic course or trackkeeping, or for automated and pre-programmed evasive manoeuvres, or for active participation of the Central Processor Unit (CPU) in navigation computation *or* sensor servicing (inertial platform)

Obstacle avoidance system for data transfer or radar control

Alarm and display system for data transfer or automatic action or interlock safety control, as in gas turbine start-up

Expansion capabilities such as fuel management, weight, and balance computations and eventual "adaptive control" of the craft are all possible. Any task aboard the ship for which specific rules of operation (based upon the status of available inputs) can be generated may be handled by the computers of the HUDAP.

In summary, the HUDAP is the culmination of automatic hydrofoil control for future ships. It will form the core through which ship control, navigation, and weapon systems can be integrated into a fighting ship.

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2 Christopher Hook, "Why Sailing Hydrofoils," Los Angeles American Institute of Aeronautics and Astronautics, January 27, 1973.

3 "The Design of Hydrofoil Boats with Particular Reference to Optimum Conditions for Operation in Waves," Engineering Report to US Navy Office of Naval Research, 29 July 1969.

4 R. E. Harris, Jr., and R. E. Smith, "Practical Experiences with Hydrofoil Craft," *Naval Engineers Journal,* August 1964.

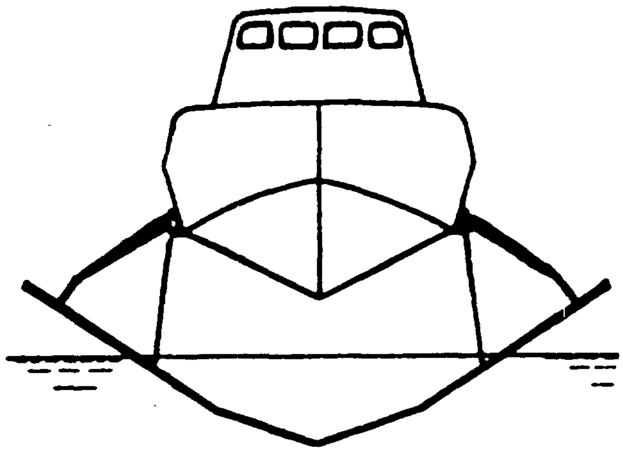


Fig. 1 Surface-piercing foil system

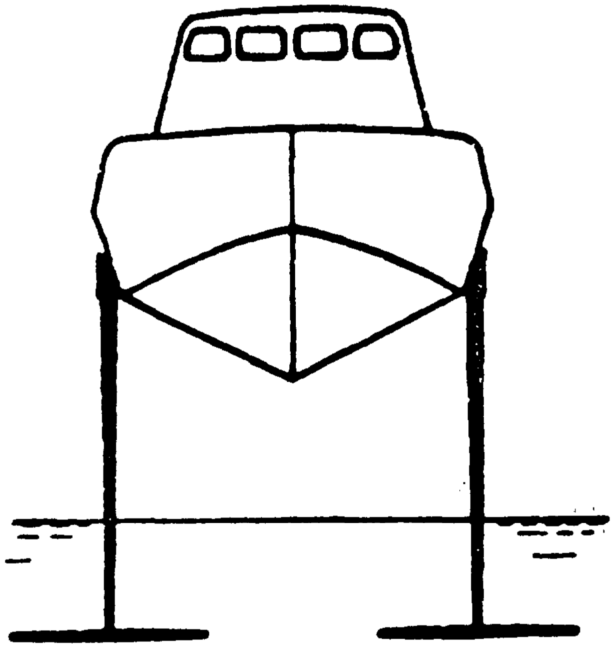


Fig. 2 Fully-submerged foil system

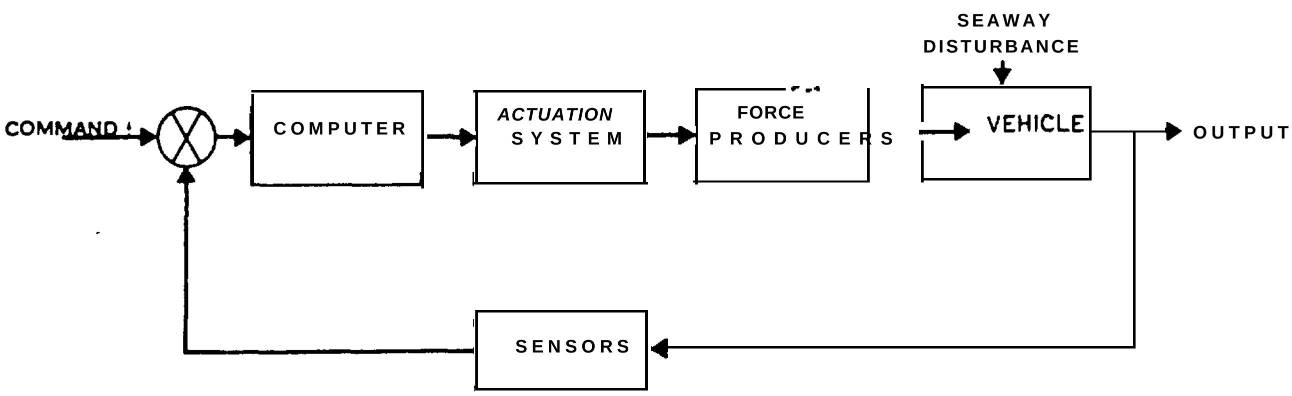


Fig. 3 Hydrofoil control system block diagram

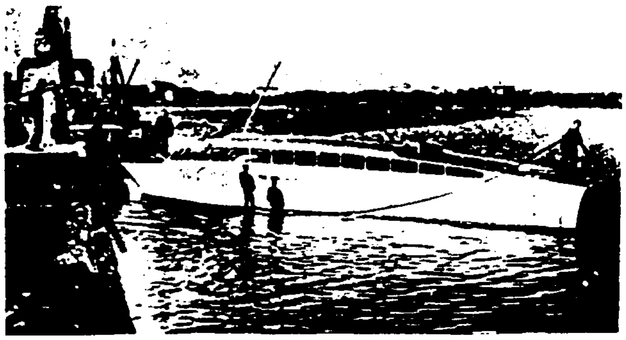


Fig. 4 Aquavion

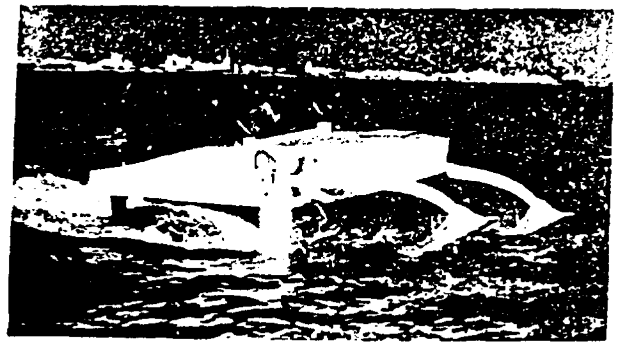


Fig. 5 Christopher Hook's Hydrofin

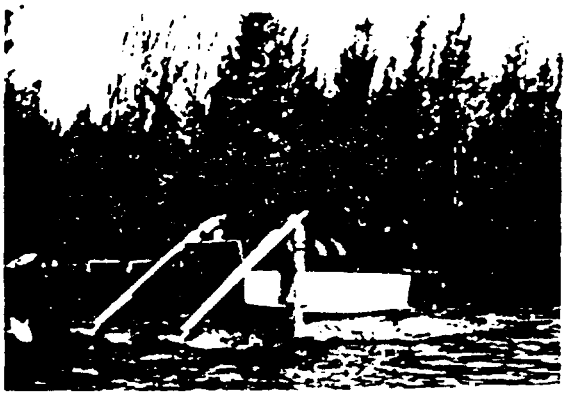


Fig. 6 [illegible]

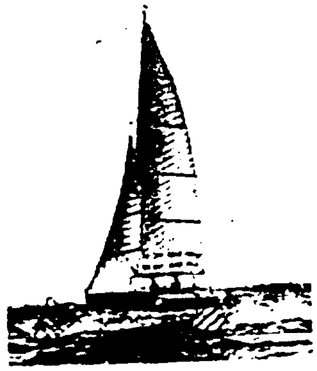


Fig. 10 Monitor

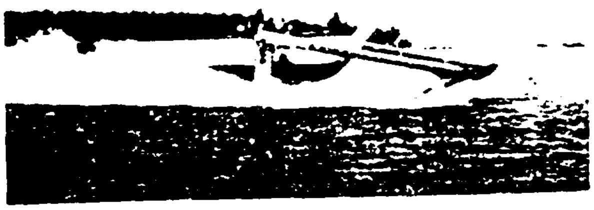


Fig. 7 Halobates

Fig. 11 Dinghy with submerged foils (1911)

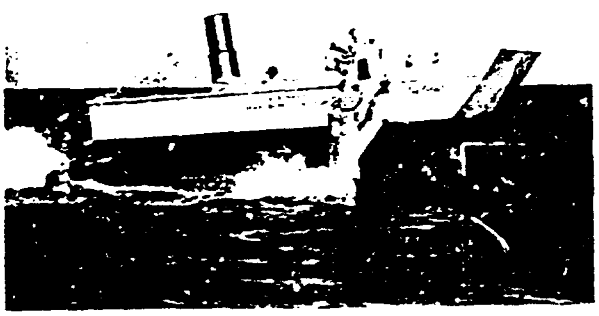


Fig. 8 Halobates with automatic control system

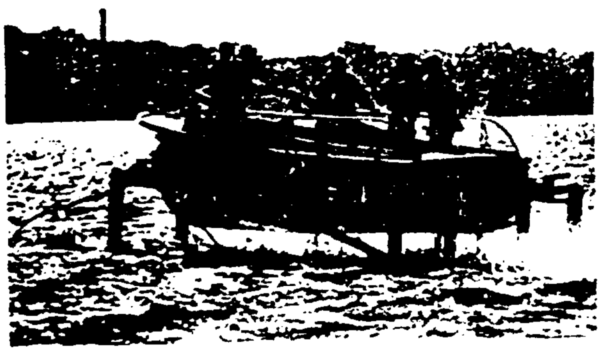


Fig. 9 Baker Manufacturing Co's High Tail

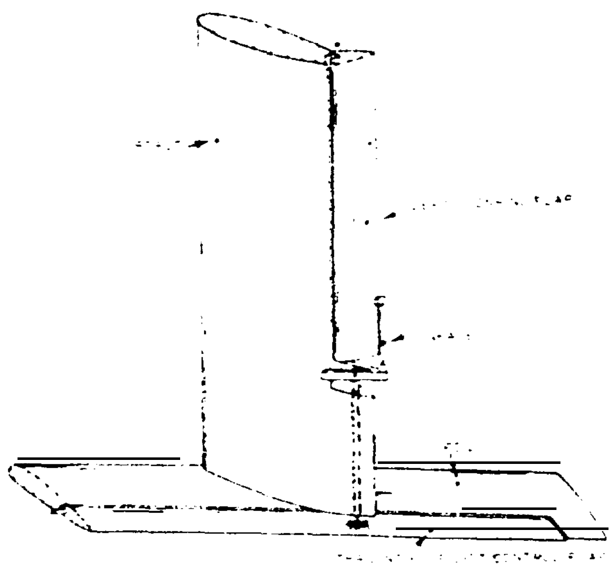


Fig. 12 Savitsky flap

Fig 13 Water Hazard IV

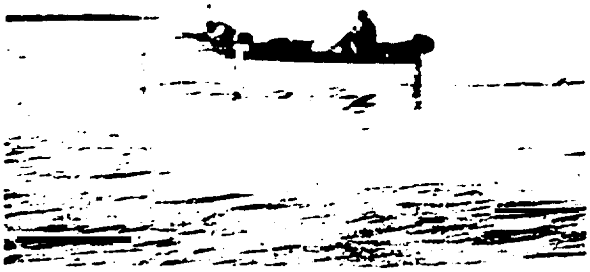


Fig. 14 Miami Shipbuilding Corporation's two-man test craft

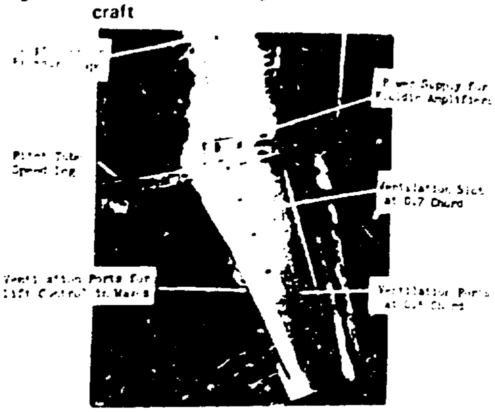


Fig. 15 Bath Iron Works test craft

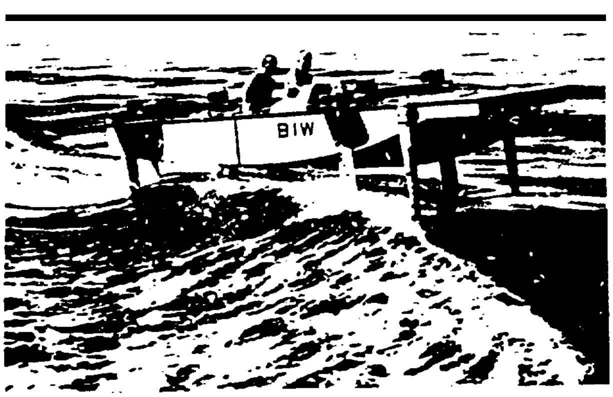


Fig. 16 ST-3A

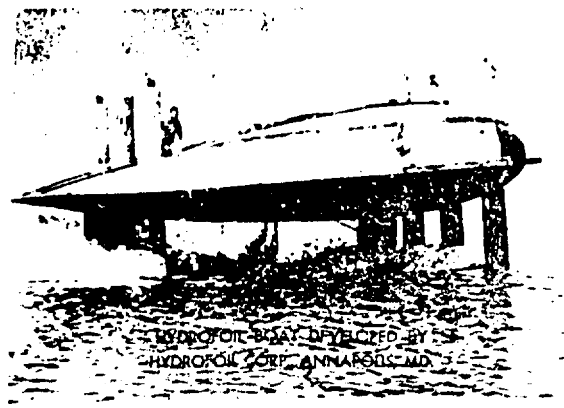


Fig. 17 Lantern, by Hydrofoil Corporation of America

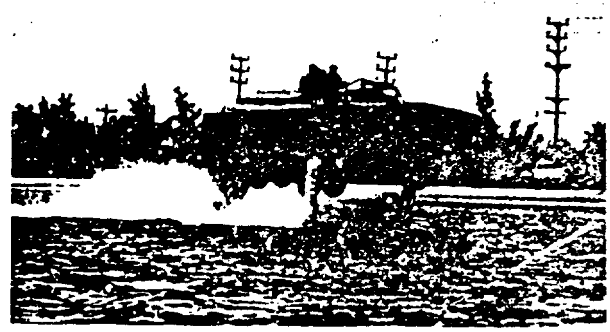


Fig. 18 Flying DWKW, by Miami Shipbuilding Corporation

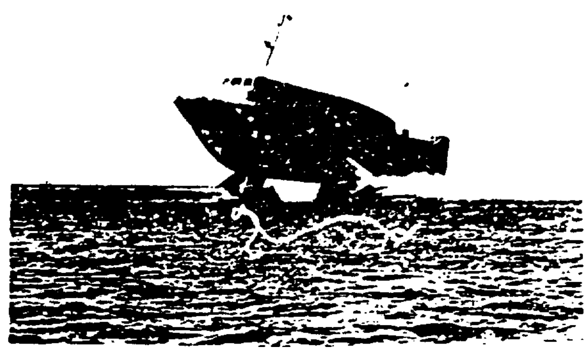


Fig. 19 Denison

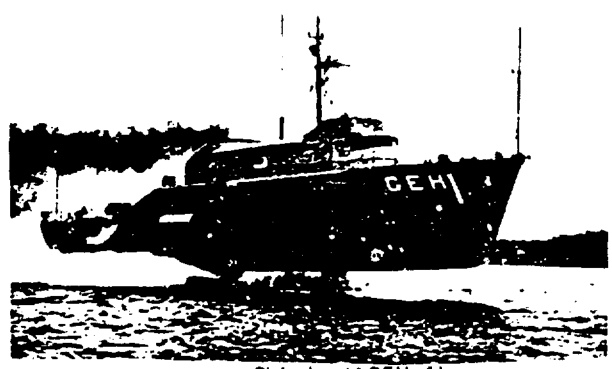


Fig. 20 Plainview (AGEH-1)

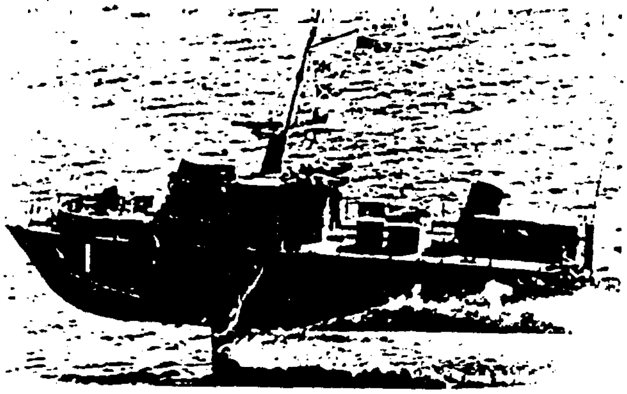
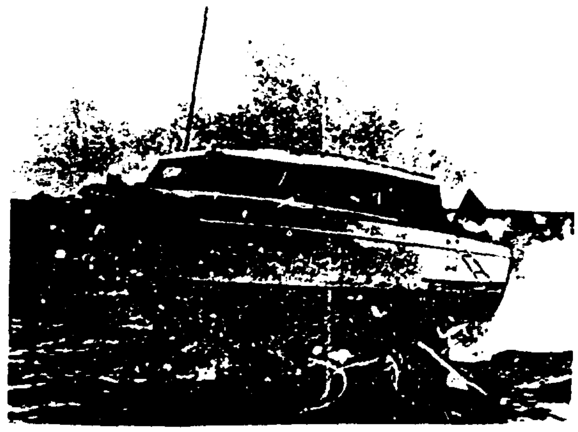


Fig. ?l Flagstaff (PGH-1)

Fig. 22 Sealegs



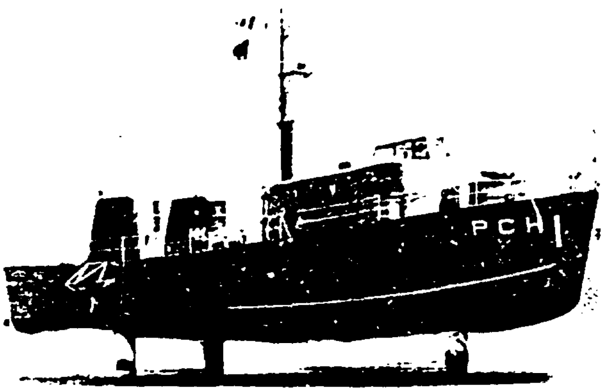


Fig. ?? High Point (PCH-1)

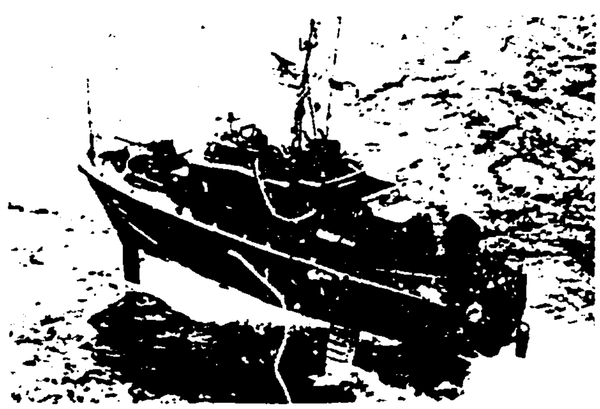


Fig. 24 Tucumcari (PGH-2)

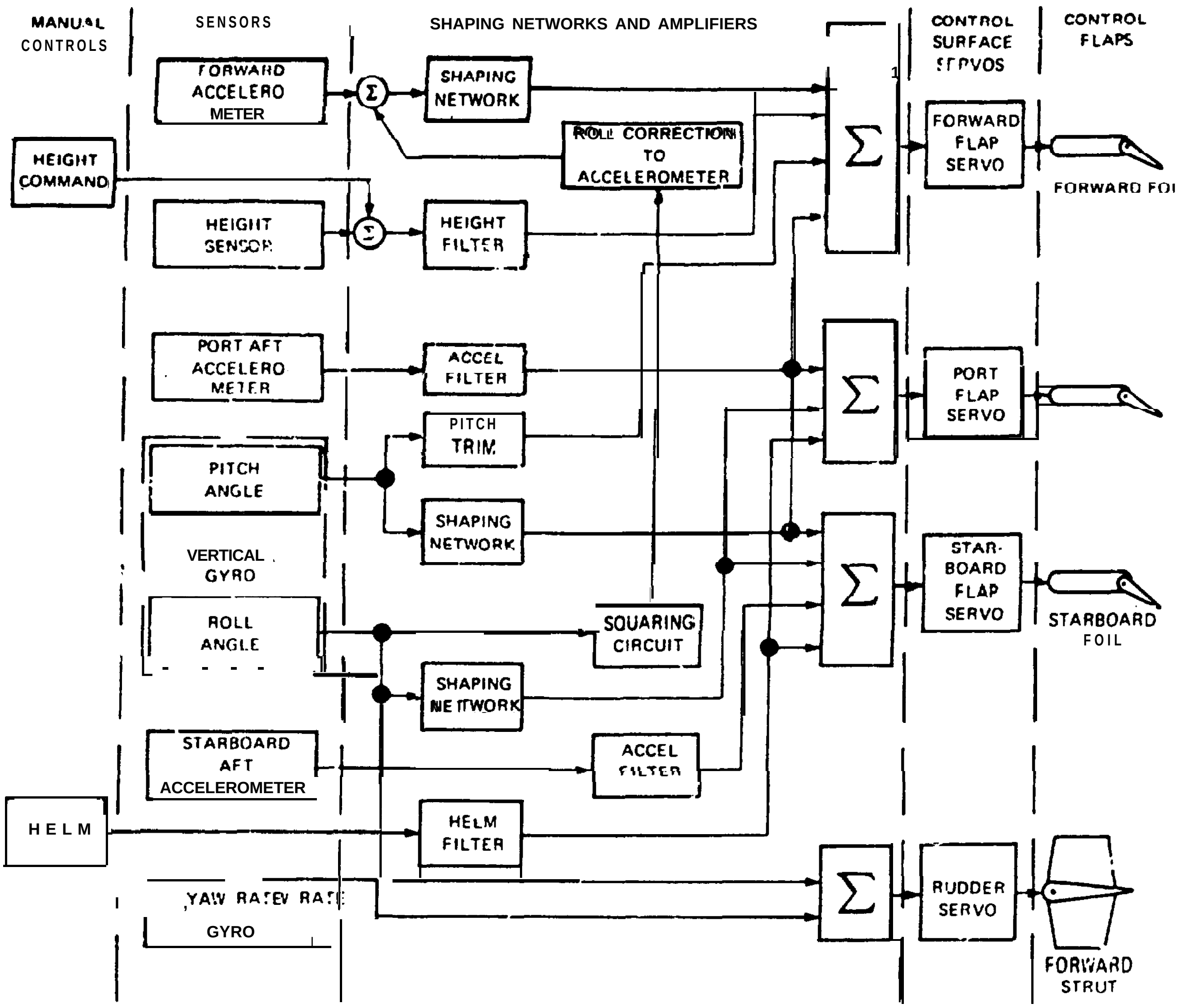


Fig. 25 Block diagram of automatic control system

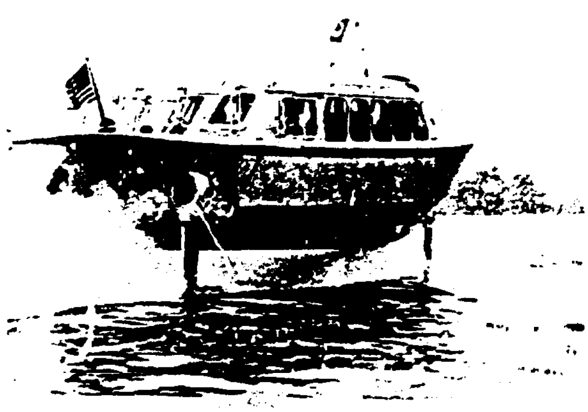
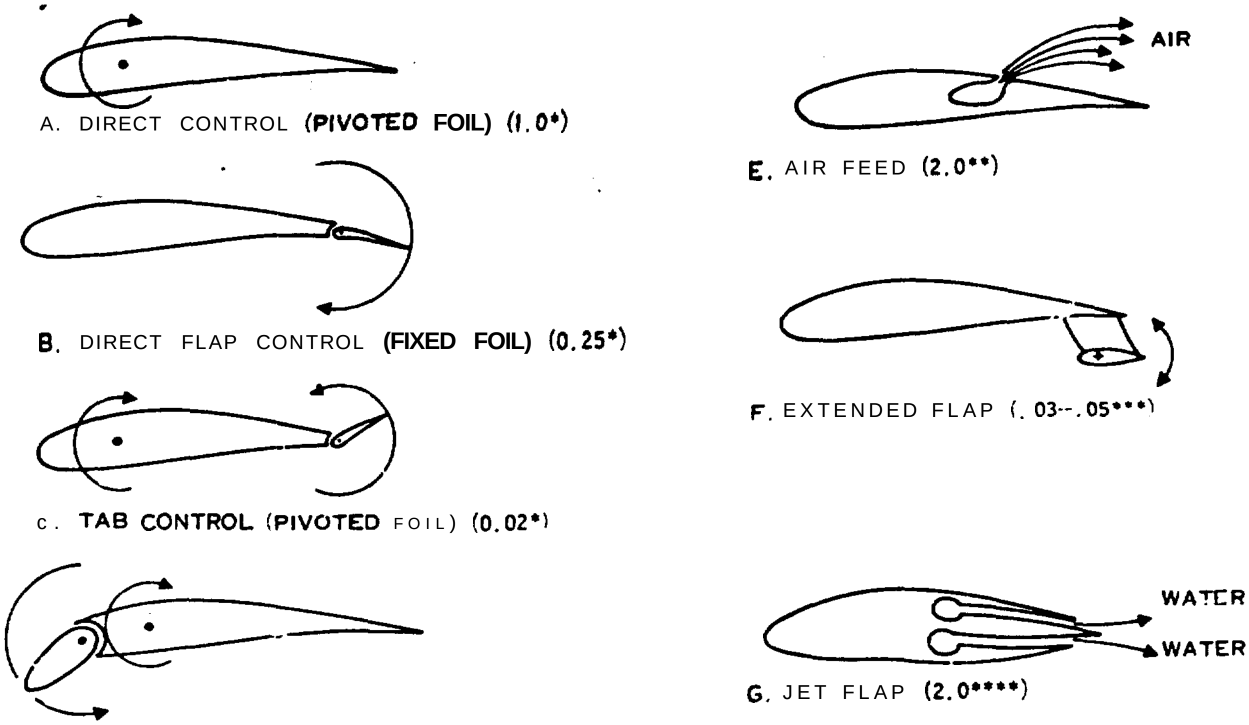


Fig. 26 Enterprise



NUMBERS IN PARENTHESIS ARE RELATIVE CONTROL POWER REQUIRED.

*Based on Bolt, Bcranck, and Newman report 2511, "Hydrofoil Design for Minimum Power."
**Based on 1965 NSRDC-SUPRAMAR Tank Tests.
***Based on The Boeing Co. estimates.
****Based on Oceanics, Inc. Report 6413, "Use of Jet Flapped Hydrofoils as Ships Antipitching Fins."

Fig. 27 Lift control schemes