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

References

[1] Crewe, P. R., "The hydrofoil boat; its history and future prospects," Quart. Trans., Inst. Naval Architects **100**, 329–373 (October 1958).

[2] Hayward, L., "The history of hydrofoils," *Hovering Craft & Hydrofoils* (Kalerghi Publications, London, England, 1966), Vol. 5.

[3] Oakley, O. H., "Hydrofoils—a state of the art summary," *Proceedings, National Meeting on Hydrofoils & Air Cushion Vehicles* (Institute of Aeronautical Sciences, Washington, D. C. 1962).

[4] Lacey, R. E., "A progress report on hydrofoil ships," Quart. Trans. Inst. Naval Architects **107**, 83–105 (January 1965).

[5] Jamieson, J. J., "Controls technology in hydrofoil ship design," *Proceedings, Ship Control Systems Symposium* (U. S. Navy Marine Engineering Laboratory, Annapolis, Md., 1966).

[6] McGanka, S. W., "Service evaluation of the control system installed onboard the hydrofoil ship HIGHPOINT (PCH-1), *Proceedings, Ship Control Systems Symposium* (U. S. Navy Marine Engineering Labaratory, Annapolis, Md., 1966).

[7] Petrie, D. M., "Operational and developmental experience on the U. S. Navy hydrofoil 'HIGHPOINT'," AIAA Paper 65-244 (1965); also J. Aircraft **3**, 79–84 (1966).

[8] Watson, F. B., "Protective coatings-foil system, PCH-1 HIGHPOINT," Boeing Company Rept. D2-133600-1 (July 1966).

[9] Stevens, D. L., Jr., "The Bureau of Ships hydrofoil craft, FRESH-1," paper presented to the Chesapeake Section, Society of Naval Architects & Marine Engineers, Washington, D. C. (February 1964).

[10] Stevens, D. L., Jr., "Design and procurement of the hydrofoil gunboat, PGH," Naval Engrs. J. **78**, 967–971 (December 1966).

OCTOBER 1967 J. HYDRONAUTICS VOL. 1, NO. 2

Development of an Autopilot for the Dolphin Hydrofoil

H. D. Ranzenhofer*
Grumman Aircraft Engineering Corporation, Bethpage, N.Y.

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

I. Introduction

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

Presented as Paper 67-353 at the AIAA/SNAME Advanced Marine Vehicles Meeting, Norfolk, Va., May 22–24, 1967; submitted June 7, 1967; revision received September 8, 1967. That portion of the development work described herein performed by the Grumman Aircraft Engineering Corporation was carried out under the sponsorship of Advanced Development Projects. Recognition is given to R. Rose, of Grumman Aerodynamics, and R. Barcus, of the Flight and Electronics Systems Section of AiResearch, for their work in the analysis and testing of the Dolphin Autopilot. [8.08]

* Head, Attitude Control Systems Group, Navigation and Control Engineering Section.

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

II. Hydrofoil Control Problem and a Solution

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

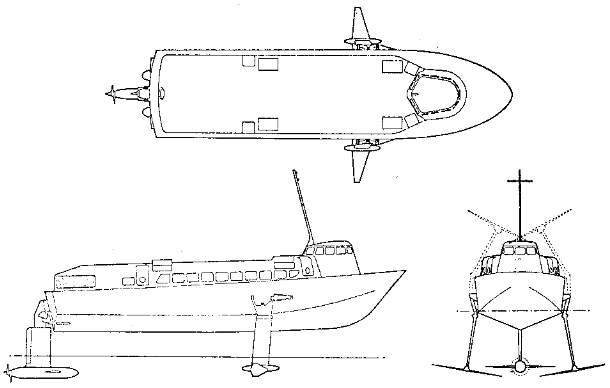

Fig. 1 Dolphin hydrofoil.

sible medium under severe constraints in allowable heave, pitch, and roll motions require rapid continuous movement of control surfaces. The purpose, then, is to maintain flight, and, in addition, to provide satisfactory performance. As far as passengers and crew are concerned, performance is defined by one criterion, i.e., comfort, which implies maintenance of low vertical accelerations in all parts of the vessel and prevention of hull impact and foil broach. Apropos of these requirements are the following two modes of foilborne operation: 1) platforming, maintenance of a flat trajectory in waves of heights less than or equal to keel-to-foil distance, satisfying flight requirements, and 2) contouring, heaving and pitching in phase with higher waves, meeting the comfort criterion.

Submerged foils help here in that they inherently tend to slice through small, high-frequency waves, exhibiting little or no response to wave inputs, and experience a resonance in low-frequency, high waves. These properties are characteristics of low-pass filters. The control problem, then, is to design a control system that enhances this filtering capability so that the resultant vehicle-autopilot system satisfies the foregoing requirements.

The solution is an autopilot that employs in its feedback loop high-pass parameters of craft motion for platforming conditions and low-pass parameters for contouring. High-pass parameters are those craft motions minimized at the upper range of wave encounter frequences, such as pitch, roll, heave, and their derivatives. Conversely, a low-pass element would be the height above the mean water level.

A basic autopilot is shown in Fig. 2. The types of sensors required are prescribed by the parameters discussed.

Basically, the control computer is required to process sensor outputs so that, for platforming, the high-pass signals are dominant, with a constant height maintained at any commanded level. In contouring, the high-pass signals effects are reduced and the height signals play a larger role as larger height errors are experienced.

Ideally, the autopilot should sense wave height and length, and position the control surfaces for the response desired. Practically, there are two objections to this approach. First, treating the ocean as a random disturbance, the over-all input function can be identified by an autopilot; however individual elements (waves) cannot be defined without resorting to sophisticated techniques at relatively prohibitive cost. Secondly, even with a system of this capability, by the time parameters of a particular wave were sensed and defined, the craft would be through it and the control surfaces positioned too late to be of any use.

Consequently, parameters are used which can be practicably sensed and identified by the autopilot, such as pitch, roll, heave, acceleration, and keel-to-water-surface distance, to provide performance most nearly satisfying our requirements at a reasonable cost.

III. Discussion

Autopilot Analysis

The analytical portion of the autopilot development program was carried out in two parts, a preliminary design effort at Grumman intended for an autopilot performance specification, followed by a more detailed system design study at AiResearch. A preliminary idea of dynamic stability is gained by applying the theory of small perturbations to the six vehicle equations of motion for an uncontrolled (fixed foil) craft in calm water,[6] and solving the resultant longitudinal and lateral stability matrices.

For a craft equipped with surface-piercing foils, such as the HS Denison, stability is provided by the rather large changes in lifting surface area with variation in foil depth. The principal contributor to the dynamic stability of submerged foil craft is a "depth effect" that exists within about two foil chord lengths of the water surface. This effect increases lift as the foil depth increases and vice versa. It dies out when the two-chord length limit is approached. The results of the stability calculation indicated that the Dolphin would be a stable craft, with reasonable damping (0.4–0.7) of the oscillatory modes.

Grumman's analog computer study[7] was part of a program to design and build an onboard autopilot simulator using the Dolphin as the study vehicle. The purpose of this device was to calculate automatically, during sea trials, the autopilot loop gains required for satisfactory foilborne performance. This subject is detailed in a subsequent paragraph.

In the program, the vehicle was simulated with five equations of motion solved for craft body axis accelerations in heave, pitch, roll, yaw, and sway, or sideslip. Foil and strut lift and drag coefficients, being nonlinear functions of foil depth, were generated independently. The craft was programmed for operation in sinusoidal waves in head, following, quartering, and beam seas, with the equations for foil depth and wave-induced orbital velocities implicit in this requirement.

The results of this computer study predicted qualitatively the performance that could be achieved by the Dolphin. Accordingly, an autopilot procurement specification was issued requiring AiResearch to perform and/or supply the following: 1) a computer study to determine nominal autopilot gains and a method of programming craft pitch during takeoff; 2) autopilot sensors, displays, controls, and selftest provisions; 3) a master checkout unit for autopilot onboard checkout and maintenance; and 4) fail-safety provisions.

The AiResearch computer study was two-fold, a 5-degree-of-freedom analog program,[8] similar in scope to the

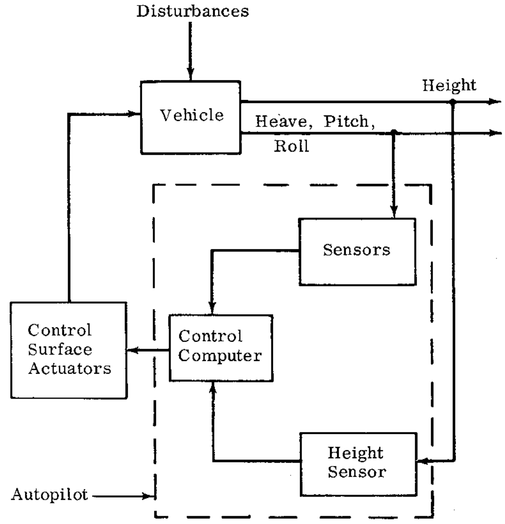

Fig. 2 Dolphin control system functional block diagram.

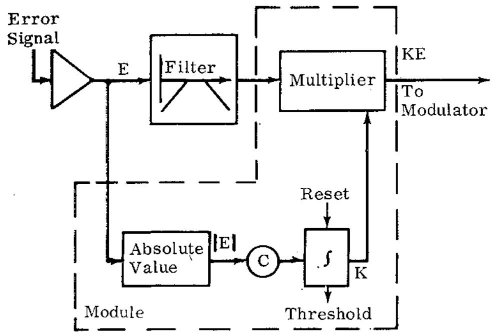

Fig. 3 AGS module block diagram (high pass).

Grumman computer study, and a 4-degree-of-freedom digital program[10] to determine autopilot requirements for takeoff. The primary objective of this work was to establish performance requirements for the control computer and sensors of a fixed gain autopilot with a degree of accuracy sufficient to ensure ultimate satisfactory operation with a minimum of trial-and-error procedure during hardware development and sea trials.

In the analysis, a mathematical model was developed for the hydrofoil craft, the autopilot, and the disturbance inputs for a 5-degree-of-freedom simulation. The computer study encompassed a wide spectrum of anticipated operating conditions and both longitudinal and lateral craft motions with heave-pitch, heave-roll, and yaw-sideslip coupling were considered. Craft performance was investigated for smooth water turns and straight runs in heading, quartering, beam, and following seas up to and including sea state 4. The stability of the craft under changing foil load distributions due to shift in the craft c.g. was also investigated.

In the takeoff program surge acceleration was made a variable, along with heave and pitch; hull lift, drag, and pitching moment terms also were introduced. Thus, by allowing all motions in the longitudinal plane, performance in smooth and head seas was simulated accurately. To make a qualitative estimate of takeoff performance in a quartering (45 deg) sea, roll was included as the fourth degree of freedom.

Automatic Gain Setting (AGS)

In the Grumman computer study, the autopilot equations expressed control surface motions as functions of craft motion, rate, and accelerations, as is usually done. However, in this case, the feedback gains were treated as variables, each a function of the error in the related channel. This serves to introduce the AGS concept and its employment as an analytical tool.

During a number of autopilot analysis and design studies for hydrofoil craft, it became increasingly evident that cost and time expended in both analysis and flight testing could be reduced substantially by automatically computing autopilot response characteristics. This could be done with an onboard analog computer, or autopilot simulator, tailored specifically to control of hydrofoil vehicles. Accordingly, this concept was developed to the point where analog computer programs could be carried out to evaluate the application of the concept to a hypothetical vehicle and then to a specific hydrofoil craft.

It was also decided that AGS studies would culminate in a set of modules incorporating the AGS function, which were to be employed in hydrofoil craft sea trials. Once gains were established they would be replaced by modules whose gains would be fixed at values computed by the AGS modules. (See Figs. 3 and 4.)

The AGS procedure is to increase gain from zero, as a function of the integral of the absolute value of error E until the particular error signal, on which the module is operating, is reduced to a value near zero. Thus, when the error is greater than a preset threshold value, the gain increases at a rate proportional to the simultaneous reduction in error. In other words, the effectiveness of the resultant feedback signal (gain $\times$ error) is increased at a decreasing rate until the desired vehicle attitude is attained.

The two types of modules, high- and low-pass, correspond to the platforming and contouring operation of hydrofoil craft. Most of the time, the craft will be required to platform small, high-frequency waves in which attitude parameters (pitch, roll, and heave) and their derivatives will be maintained as close to zero as possible.

With these requirements, the high-pass modules are designed to operate as previously described. Height control, however, should be more effective at low (contouring) than at high (platforming) frequencies. Moreover, it was often found that best performance was obtained with an adaptive height channel. Therefore, the low-pass module's function is slightly different from that of the high-pass units in that, in addition to the gain, a height channel gain schedule is computed as a function of height error. To accomplish this, gain-limiting is based on a comparison of signals proportional to gain height error. The gains resulting from craft operation in a number of different sea states will result in a height gain schedule. If these results yield little or no variation in the height gains required, then, of course, such a schedule will be unnecessary.

It is recognized that, although the gains should stabilize at values well within the stability region, exceptional circumstances could cause one or more gains to increase to a point where instability results. These circumstances fall into two categories, surface actuators with a frequency response

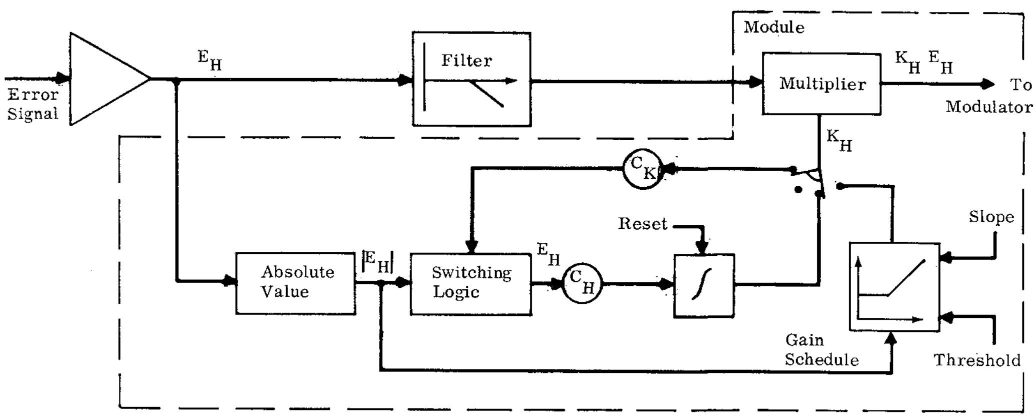

Fig. 4 AGS module block diagram (height).

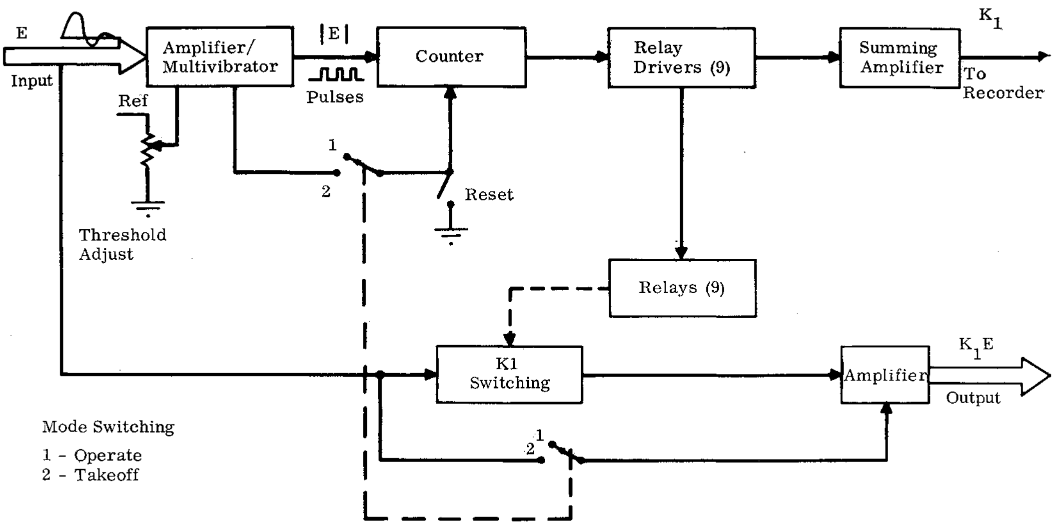

Fig. 5 AGS module mechanization (high pass).

characteristic of a higher significant order than unity, and malfunctioning of the AGS module.

In our hydrofoil analytical work, control surface actuators characterized by a single lag have generally been assumed; in fact, such is specified as a design goal to the actuator vendor. The assumption is valid as long as the higher orders are of such frequency magnitudes that they can be neglected. However, occasionally one encounters a case where operating loads are a substantial percentage of force capability, or where the entrained fluid volume of the actuator is relatively large, or both. These conditions tend to add roots to the characteristic equation and could yield instability if the gains were sufficiently high. Moreover, high gains tend to amplify nonlinear effects, such as backlash, one result of which is a limit cycle.

This problem was examined as part of a theoretical study of the AGS concept.[10] One solution found was to provide sufficient feedback channels to counteract the destabilizing tendencies of excess roots of the characteristic equation. In reality, this may not be practical because, very often, the actual number of actuator roots may not be known and, in any case, a high degree of complexity would result. Among the several ways of solving the high-order actuator problem the following two have suggested themselves as the most obvious and easiest to implement: 1) limit rate feedback gain so that the over-all system gain (craft × actuator × rate) never attains a value that results in instability, and 2) limit position feedback gain so that the feedback zero (position/rate) is always less than unity.

Both of these solutions are based upon the analysis reported in Ref. 10. In the event of a malfunction, divergence would be limited by the saturation level of the actuator servo amplifier. Moreover, danger to the vehicle is negated by the fail-safety features outlined in the Sec. IV of this paper.

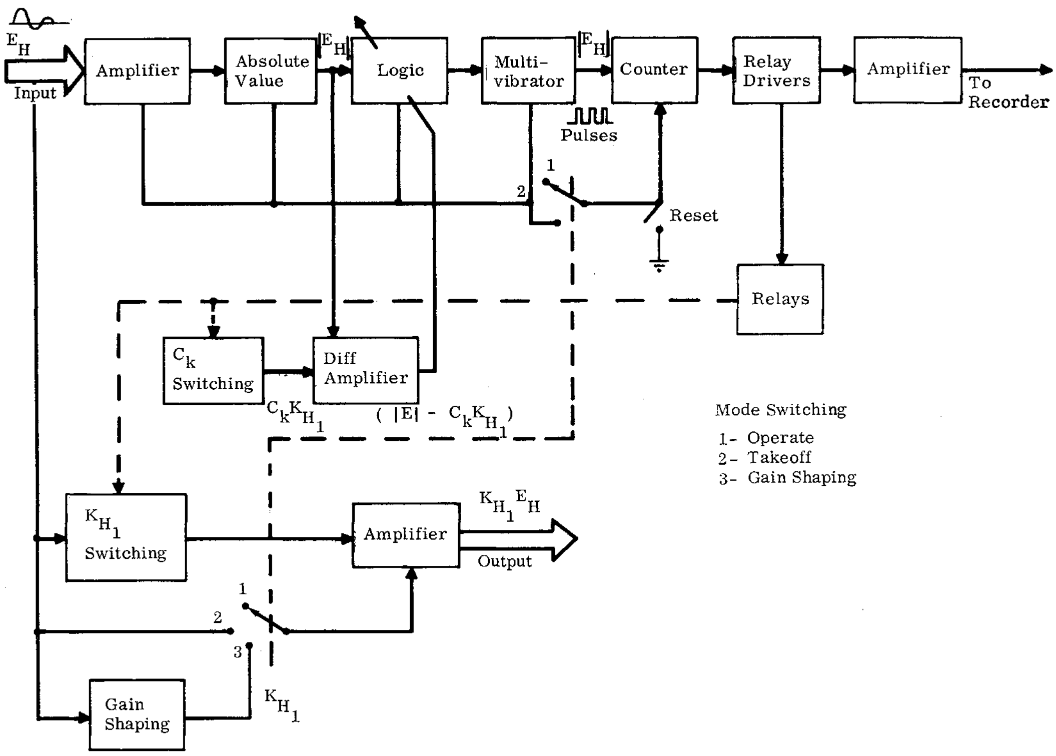

Fig. 6 AGS module mechanization (height).

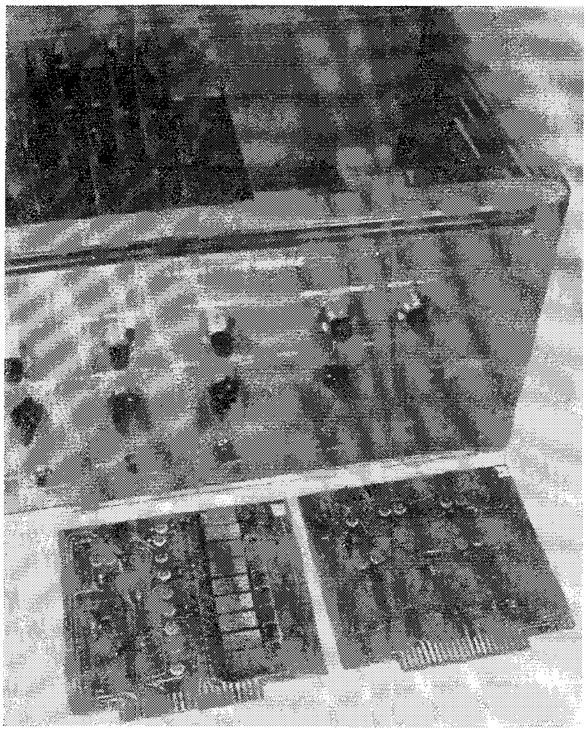

Fig. 7 AGS module.

Concerning the use of AGS in sea trials, it is expected that varying sea conditions and the shakedown nature of the trials will complicate the task of establishing and maintaining operation in particular sea states, and numerous takeoffs and landings will no doubt occur. Therefore, to facilitate the calculation of proper autopilot gains, the AGS integrating circuits will be reset to zero and the gain allowed to rise again if the craft is landed or if a reduced sea state is encountered. Reset in any case will be at operator's discretion.

Grumman's program resulted in the issuance of a procurement specification to AiResearch for the AGS modules in addition to that for the Dolphin autopilot. A set of the following AGS modules was ordered: 1) four high-pass modules, to be used in the pitch, roll, heave acceleration, and lateral acceleration channels, plus one spare, and 2) one low-pass height channel module, plus one spare.

To provide stable and continuous computation of gain throughout the rather wide range required, AiResearch has employed digital circuitry. (See Figs. 5 and 6.) Briefly, an error signal E is generated in the form of 5-v pulses, whose frequency is proportional to the magnitude of the error signal. The E pulses are counted in binary fashion by a set of nine flip-flops. Each of these networks pulses a relay driver, which, in turn, actuates a two-position relay. This switching, incorporated in a ladder network, results in a total of 2^9 or 512 possible states, or impedances, to which the switching network can be set. Thus, for both types of modules, the variable gain, K_1 is increased in increments of 0.0196.

The gain value computer in each module is obtained by summing the relay driver outputs and recording the result. The summing amplifier output is an analog signal corresponding to the gain switching network state.

The output signal of each AGS module represents the product of variable gain K_1 and the input error signal E. The over-all open-loop channel gain K is the product of K_1 and the nominal gain K_0 established in sensors and autopilot circuits external to the AGS module. Thus, K is increased in multiples of K_0.

There are three modes of module operation—operate, takeoff, and gain shaping, the latter applying to the height module only. The AGS modules each consist of two circuit boards, with an additional board required for the height module gain schedule. The units are entirely solid state, the flip-flops being Fairchild DT L950 micrologic devices. The set of modules is contained in a portable case with a single cable arranged to plug into a matching receptacle on the autopilot control computer. (See Fig. 7.)

IV. Results and Conclusions

Analysis

Automatic gain-setting

The Grumman studies indicated that the design of hydrofoil autopilots through use of an onboard simulator was indeed feasible. This conclusion was supported by the 5-degree-of-freedom analog study consuming only about half the time of previous simular programs. It was also discovered that certain of the feedback channels used would not be necessary, since the computed gains for these channels were negligible. Thus, by performing a gain-setting role, the modules help to configure the autopilot by indicating the need for feeding back any of the craft motion parameters.

To date, the AGS modules have not been tested in hydrofoil sea trials, but it is intended to do so at the earliest opportunity. Meanwhile, the results obtained have engendered studies of the application of the technique in the area of aircraft autopilot development and the expansion of the AGS concept to self-adaptive systems for both hydrofoils and aircraft.

Dolphin foilborne performance

Dolphin performance, with autopilot gains fixed at the values determined by the simulator, was a compromise between ideal platforming and ideal contouring. This was necessitated by the intention of keeping the autopilot simple and the costs down. However, two alternative methods of providing both platforming and contouring were studied. One was the retention of the automatic height gain adjustment used in the simulator. The other was a manual switching of height channel gain for platforming and contouring. The latter method is employed in the Dolphin system. The predicted heave performance is given in Fig. 8 and pitch and roll motions in Fig. 9.

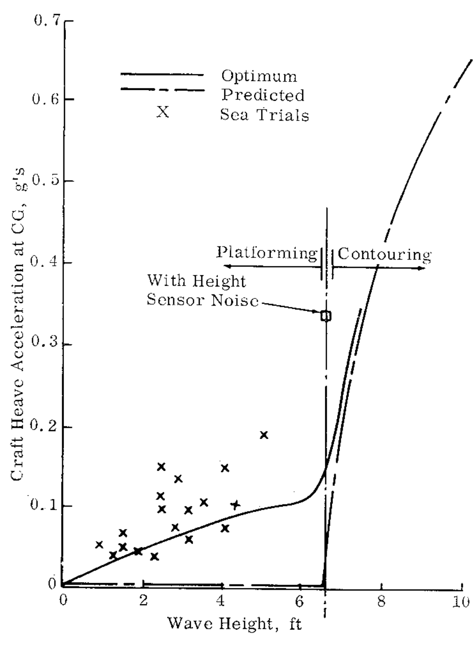

Fig. 8 Dolphin heave acceleration in waves.

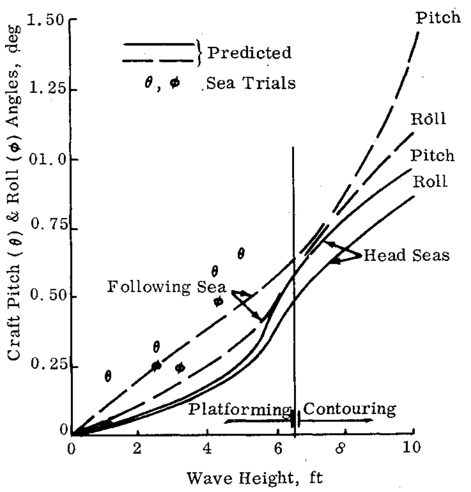

Fig. 9 Dolphin pitch and roll motions in waves.

Height sensor noise

To anticipate craft performance with height sensor noise, computer runs were made using a height signal-to-noise ratio of 3 to 1 (10 db). This ratio is much lower than that normally required (40 db) and imposed a severe task upon the control system. As a result foilborne operation was maintained, although performance was degraded to 0.36 *g*'s of heave acceleration. (See Fig. 8.) No such noise effects were found during actual sea trials.

Height sensor location

In order to provide maximum anticipation of wave encounter, the height sensor should be mounted as far forward as possible, thus requiring a radar or sonic device. In view of high cost and unknown reliability of radar and sonic height sensors, however, the possibility of using the contact type of unit on the forward struts was investigated. With proper filtering, both locations yielded good platforming. However, the strut-mounted unit's contouring performance was inadequate because of lack of anticipation afforded by the bow-mounted unit.

Takeoff performance

The chief control restraint imposed by takeoff conditions is to limit the positive travel of the forward foils. This must be done to prevent the foils being driven by the large height error to their maximum positions, thereby increasing drag to the point where takeoff could not be achieved. Two limiting methods were used, namely, pitch channel cross-coupling with the forward foil control channels, and limiting foil actuator commands, in accordance with drag calculations, to 70% of maximum. With pitch channel cross-coupling the forward foils reached angles of only 40% of their maximum value. The 70% limit resulted in similar takeoff times. It was also found that takeoffs could be achieved manually, if necessary. Best takeoff performance was attained by programming pitch as a function of height error and retaining pitch cross-coupling.

Fail-safety

It was determined that if hardover sensor and/or circuit failure occurred, provision should be made to automatically position the foils at suitable null positions. Simultaneously, the helmsman, having been warned by visual and aural devices would throttle back the engine. Foil null positions are defined as the mean positions about which the foils have been operating in the time period prior to failure. The voltage source of these null signals are independent of the control computer circuitry that receives inputs from sensors.

Autopilot mechanization

Selection of sensors and the control computer mechanization was carried out by AiResearch as a result of the studies previously described.

Control computer

The control computer contains the circuitry required to transform the sensed parameters into command signals for the control surface actuators in accordance with the performance requirements previously discussed. (See Fig. 10.) Subsidiary functions, such as turn coordination, height and attitude train, a variety of operating modes (standby, takeoff, and cruise), failsafe monitoring, and self-test are also supplied. (For clarity, the latter two mechanizations are not shown in Fig. 10.)

The computer is a functionally modular assembly using solid-state circuitry throughout and interchangeability insofar as possible. (See Fig. 11.) It contains a power supply which provides 400-cycle power to the sensors, as well as power used internally, by static inversion of the ship's power.

Sensors

The height sensor has received much consideration because of its state-of-the-art status. After a survey of manufacturers in this field and some field testing, it was decided to use the pulsed sonic type produced by Arma Division of the American Bosch Arma Corporation for the height channel, a low-pass filter is employed, whose chief function will be to negate the effects of small surface chop. The heave acceleration channel also required a noise filter to avoid vibration effects. Two accelerometers are located in the hull at the forward strut mounting areas. This places them at one of the most likely nodal points of hull bending if such a mode should exist to an extent likely to affect sensor outputs. The internal sensors are types that are readily available for aircraft, with basic characteristics as listed in Table 1.

Controls and displays

All command and monitoring functions are brought out to three panels, helmsman's control (Fig. 12), self-test and performance monitoring, and master warning. These panels provide manual fail-safe capability, as well as devices warning the helmsman of autopilot malfunction.

Table 1 Basic characteristics of the inertial sensors

Vertical gyro (2-axis)	
Range	± 30 deg
Drift rate	0.25 deg min
Repeatability to vertical	± 0.25 deg
Rate gyros (2)	
Range	± 10 deg/sec pitch
	± 30 deg/sec roll
Damping	0.5
Undamped natural frequency	15 cps
Accelerometers (3)	
Range	± 5.0 *g* vertical (2)
	± 0.5 *g* lateral
Linearity	± 0.5%
Damping	0.5
Undamped natural frequency	20 cps

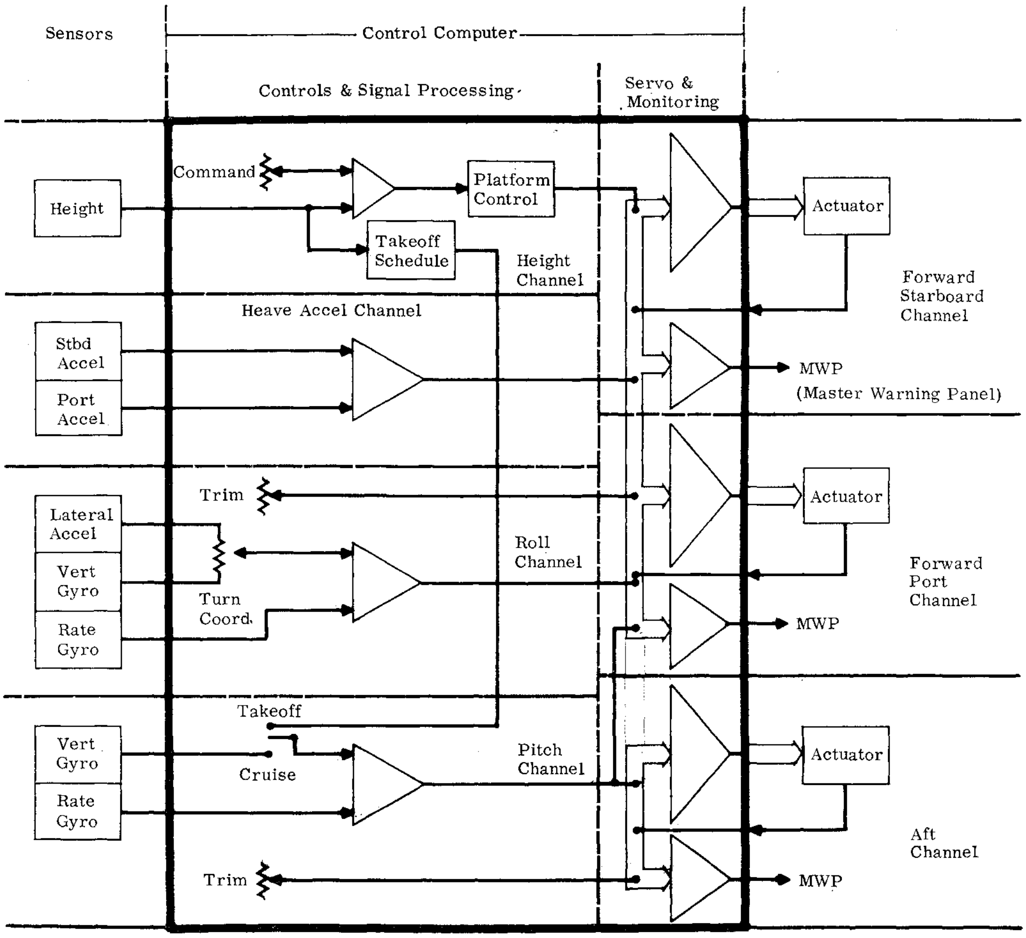

Fig. 10 Dolphin autopilot.

Sea trials foilborne performance

Sea trials took place in the Elbe River and in the Baltic Sea, off Kiel. During bench and installation checkouts no trouble of any significance was experienced with the autopilot.

Calm water trials confirmed the fixed-foil stability predicted in the analytical studies. Transient responses in heave and pitch were characterized by damping ratios of approximately 0.5.

For takeoffs, pitch commands programmed as a function of height, as indicated by the AiResearch studies proved successful. The smoothness of takeoffs is illustrated by the fact that passengers were frequently unaware of the transition from hullborne to foilborne operation.

In the open sea, the Dolphin encountered waves up to 6 ft high at all sea headings and was found to perform excellently. (See Fig. 8 and 9.) For comparison of predicted with actual results, it should be pointed out that sinusoidal waves of average length, obtained statistically,[1] were used in the analog programs, and that the Baltic Sea in winter is characterized chiefly by waves whose length-to-height ratios are among the smallest to be found. Moreover, since heave accelerations are a function of the square of wave encounter frequency, it follows that one can expect acceleration values higher than those predicted.

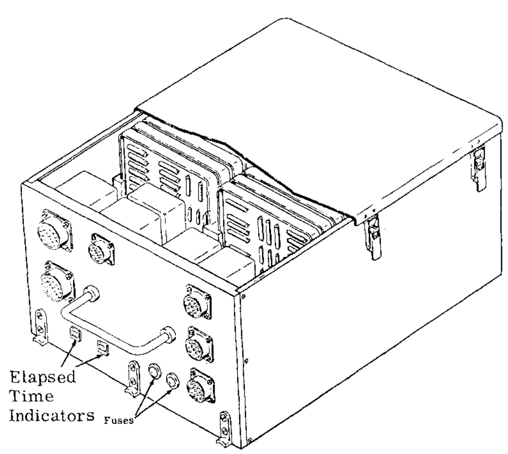

Fig. 11 Autopilot control computor.

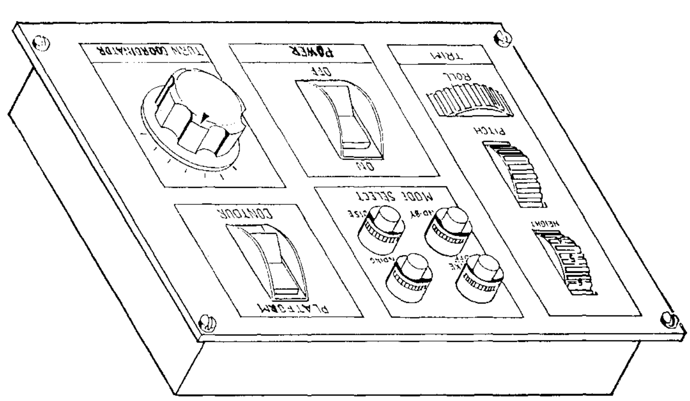

Fig. 12 Helmsman's control panel

The connection between heave acceleration and comfort is intuitively rather obvious. What is not so obvious is a definition of comfort. There has been much work done along these lines, where, in addition to accelerations, such things as frequency and duration of occurrence are involved. In the final analysis, everyone on board a vehicle has his own definition of comfort, depending a good deal upon intangibles. Suffice it to say that at no time during the Dolphin trials was there an indication of discomfort.

Conclusions

The conclusions are briefly summarized as follows: The Dolphin is inherently stable, with fixed foils, at design cruising speed in calm water. Dolphin performance in the open ocean makes the craft eminently suitable for comfortable, rapid transport of large numbers of passengers and/or cargo over selected routes in many parts of the world.

References

[1] Pierson, W., Jr., Neumann, G., and James, R. W., "Practical methods for observing and forecasting ocean waves," U.S. Navy Hydrographic Office Publication H.O. 603 (1955).

[2] Ranzenhofer, H. D., "Hydrofoil research ship AG(EH) autopilot development program—five-degree-of-freedom analog computer simulation," Grumman Rept. DA M23-335.1 (July 1962).

[3] Blaiklock, W. C. and Ferris, E. W., "Development and testing of motion measuring instrumentation for the XCH-6 hydrofoil craft," Grumman Rept. MPD 47.135(R) (January 1963).

[4] Ranzenhofer, H. D., "Hydrofoil ship FRESH-I stability and control study," Grumman Rept. DA M51-200.1 (April 1963).

[5] Ranzenhofer, H. D., "Hydrofoil ship FRESH-I analog computer study," Grumman Rept. DA M51-200.2 (May 1963).

[6] Kaplan, P., Hu, P. N., and Tsakonas, S., "Methods for estimating the longitudinal and lateral dynamic stability of hydrofoil craft," Stevens Institute of Technology ETT Rept. 691 (1958).

[7] Ranzenhofer, H. D., "An on-board autopilot simulator for hydrofoil craft—five-degree-of-freedom analog computer study," Grumman Rept. ADR 06-11-64.1 (December 1964).

[8] Vesque, R. E., "Analog computer study—Dolphin hydrofoil control system," AiResearch Manufacturing Division Rept. 66-0440 (June 1966).

[9] Vesque, R. E., "Digital computer study—Dolphin hydrofoil takeoff program," AiResearch Manufacturing Division Rept. 66-0591 (July 1966).

[10] Ranzenhofer, H. D., "An on-board simulator for hydrofoil craft—preliminary study of a method of automatic gain adjustment," Grumman Rept. ADN 06-11-69.1 (October 1964).