CONTROL SYSTEM FOR HYDROFOIL.

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ABSTRACT

A control system for a hydrofoil of the type having forward and aft submerged foils for supporting the craft while foil borne. In the preferred embodiment of the invention, separate pairs of starboard and port control flaps are provided on the aft foil; while the forward foil, also provided with flap means, is carried at the lower end of a pivoted strut which acts as a rudder. The system incorporates a high degree of redundancy for safety and failproof operation. Craft motions are sensed by gyroscopes and accelerometers which produce signals for controlling the flaps to provide smooth riding characteristics and a minimum of acceleration on passengers and crew for all seaway conditions. Turning of the craft is achieved by initially actuating the flaps to bank the craft about its roll axis, followed by a rudder action. Pitch is controlled by both the forward and aft flaps; motions about the roll axis are controlled by the aft flaps only; while the height of the craft while foil borne is controlled by the forward flap means only.

17 Claims, 8 Drawing Figures
Fig. 6B
Fig. 6C
CONTROL SYSTEM FOR HYDROFOIL

BACKGROUND OF THE INVENTION

As is known, in a hydrofoil seacraft of the submerged foil-type, the hull of the craft is lifted out of the water by means of foils which are carried on struts and pass through the water beneath the surface thereof. In passing through the water, and assuming that sufficient speed is attained, the foils create enough lift to raise the hull above the surface and, hence, eliminate the normal resistance encountered by a ship hull in passing through the water.

In the usual case, there are forward and aft foils, both provided with control flaps similar to those used on aircraft. The other essential element is the rudder which pieces or is submerged beneath the surface of the water and is either forward or aft of the craft, depending upon its design. In most hydrofoils, the flaps are used primarily to cause the craft to ascend or descend and to control the craft about its pitch and roll axes; however, they can also be used in combination with the rudder to bank the ship about its roll axis during a turn.

The flaps are also used to stabilize the craft during movement on water. For example, pitching or rolling motions can be minimized by proper counterbalancing movement of the flaps. In the past, hydrofoils have been provided wherein a vertical gyro is employed to sense roll and pitch, together with sensors for producing electrical signals proportional to the height of the hull above the surface as well as vertical and lateral acceleration of the craft. These electrical signals are utilized in circuitry for controlling the flaps to provide a smooth ride through the sea.

While prior art control systems of this general type are at least partially effective, many leave something to be desired in terms of response characteristics and smooth riding capability.

SUMMARY OF THE INVENTION

In accordance with the present invention, a new and improved control system for a hydrofoil with submerged foils is provided which enables a higher degree of safety than prior art control systems while at the same time providing for smoother operation in rough seas as well as better response characteristics.

The control system of the invention provides continuous control of the foil-borne craft by sensing craft motions, combining the motion signals with manual pilot commands, and converting these signals into appropriate control surface deflections. In the hydrofoil of the invention, the control surfaces consist of trailing edge flaps on forward and aft foils together with a swiveled forward strut or rubber. The port and starboard flap segments on the forward foil operate in synchronism and are connected to a single hydraulic actuator. The aft foil has trailing edge flaps, two on the port side and two on the starboard side. Each flap is driven by a separate hydraulic actuator. The automatic control system or computer operates upon sensed motions and manual inputs to provide commands to the control surface servos.

The inputs to the control system are obtained from manual input commands as well as sensed craft motions. The manual inputs to the system consist of a foil depth command which establishes the desired foil depth, a helm signal which provides turning commands, and a heading hold switch which engages or disengages the automatic heading hold function. The sensors consist of one or two vertical gyro which sense pitch angle and roll angle, a height sensor which can be radar or ultrasonic and which measures the distance from a point on the bow to the water surface, a yaw rate gyro, three vertical accelerometers, and one forward lateral accelerometer. As mentioned above, the signals from these sensors are combined with the manual input commands to control the flaps and maintain smooth riding conditions while maintaining the craft on a desired course.

One important feature of the invention resides in the fact that in turning the craft, the trailing edge flaps on the aft foils are initially actuated to bank the hydrofoil or cause it to roll. This roll is then sensed to vary rudder position, which results in a much larger roll control margin during turning.

In another aspect, the control system of the invention is such that the height of the hydrofoil above the surface of the water is controlled by flaps on the forward foil only, while pitch is controlled by flaps on both the front and back foils.

Another important aspect of the invention resides in the provision of redundant hydraulic and electrical control systems. Two hydraulic pumping systems are provided, either of which can be connected through shuttle valves to the forward flaps and rudder. One aft flap on each of the starboard and port sides is connected to one hydraulic system; while the other aft flap on each side is connected to the other hydraulic system such that partial aft flap effectiveness is achieved even if one hydraulic system should fail. SIMILARLY DUAL ROLL SIGNALS AND DUAL HELM SIGNALS ARE GENERATED. THE DUAL ROLL SIGNAL MAY BE DERIVED FROM TWO SEPARATE VERTICAL GYROS, OR FROM TWO SEPARATE ROLL SIGNAL PICKOFFS ON A SINGLE VERTICAL GYRO. These roll and helm signals are both applied to separate derivative amplifiers which control the port and starboard aft flaps, respectively.

Another important aspect of the invention involves the generation of acceleration signals which are used for ride smoothing. A lateral acceleration and vertical acceleration signal are developed at the vicinity of the forward strut base (top of strut) and are applied to the rudder and forward flaps, respectively. The forward vertical acceleration signal is applied to an electronic shaping network which generates a pseudo integral of acceleration signal in addition to the acceleration signal itself.

Finally, an important feature of the invention is the generation of vertical acceleration signals on both the port and starboard sides of the craft. These are applied to the respective aft port and aft starboard flap control systems to achieve a smoother ride in a seaway.

The above and other objects and features of the invention will become apparent from the following detailed description taken in connection with the accompanying drawings which form a part of this specification, and in which:

FIG. 1 is a side view of the hydrofoil of the invention;
FIG. 2 is a bottom view of the hydrofoil of FIG. 1 showing the positions of the flaps on the forward and aft foils of the craft as well as the positions of the various motion sensors;
FIG. 3 is a schematic illustration of the control surface hydraulic actuation system of the invention;
FIG. 4 is a perspective view of the hydrofoil of the invention showing its relationship to its pitch, roll and yaw axes;
FIG. 5 is a simplified block diagram of the overall control system for the hydrofoil of the invention; and FIGS. 6A–6C, when placed side-by-side, comprise a detailed block diagram of the control system of the invention for the forward and aft flaps as well as the forward rudder.

When reference now to the drawings, and particularly to FIG. 1, the hydrofoil shown includes a conventional hull 10 which can be provided with a propeller or the like and an inboard motor, not shown, in order that it can traverse the surface of water as a conventional displacement ship. Pivotedly connected to the hull is a forward, swiveled strut or rudder 12 which is rotatable about a vertical axis in order to steer the craft in the foil-borne mode of operation. The rudder 12 can also be swiveled upwardly in the direction of arrow 14 to clear the surface of the water when the craft is operating as a conventional displacement ship. Carried on the lower end of the rudder 12 is a forward foil 16 (FIG. 2) which carries at its trailing edge control surfaces or flaps 18 which are interconnected and operate in synchronism. In this respect, it can be said that there is a single forward flap mean.

In the aft portion of the craft, struts 20 and 22 are pivotally connected to the hull 10 about an axis 21. The struts 20 and 22 can be rotated downwardly into the solid-line position shown in FIG. 1 for foil-borne operation, or can be rotated backwardly in the direction of arrow 24 and into the dotted-line position shown when the craft operates as a conventional displacement ship. Extending between the lower ends of the struts 20 and 22 is an aft foil 26 which carries, at its trailing edge, two starboard flaps 28 and 30 and two port flaps 32 and 34. As will be seen, each set of starboard flaps and each set of port flaps normally operate in synchronism; however each flap in the port or starboard pair is provided with a separate hydraulic actuation system as well as a separate electrical servo system for redundancy and safety purposes so that one can operate even though the electrical or hydraulic system for the other should fail.

Carried between the struts 20 and 22 and pivotally connected to the hull 10 about axis 21 is a gas turbine water jet propulsion system which provides the forward thrust for the craft during foil-borne operation. It should be understood, however, that a propeller or other type of thrust-producing device can be used in accordance with the invention.

With the rudder 12 and struts 20 and 22 retracted, the craft may transit in the hull-borne mode. Assuming that the control system about to be described is inactive, the strut-foil system in its retracted position modifies the ship sea state response similar to the condition of bilge boards and skegs. The struts provide roll damping and increase the ship's directional stability. The foil system increases damping of the ship's pitch. At higher hull-borne speeds where the control flaps become effective, activation of the automatic control system provides a hydrofoil ship with a sea state response superior to a gyro-stabilized conventional ship.

In the foil-borne mode of operation, both the rudder 12 with its foil 16 and struts 20 and 22 with their foil 26 are rotated downwardly into the solid-line positions shown in FIG. 1 and locked in position. In order to become foil-borne, the pilot sets the desired foil depth in a manner hereinafter described and the throttles are advanced. The ship, therefore, will accelerate and the hull will clear the water and continue to rise until it stabilizes at the commanded foil depth. The normal landing procedure is to simply reduce the throttle setting, allowing the ship to settle to the hull as the speed decays. During foil-borne operation in normal water conditions, the hull does not contact the water surface and hull impacts do not occur. At higher sea state operations, two types of hull impacts can occasionally occur. The first results from "cresting" higher waves. In this type of impact, the hull contacts and burrows the wave crest without loss of foil lift. The second type of hull impact results from "broaching" the foil in the trough of a wave. The foil loses lift until hydrodynamic flow is again reestablished, and the hull may or may not impact the wave surface. The hull is designed to retain water-tight integrity for both types of impact originating from any flying height and for all possible ship orientations. Utilizing the control system of the invention hereinafter described in detail, the resulting vertical motions and accelerations are not hazardous to the crew or passengers.

Mounted on the hull, as shown in FIG. 2, are sensors for producing electrical signals indicative of craft motion. Thus, at the bow of the craft is an ultrasonic height sensor 36 which produces an electrical signal proportional to the height of the bow above the surface of the water during foil-borne operation. Also at the bow of the ship is a forward vertical accelerometer 35 which produces an electrical signal proportional to vertical acceleration. Mounted on the hull at the top of the rudder 12 is a lateral accelerometer 38 which, of course, produces an electrical signal proportional to lateral or sideways acceleration of the craft. Mounted on the top of the starboard strut 20 is an aft starboard vertical accelerometer 40, and mounted at the top of the port strut 22 is an aft port vertical accelerometer 42. A vertical gyro 44 or a pair of vertical gyros is mounted in the craft, preferably near the center of gravity, for producing signals proportional to the angle of the craft with respect to vertical about its pitch and roll axes. Finally, a yaw rate gyro 45 is provided in the forward portion of the craft.

With reference now to FIG. 3, the hydraulic system for actuating the forward and aft flaps is shown. The hydraulic system provides hydraulic power from two separate hydraulic power sources or systems A and B driven by separate prime movers to actuate the control surfaces or flaps. The aft outboard flap and forward flap actuators are normally driven from system A; while the aft inboard flap and rudder actuators are normally driven from system B. A shuttle valve 46 under the control of manual switches in the pilothouse can transfer the forward flap actuator 48 from system A to system B in the event of a loss of pressure in system A. A similar shuttle valve 49 connected to the actuator 50 for rudder 12 can transfer the rudder actuator from system B to system A in the event of loss of pressure in system B. The shuttle valves 46 and 49, as well as different hydraulic systems for inboard and outboard aft flaps, provide the ship with a fail-safe operational capability for any potential single hydraulic system failure.

The aft hydraulic system shown in FIG. 3 includes hydraulic actuators 52 and 54 for the outboard aft flaps 28 and 32, respectively. The actuators 52 and 54 are connected to hydraulic system A. Similarly, the aft inboard flaps 30 and 34 are connected to hydraulic actuators 56 and 58, respectively, which are powered by hydraulic system B. Thus, even though one of the two hy-
draulic systems A or B should fail, at least one of the flaps on both the port and starboard sides will still operate. Normally, both the inboard and outboard flaps on either side of the craft operate simultaneously and in synchronism, the dual sets of flaps being provided primarily for redundancy and safety purposes.

Motions of the craft about its roll, pitch and yaw axes can perhaps best be understood by reference to FIG. 4. The roll axis about this axis will be sensed by the vertical gyro 44 as well as the aft accelerometers 40 and 42. The gyro 44 will produce an output signal proportional to the amount of degree of roll; while the accelerometers 40 and 42 will produce signals proportional to the angular acceleration about the roll axis. The pitch axis in FIG. 4 is identified by the reference numeral 62. Any movement about this axis will be sensed by the vertical gyro 44 as well as both the forward and aft accelerometers 35, 42 and 40. Finally, the yaw axis is identified by the reference numeral 64 in FIG. 4, and any movement about this axis will be sensed by the yaw rate gyro 45 as well as the lateral accelerometer 38.

In the control system of the invention, the height of the hull above the water is controlled solely by the forward flap 18. In order to raise the hull from the surface of the water, the forward flap is rotated downwardly, thereby increasing the lift afforded by the forward foil 16 and causing the hull to elevate out of the water. In order to eliminate or minimize pitching motions about the pitch axis 62, both the forward and aft flaps are employed. However, the forward and aft flaps operate in opposite directions to correct any pitch condition. For example, if the bow of the craft should dip, the forward flap will be rotated downwardly; while the aft flaps 28–32 will be rotated upwardly to produce a moment counterbalancing the pitching moment caused by waves or the like. Compensation for movement about the roll axis is achieved solely by the aft flaps 28–32; however in this case the starboard flaps move in a direction opposite to the port flaps to correct for undesired rolling motion. In turning the craft, the aft flaps are initially positioned to cause the craft to bank about its roll axis; when the rudder 12 is rotated to follow through. As was explained above, this gives a much better and smoother turning action since the correct roll inclination is achieved before any substantial turning of the craft occurs via the rudder.

A simplified block diagram of the control system of the invention is shown in FIG. 5, it being understood that this is not the actual control system but included herein to facilitate and simplify the explanation of the manner in which the control is carried out. The pilothouse controls include a signal on lead 66 from a depth signal generator 68. Additionally, a turn signal on lead 70 is derived from the helm 72 in the pilothouse. As will be seen from the detailed description of the system herein after, the helm signal can be derived either from the helm itself or from a heading hold circuit. In the latter case, the signal is derived by comparison of actual ship heading with a compass heading or the like; and if the two are not the same, then an error signal is derived for commanding a turn until the desired and actual headings are the same.

As can be seen from FIG. 5, the signal from the height sensor 36 proportional to actual height is compared with the desired height signal on lead 66 in a depth error amplifier 74. If the two signals fed to the amplifier 74 are not the same, then a signal is developed on lead 76 and applied to a forward flap servo system 78 which causes the forward flap 18 to rotate downwardly or upwardly, depending upon whether the hull should rise or descend. When it is desired to turn the craft about its yaw axis, a signal on lead 70 proportional to helm position from null is applied to a roll derivative amplifier 80 where it is compared with a signal on lead 82 from vertical gyro 44 proportional to the roll angle about axis 60 (FIG. 4) relative to vertical.

At the beginning of a turn, and assuming that the water through which the hydrofoil is traveling is smooth, the signal on lead 82 will be zero, or substantially zero. The roll derivative amplifier compares the signal on lead 82 with that on lead 70; and assuming that the two are not the same, as is the case for the conditions just described, then an output signal appears at the output of the amplifier 80 and is applied to inboard and outboard port flap servos 84 and 86. At the same time, it is applied in an inverted form to the inboard and outboard starboard flap servos 88 and 90. The result, of course, is that one set of aft flaps will rotate downwardly while the other set rotates upwardly to cause the craft to bank about its roll axis. This action will continue until the angle of roll as sensed by the gyro 44 is such as to generate a signal which nulls out the helm signal on lead 70. However, at the same time, the signal on lead 82 proportional to roll angle is also applied to the rudder servo 92. This causes the rudder 12 to rotate after the craft begins to bank about its roll axis, causing the craft to turn in the direction to which the craft has been banked. Thus, the craft banks to the right in response to a signal from helm 72, the rudder 12 will thereafter rotate to steer the craft to the right. As was explained above, this gives a much smoother turn for all sea conditions encountered with a minimum of acceleration forces on the passengers and crew.

Stated in other words, the system is such that the craft will assume the correct roll angle before banking. This may not occur if the rudder is rotated immediately as, for example, when the craft banks to the left because of sea conditions when a right turn is initiated.

As the ship turns, the yaw rate gyro 45 will produce a signal on lead 94 proportional to the rate of turning about the yaw axis; and this is utilized in the rudder servo 92 to limit the rate of turning. The same is true of the forward lateral accelerometer 38 which produces a signal on lead 96 proportional to lateral acceleration. This is applied to the rudder servo 92 in order to limit the lateral acceleration. Thus, if the craft is turning into a position where it is broadside to the direction of a strong wind and accompanying waves, the yaw rate gyro 45 and lateral accelerometer 38 will sense the thrust on the craft and limit the rate of turning. Of course, after the desired turn is executed and the helm 72 rotated back to its center or null position, the signal on lead 70 decreases back to zero; whereupon the positions of the aft flaps are reversed to cause the craft to come back up into a vertical position about the roll axis. At this point, the output of the vertical gyro 44 on lead 82 decreases to zero; the rudder 12 is centered; and the craft is again stabilized.

The remaining control actions are primarily for the purpose of eliminating or minimizing undesirable pitching and rolling actions. Thus, the forward accelerometer 35 senses acceleration at the bow, either upward
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or downward, and produces an electrical signal for controlling the forward flap 18 to counteract movement about the pitch axis 62 (FIG. 4). The output of the forward accelerometer 35, however, is combined in integral amplifier 100 with a signal proportional to the roll signal squared as derived from circuit 98 before the combined signal is applied to the forward flap servo 78. This is for the reason that during a turn and while the craft is being banked about its roll axis, and during normal rolling action in heavy seas, the rolling movement produces a component of vertical acceleration which must be taken into consideration.

A signal proportional to the angle of the craft about the pitch axis is derived from vertical gyro 44 on lead 102. This is applied to a pitch derivative amplifier 104 which produces an output signal which varies as a function of pitch angle from horizontal and the rate of change of pitch angle. The output of the pitch derivative amplifier 104 is then applied to all of the flap servos and is also applied in inverted form to the forward flap servo 78 to achieve differential control. This signal is used for stability augmentation, ride smoothing in a seaway, and automatic pitch trim control.

Assuming that the craft is rolling about its roll axis 60, a signal will be derived on lead 82 which is again applied to the roll derivative amplifier 80. The signal on lead 82 under these circumstances will first increase in one direction or polarity, then recede back to zero and increase in the other direction or other polarity and again recede back to zero as the craft rolls from side-to-side. This again produces at the output of the roll derivative amplifier a signal which varies as a function of both the roll angle as well as the rate of change roll angle. This signal is applied to the aft flap port and starboard servos so as to achieve differential action that counteracts the rolling movement. In other words, a signal of one polarity is applied to the port flap servos; while a signal of inverted polarity is applied to the starboard flap servos to achieve rotation of the respective port and starboard flaps in opposite directions to counteract a rolling motion.

The output of port vertical accelerometer 42 is applied to both the inboard and outboard port flap servos 84 and 86 and acts to vary the aft port flap positions to counteract any vertical acceleration or heave on the port side. Similarly, the output of the starboard vertical accelerometer 40 is applied to both the inboard and outboard starboard flap servos 88 and 90 to achieve the same action and counteract vertical accelerations on the starboard side of the craft.

The complete control system is shown in FIGS. 6A–6C wherein elements corresponding to those of FIG. 5 are identified by like reference numerals. The control flaps and the rudder are shown interconnected via broken line 106 and block 108 identified as "craft motions" to complete the servo system and show that actuation of the control flaps and rudder effect motions which, in turn, vary the outputs of the various sensors such as the gyro, the accelerometers, and so on.

It will be noted that the forward vertical accelerometer 35 is connected through an amplifier-demodulator 110 to the integral amplifier 100 where the signal is combined with a signal from circuit 98 proportional to the absolute value of roll squared as explained above. The output of the integral amplifier 100 is a signal which varies as a function of both heave acceleration at the forward strut (i.e., rudder 12) as well as heave velocity at the forward strut. This signal is applied through a scaling network 112 to the forward flap servo 78 shown enclosed by broken lines. The operation of the forward flap servo is identical to that of the servos for the remaining flaps as well as the rudder 12. A detailed explanation of operation of the servos will be given hereinafter.

The pitch output from the vertical gyro 44 is applied through an amplifier-demodulator 114 to the pitch derivative amplifier 104 to produce an output signal on lead 116. This signal varies as a function of pitch angle from horizontal as well as pitch rate. The signal is applied through scaling network 118 to the forward flap servo 78 and is also applied in inverted form through scaling network 120 to each of the servos for the flaps 28–34 on the aft foil. As was explained above, the control action is such that in response to a pitching motion, the flap 18 on the forward foil 16 is rotated in one direction; while the aft flaps are rotated in the opposite direction to produce a moment which counterbalances or counteracts the pitching moment induced in the craft by rough water, for example.

As shown in FIG. 6A, there are actually two roll outputs from the vertical gyro 44, the two outputs being used for redundancy and safety purposes. One output is applied through an amplifier-demodulator 122 to two derivative amplifiers 80A and 80B; while the other roll output is applied through an amplifier-demodulator 124 to both the same port and starboard derivative amplifiers 80A and 80B. An alternate implementation would replace the two roll outputs from one vertical gyro with two separate vertical gyros.

The helm 72 likewise has two redundant and equal outputs, one of which is applied through an amplifier-demodulator 126 to a filter 128 and the other of which is applied through an amplifier-demodulator 130 to a filter 132. The resulting filtered output of filter 128 is applied through lead 134 to both derivative amplifiers 80A and 80B. Similarly, the output of filter 132 is applied through lead 136 to both the derivative amplifiers 80A and 80B. An explanation of the details and function of amplifiers 80A and 80B, capable of producing output signals which vary as a function of both roll angle and rate of change of roll angle, can be had by reference to Analog Computation, A. S. Jackson, 1960, McGraw-Hill Book Company, Inc., New York.

A heading hold circuit 138 under the manual control of the pilot is adapted to produce an output signal which is applied through an amplifier-demodulator 140 and lead 142 to both of the derivative amplifiers 80A and 80B. Actually, the heading hold circuit will be disabled when the helm is activated under the control of the operator to manually produce turning signals. On the other hand, when it is desired to hold a certain heading of the craft, the heading hold circuit is activated whereby if the desired heading is directly east, for example, then the hold circuit will produce an output signal by comparison with a compass setting to cause the craft to turn whenever it veers off the desired course. In other words, the output of the heading hold circuit 38 and that of the helm 72 are used in the alternative.

The output of the port roll derivative amplifier 80A is applied through a scaling network 144 to the outboard port flap servo 86 as well as the inboard port flap servo 84. Similarly, the output of the starboard roll derivative amplifier 80B is applied through scaling net-
work 146 to both the outboard starboard flap servo 90 as well as the inboard starboard flap servo 88. It will be apparent, of course, that the two circuits 80A and 80B are identical in function and are redundant for safety purposes. Thus, if one or the other of the circuits should fail, one set of flaps, either starboard or port, will still be effective in controlling the craft. Similarly, if one of the two helm or roll signal channels should fail, both the starboard and port flaps will still be effective to control the craft.

The output signal from the aft starboard vertical accelerometer 40 is applied through amplifier-demodulator 148 and scaling network 150 to the inboard and outboard starboard flap servos 88 and 90. Similarly, the aft port vertical accelerometer 42 is connected through amplifier-demodulator 152 and scaling network 154 to both the inboard and outboard port flap servos 84 and 86. These signals are used for ride smoothing in a seaway. That is, vertical acceleration on the port side causes actuation of the port flaps to counteract the acceleration. Similarly, acceleration on the starboard side actuates the starboard flaps to counteract starboard acceleration. The aft port and starboard accelerometers are not used for redundancy purposes; but since both starboard and port accelerations are sensed and used to control the flaps, a smoother ride is achieved.

The height sensor 36 is connected to the depth error amplifier 74 as previously explained along with a signal on lead 156 from an amplifier-demodulator 158 connected to the depth command 68. The height sensor 36 is of the ultrasonic type. Its output is filtered or integrated such that the actual height signal will not fluctuate appreciably when the ship is traveling through rough water and the actual distance between the surface and the hull is changing rapidly due to the undulation of waves beneath it. The output of depth error amplifier 74 is applied through scaling network 160 to the forward flap servo 78 as explained above. Thus, control of height is entirely by way of the forward flap 18.

The output of the yaw rate gyro 45 is applied through an amplifier-demodulator 162 and scaling network 166 to the rudder servo 92. Also applied to the rudder servo, and after passing through amplifier-demodulator 168 and scaling network 170, is a signal proportional to forward lateral acceleration. Finally, the outputs of both amplifier-demodulators 122 and 124, proportional to roll angle, are applied through scaling network 172 to the rudder servo 92. As was explained previously, the control action is such that when the helm is turned, the aft flaps are initially actuated to bank the craft about its roll axis; whereas the banking action is sensed by the vertical gyro to produce roll angle signals which are fed to the rudder servo 92. This, in turn, causes the rudder to turn in the direction of banking. After the craft is turned in the proper direction and the helm returned back to its center or null position, the aft flaps cause the craft to return to its upright position; whereupon the roll output signals tend to return to zero and the rudder will return back to its center or null position.

It is a feature of the invention that even though the helm is not turned, rolling action of the craft will not only actuate the aft flaps but will also actuate the rudder 12 due to the fact that the roll outputs of the gyro 44 are connected to the rudder servo 92. In this manner, if the craft should roll to the right due to the action of wind or waves, for example, the rudder will be actuated to steer the craft to the left or into the oncoming wind or wave where the roll action is minimized.

As was mentioned above, all of the flap servos, as well as the rudder servo, are identical. Accordingly, only the forward flap servo 78 will be described in detail. It includes a forward flap servo amplifier 176 which, in effect, comprises an operational amplifier having four inputs applied to one of its two input terminals through resistors. Preferably, the operational amplifier is of the integrating type having a capacitive feedback path in order to prevent rapid or abrupt response characteristics. In the case of servo 78, the five inputs to the operational amplifier 176 comprise signals on leads 178, 180, 182, 184 and 186. The signal on lead 178 varies as a function of both pitch angle from horizontal as well as pitch rate. The signal on lead 180 varies as a function of craft height as explained above. The signal on lead 182 is derived through a scaling network 188 from the output of amplifier-demodulator 114 and varies as a function of actual pitch angle. The signal on lead 184 varies as a function of forward acceleration; while the signal on lead 186 is a feedback signal proportional to actual flap position. That is, the forward flap actuator 48 (see also FIG. 3) is connected through a mechanical linkage 190 to the flap 18. This same mechanical linkage 190 is connected to a primary position transducer 192 which produces a signal on lead 194 whose magnitude varies as a function of the angular position of the forward flap 18 and whose polarity depends upon whether the flap is rotated upwardly or downwardly from its central or null position. This signal is applied through a feedback demodulator 196 and scaling network 198 to the input of the servo amplifier 176. The arrangement, of course, comprises a conventional servo system wherein an output signal from the servo amplifier 176 will actuate the forward flap servo valve in actuator 48 to vary the position of flap 18. When the position is varied, a feedback signal is generated at the output of network 199; and this signal persists until it nulls out or cancels the combined input signal on the other input leads 178–184 which initiated the control action.

Let us assume, for example, that it is desired to increase the height of the craft above the surface. A signal of one polarity (e.g., positive) will be applied to the input of amplifier 176 via lead 180. This causes the flap 18 to rotate downwardly, thereby producing a negative signal on lead 186 which tends to null out the positive signal on lead 180. As the actual height increases, the error signal on lead 180 will decrease, thereby causing a counter-rotation of the flap 18 and a decrease in the feedback signal on lead 186 until a null condition is again reached with the flap centered and the new, desired height reached. The foregoing, of course, assumes that no other signals are being applied to the input of the servo amplifier 176. In actual practice, however, a number of signals will be applied simultaneously from the various inputs, some of which are additive and some of which are subtractive depending upon forward acceleration, pitch angle, and the like. These, when combined at the input of amplifier 176, will effect a desired inclination of the forward flap tending to compensate for all of the various error signals introduced into the system.

Although the invention has been shown in connection with a certain specific embodiment, it will be
readily apparent to those skilled in the art that various changes in form and arrangement of parts may be made to suit requirements without departing from the spirit and scope of the invention.

What is claimed is:

1. In a control system for a hydrofoil craft having forward and aft foils, the combination of separate port and starboard flap means on at least one of said foils, rudder means associated with said foils, means for generating a command signal for turning said craft, means responsive to said command signal for initially actuating said separate flap means to cause said craft to bank about its roll axis in the direction of a desired turn, means for sensing banking of the craft about its roll axis in response to actuation of the separate flap means, and apparatus coupled to said sensing means for thereafter actuating the rudder means to turn the craft in said direction of desired turn.

2. The control system of claim 1 wherein said separate port and starboard flap means are on the aft foil, and including control flap means on the forward foil, the rudder means comprising a strut extending downwardly from the bow of the craft and carrying at its lower end said forward foil.

3. The control system of claim 1 wherein said command signal is generated by a helm and wherein said means for sensing banking of the craft about its roll axis comprises a gyroscope adapted to produce an output signal which varies as a function of the roll angle of said craft.

4. The control system of claim 3 including means for producing two identical and redundant command signals from said helm, means for producing two identical and redundant signals from the gyroscope, and means for applying both roll signals and both command signals to both of said derivative amplifiers.

5. The control system of claim 1 wherein said means for sensing banking of the craft about its roll axis includes a gyroscope for producing an electrical roll signal which varies as a function of the roll angle of said craft, and including derivative amplifier means responsive to said command signal and to said electrical signal produced by the gyroscope for generating an electrical signal for controlling said separate flaps.

6. The control system of claim 5 wherein said derivative amplifier means includes two derivative amplifiers both responsive to said command signal and to said electrical signal produced by the gyroscope, the output of one of said derivative amplifiers being used to control the port flap means and the output of the other derivative amplifier being used to control the starboard flap means.

7. The control system of claim 1 wherein said means for sensing banking of the craft about its roll axis also senses roll of the craft about its roll axis due to an undulating motion of the water beneath the craft, said apparatus for actuating the rudder means being effective to rotate the rudder means in response to such undulating motion as well as to banking of the craft in response to a turning command signal.

8. The control system of claim 1 including a yaw rate gyro mounted on said craft, and means operatively connecting said yaw rate gyro to said rudder means to limit the rate of turning of the rudder means as a function of yaw rate.

9. The control system of claim 8 including a lateral accelerometer mounted on said craft, and means operatively connecting said yaw rate gyro to said rudder means to limit the rate of turning of the rudder means as a function of lateral acceleration of the craft.

10. The control system of claim 9 wherein the rudder means is positioned at the bow of the ship above said forward foil.

11. In a control system for a hydrofoil craft having forward and aft foils, the combination of control flap means on the forward foil, flap means on the aft foil, means for sensing the height of said craft above the surface of the water when it is foil-borne and for producing an electrical signal proportional to said height, means for producing an electrical signal proportional to desired height of said craft above the water, means for comparing said first and second electrical signals to derive an error signal when the first and second signals are not the same, and means responsive to said error signal for controlling the position of only the control flap means on the forward foil to cause the hydrofoil craft to rise or descend until said error signal is zero.

12. The control system of claim 11 including vertical accelerometer means mounted at the bow of said craft for producing an electrical signal proportional to vertical acceleration of the bow, and means responsive to said last-named electrical signal for varying the position of said control flap means on the forward foil as a function of vertical acceleration thus sensed.

13. The control system of claim 11 including gyroscope means for producing an electrical signal which varies as a function of the pitch angle of said craft, and means responsive to said last-named electrical signal for varying the position of the flap means on said forward foil.

14. In a control system for a hydrofoil craft having forward and aft foils, the combination of control flap means on the forward foil, separate port and starboard flap means on the aft foil, means including a gyroscope for producing an electrical signal which varies as a function of both the pitch angle of said craft as well as a function of the rate of change of said pitch angle, means responsive to said electrical signal for controlling both the control flap means on the forward foil as well as the flap means on the aft foil to counteract any pitching action of the craft, an aft port vertical accelerometer above the aft port foil, an aft starboard vertical accelerometer above the aft starboard foil, means operatively connecting the aft port vertical accelerometer to the port flap means on the aft foil whereby the port flap means will be actuated to counteract vertical acceleration forces on the port side of the craft, and means operatively connecting the aft starboard vertical accelerometer to the starboard flap means on the aft foil whereby the port starboard flap means will be actuated to counteract vertical acceleration forces on the starboard side of the craft.

15. In a control system for a hydrofoil craft having forward and aft foils, the combination of flap means on the forward foil, separate pairs of port and starboard flaps on the aft foil, a first pair of hydraulic actuators for actuating one port and one starboard flap of each pair, a second pair of hydraulic actuators for actuating the other flap of each pair of port and starboard flaps, a single hydraulic actuator for the forward flap means, a first source of fluid under pressure for actuating the first pair of hydraulic actuators, a second source of fluid under pressure for actuating the second pair of hydraulic actuators, and shuttle valve means for connect-
The control system of claim 15 including a rudder for the hydrofoil, a single actuator for actuating said rudder, and shuttle valve means for connecting said single rudder actuator to either the first or second source of fluid under pressure.

17. In a control system for a hydrofoil craft having forward and aft foils, the combination of separate port and starboard flap means on said foils, each of said separate starboard and port flap means including an inboard and an outboard flap, separate actuators for the inboard and outboard flaps of each flap means, separate power sources for the actuators for the inboard and outboard flaps respectively, means for generating a command signal for turning said craft, means responsive to said command signal for initially actuating the actuators for said separate flap means to cause said craft to bank about its roll axis in the direction of a desired turn, means for sensing banking of the craft about its roll axis in response to actuation of the actuators for the separate flap means, and apparatus coupled to said sensing means for thereafter actuating the rudder means to turn the craft in said direction of desired turn.

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