

Sept. 6, 1966

V. BUSH

3,270,699

HYDROFOIL CRAFT

Filed March 4, 1965

5 Sheets-Sheet 1

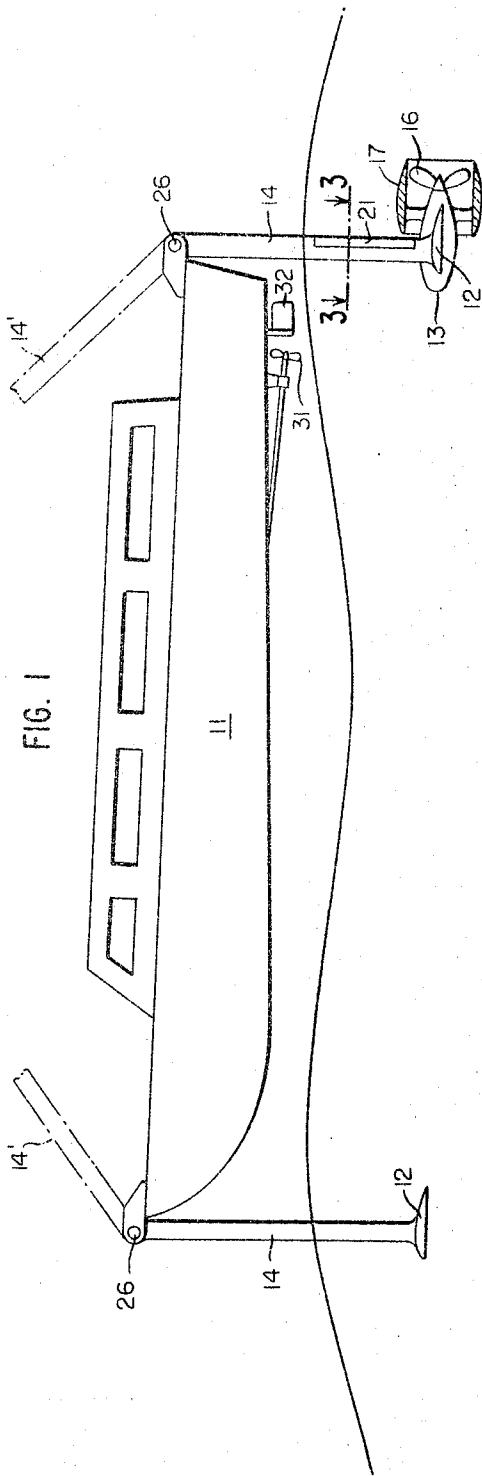


FIG. 1

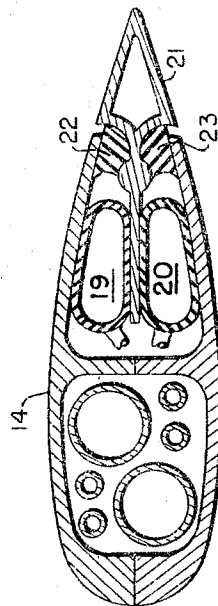


FIG. 3

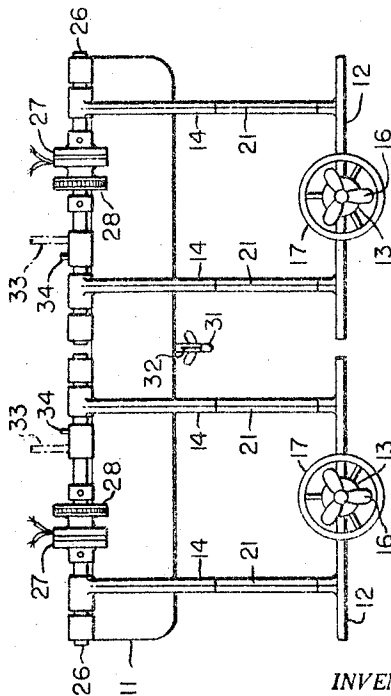


FIG. 2

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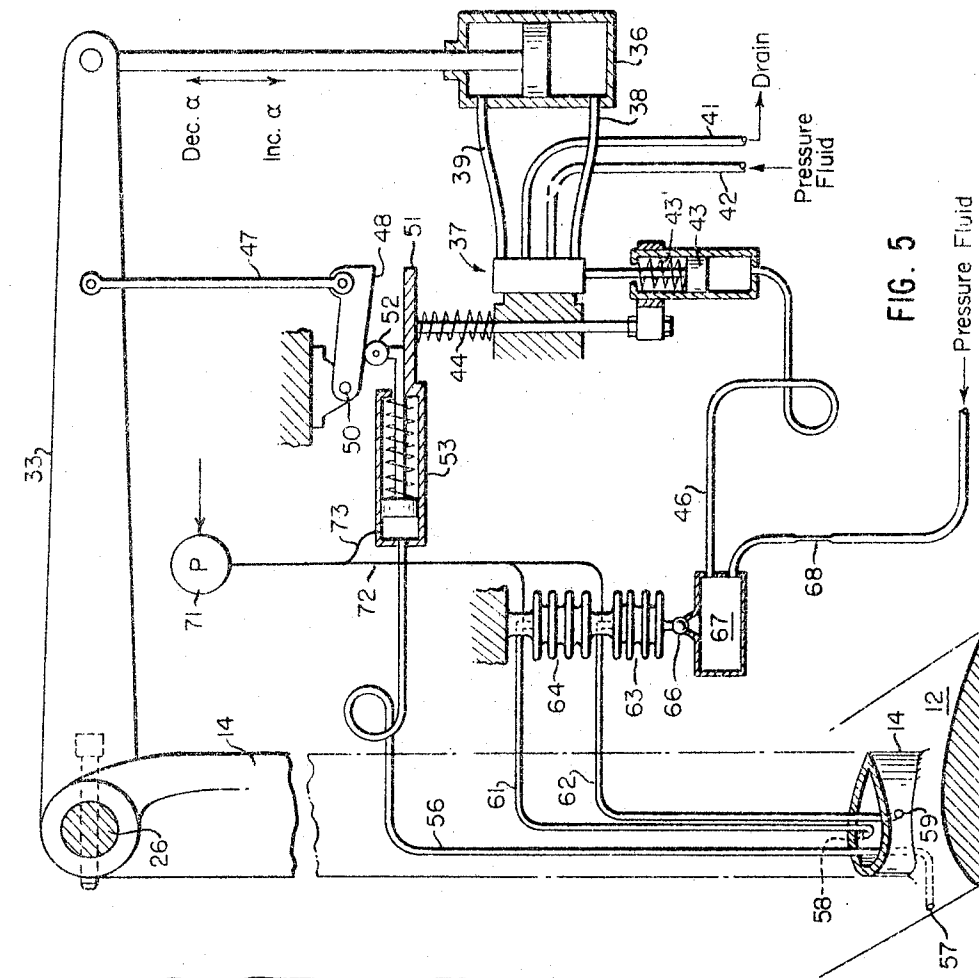
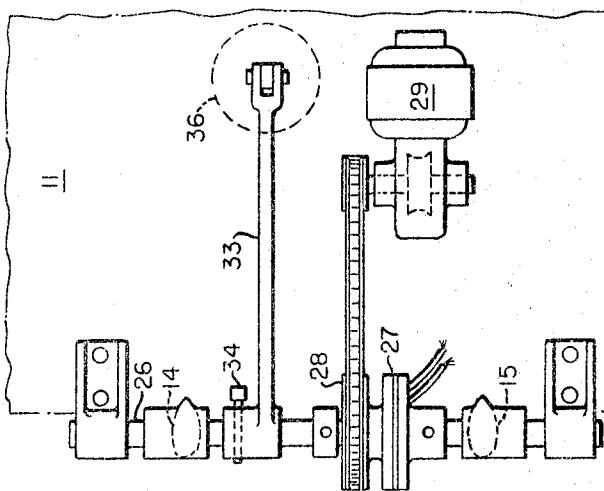
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HYDROFOIL CRAFT

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5 Sheets-Sheet 2



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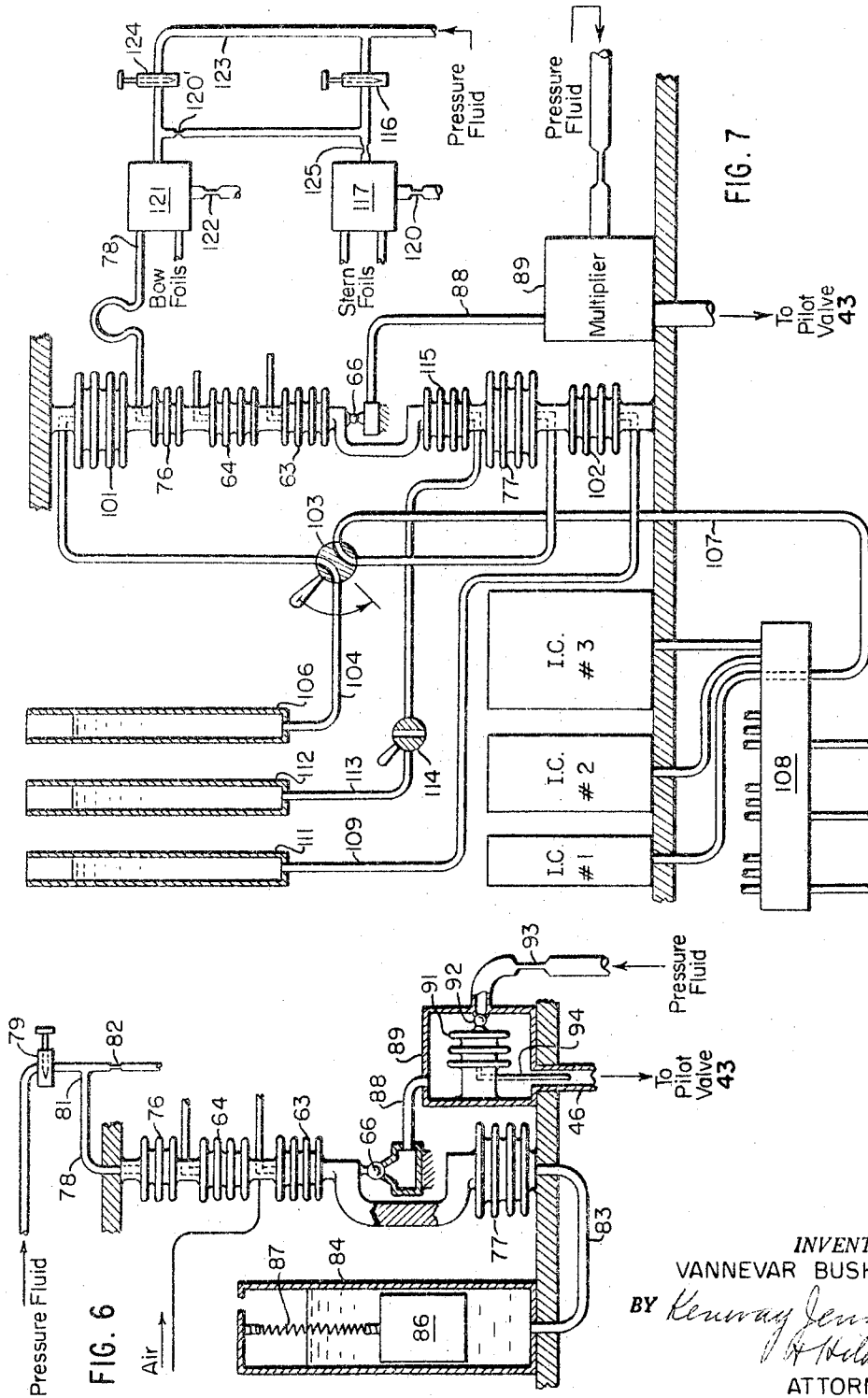
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HYDROFOIL CRAFT

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5 Sheets-Sheet 3



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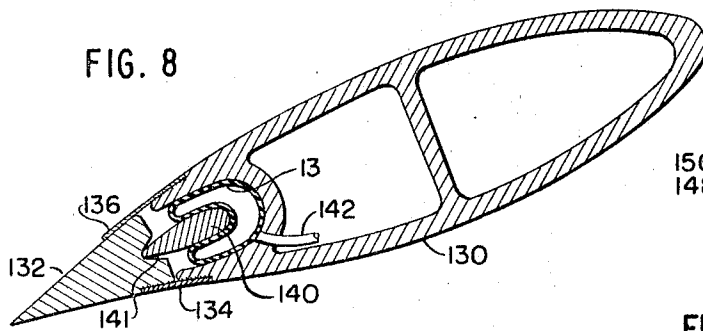
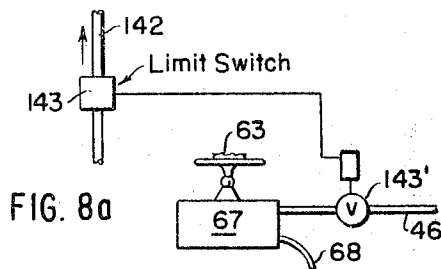
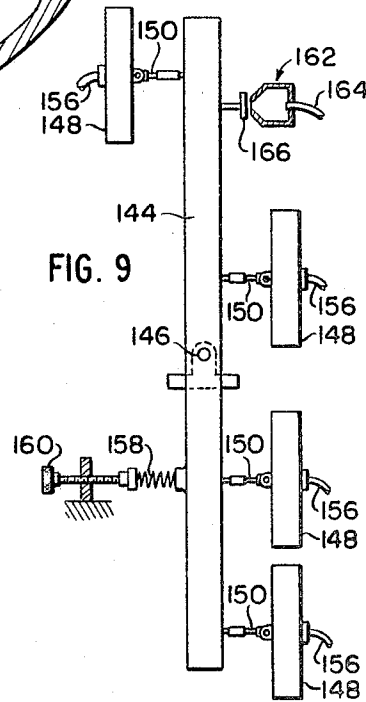
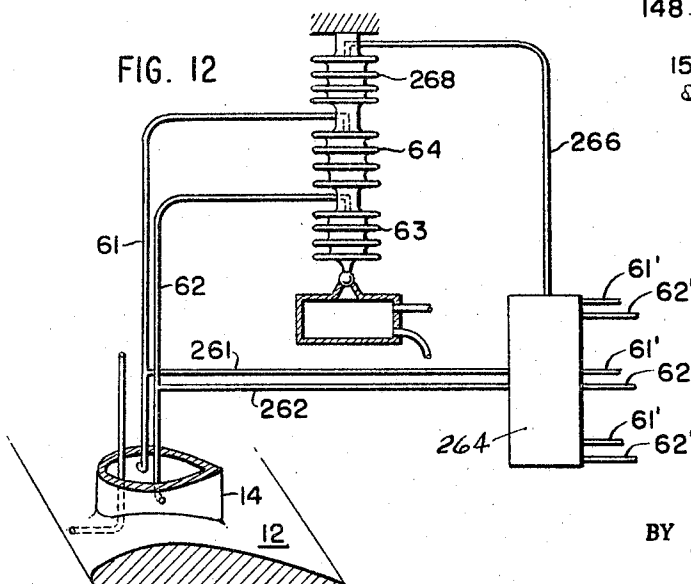
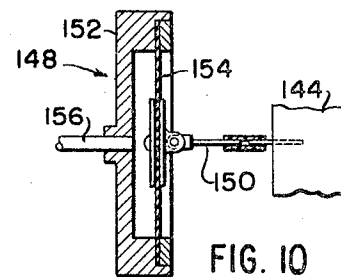
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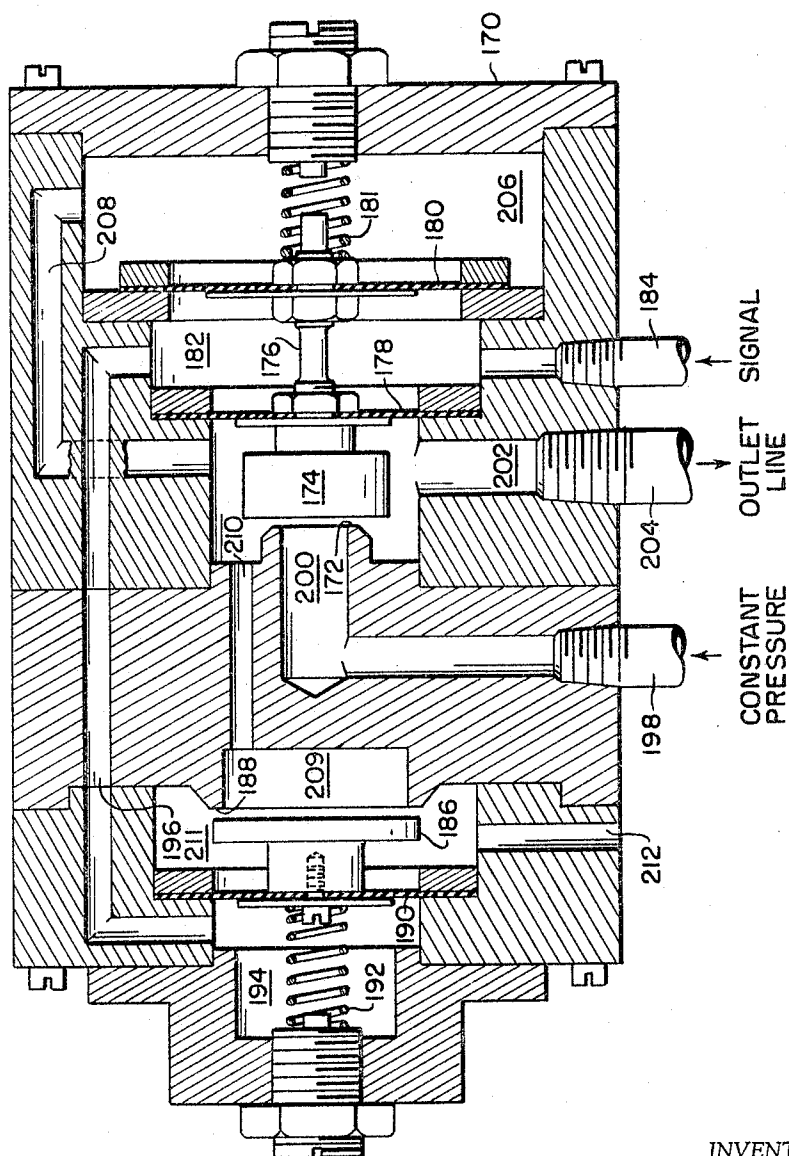
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FIG. 11



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3,270,699

HYDROFOIL CRAFT

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24 Claims. (Cl. 114—66.5)

This invention relates to hydrofoil craft, particularly operating controls for the type of hydrofoil craft whose foils remain fully submerged while the craft is in flight.

As is well known to those skilled in the art, there are two main types of hydrofoil craft, namely, surface hydrofoil and submerged hydrofoil craft. With the surface type, the foils rise out of the water as the craft approaches cruising speed which decreases their efficiency. Such craft have the advantage of simplicity in that control of attitude and elevation of the hull is self-adjusting; the craft merely rises until the foil area remaining submerged and operating at a constant attack angle, is just sufficient to support the weight of the craft. However, pitching is a series problem with this type of craft. For example, the craft may be proceeding in calm water at full speed, with 20% of its foil area submerged, when suddenly it meets with a wake which submerges the full forward foil area. The greatly increased amount of lift which results, tends to throw the bow violently upwardly, and many serious accidents have been attributed to this cause. For a similar reason, behavior of the craft in rough water is unsatisfactory.

In submerged hydrofoil craft, the foils remain fully submerged, even at top speed, and the hull elevation above the water is maintained steady by control of the angle of attack of the foils, that is, the angle between the chord lines of the foils and the direction of progress of the craft through the water. The problem of pitching is avoided because abrupt changes in lift cannot occur. Submerged hydrofoil craft also require less driving force per square foot of operating foil because the foils are operating in relatively undisturbed water, and hence are more efficient. A disadvantage of the submerged type of hydrofoil craft is that it requires modes of control of the foils which in the past have been difficult and costly to implement. Another disadvantage is the deep draft of the craft when on displacement, for then the foils are some distance below the hull.

One of the more serious problems of submerged hydrofoil craft relates to wave motion. It has been found that water particles below the surface of waves move in orbits which are circular in deep water and elliptical in shallow water, the diameter of the orbits decreasing rapidly with depth below the surface. However, the time it takes a particle to traverse a given circle corresponds to the time it takes the wave to progress one wave length and is independent of depth, so that particle velocities decrease with increasing depth. The resultant of the particle velocities and the velocity of the craft determines the apparent direction in which a foil is met by water. In waves, therefore, the angle of attack of a foil varies as the craft proceeds through the waves, producing a corresponding variation in lift. If the foil angles are fixed, variations in lift due to this cause may run as high as 50% of normal. When relatively small waves are being met rapidly, as when the craft is proceeding against a moderate sea, such variations in lift are compensated by the inertia of the craft. Experience has shown, however, that when waves are being met relatively slowly, as with a following sea, the performance of conventional controls leaves much to be desired. In the past, controls similar to or identical with autopilot controls for aircraft have been utilized, but such controls do not perform properly in these circumstances.

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An object of the present invention, therefore is to provide an improved control system for submerged hydrofoil craft.

A more specific object is to provide precise automatic control of the attitude and elevation of such craft so that it can be headed in any direction in rough seas as well as in smooth.

Another object is to provide a more simple and reliable control system embodying fluid transducers and actuators.

Still another object is to provide a novel form of steering mechanism for such craft.

A further object is to provide a hydrofoil craft having retractable foils so that it can be operated in shallow water.

The novel features of the invention together with further objects and advantages will become apparent from the following detailed description of a preferred embodiment and the drawings to which the description refers.

In the drawings:

FIG. 1 is a profile view in elevation of a hydrofoil craft in accordance with the invention;

FIG. 2 is a rear view in elevation of the craft;

FIG. 3 is a sectional view taken on line 3—3 of FIG. 1;

FIG. 4 is a diagrammatic view of the retraction mechanism for one of the craft's hydrofoils;

FIG. 5 is a diagrammatic view of a simplified form of control system for controlling the angle of attack of one of the foils as a function of the speed and elevation of the craft;

FIGS. 6 and 7 are diagrammatic views of a more refined form of control system in accordance with this invention;

FIG. 8 is a detail view of a flap control to vary the lift coefficient of a foil; FIG. 8a is a detail to be referred to;

FIG. 9 is a diagram illustrating a system utilizing parallel-connected devices for effecting composition of multiple signals;

FIG. 10 is a sectional detail view of the preferred form of cell for use in the system of FIG. 9;

FIG. 11 is a diagrammatic view of a preferred form of multiplier; and

FIG. 12 is a diagram of a system according to the present invention for effecting stabilization of the craft under certain sea conditions.

With reference first to FIGS. 1 and 2, it will be observed that the numeral 11 represents generally the type of hull which is preferred for the hydrofoil craft according to the present invention. As shown, the hull has an unusually broad beam to take advantage of the fact that only during takeoff will the hull be met by waves and then only at relatively low speeds. The advantage of a broad beam, of course, is that for a given hull length, the amount of space available for passenger use and for storage is much greater. A hull with a broad beam can also accommodate relatively long foils which have less induced drag and which provide greater lateral stability. The foils themselves are designated by the numeral 12. There are four of them, each taking the form of a pair of wing-like elements which are supported near their ends by a pair of depending struts 14 and carry between them a nacelle 13. The two rear nacelles are adapted to serve as housings for motors, and the motors (not shown) drive propellers 16. Preferably, the propellers are of a type designed to operate within a shroud 17 as this type of propeller provides high thrust at low speeds, a characteristic which is desirable for takeoff. Typically, the craft will cruise at approximately 30 knots with a takeoff speed in the

10-12 knot region. Hydraulic motors for driving the propellers are preferred because of their relatively high power to weight and size ratio. Fluid under pressure is supplied to these hydraulic motors by means of lines which pass inside the struts, the input ends of the lines being connected in common to a high pressure hydraulic pump (not shown) located at some convenient point within the hull proper.

Two of the rear struts are provided with flaps 21 for steering. As shown in FIG. 3, each flap has a vane portion which projects into the strut. This portion is constrained to pivot by clamping members 22 and 23 of extruded rubber or the like. The major surfaces of the vane are disposed between pressurized bags of air 19 and 20. Angular movement of the flap for steering is produced by control of the relative pressures in the two bags. For example, a pair of balanced relief valves can be operatively connected to the bags and the wheel of the craft can be mechanically connected to the relief valves. In this way, flap deflection can be made very nearly proportional to angular displacement of the wheel with respect to a center or neutral position. If more exact steering control is deemed necessary, all of the stern struts can be provided with these flaps.

In order to maintain a straight course, it is important that the effective area of the rear struts be greater than that of the forward struts. That is to say, the struts themselves provide lift or sidewise thrust which is a function of the angle of the chord line of the struts relative to their line of progress through the water. If the craft is proceeding through the water at relatively high speed, there is a tendency for minor disturbances such as localized turbulence to deflect it from its course. As a consequence, both forward and after struts experience lift but if the effective area of the rearward struts is the greater, they will act to bring the craft back on course.

In FIG. 4 the manner in which the struts are mounted on the hull is shown more in detail. To each pair of cooperating struts 14 there is rigidly joined a shaft 26 which extends in a generally horizontal direction at right angles to the center line of the hull. Shaft 26 is connected by a clutch 27 to a sprocket 28 which is chain driven by a motor 29. By means of motor 29, the shaft 26 can be rotated and the foils raised out of the water into a retracted position, as shown by the dotted lines in FIG. 1. With the foils retracted, the draft of the craft is substantially decreased as is advantageous for navigating within a harbor or adjacent to docking areas. In fact, it is preferred that the craft be provided with an auxiliary screw 31 and rudder 32 for navigating at low speeds in a displacement mode. Of course another advantage of the foils being retractable is that the foils, especially the two after ones with their self-contained motors and steering mechanisms, are made readily accessible for servicing.

Also mounted on the shaft 26 is a control lever 33 which does not rotate with the shaft whenever the clutch 27 is engaged to raise or lower the corresponding foil. Once the foil has been lowered into operating position, however, clutch 27 is disengaged, and a pin 34 is provided to fix the lever to the shaft.

In FIG. 5 there is shown a simplified form of control mechanism for moving the lever 33 in order to establish the desired angle of attack, four such mechanisms being employed, one for each foil. As shown in FIG. 5, lever 33 is connected at one end to a hydraulic cylinder or actuator 36, and a valve 37 is provided to control the operation of the actuator 36. A four-way type valve is preferred, the same being coupled to the actuator by means of two lines 38 and 39, to a drain line 41, and a pressure fluid supply line 42. When the valve is moved away from a neutral position in one direction, it admits oil under pressure to one end of the cylinder by way of line 38 and opens the other end of the cylinder through line 39 to exhaust. Conversely, movement of the valve away from a neutral position in the opposite direction, admits oil

under pressure to the opposite end of the cylinder by way of line 39 and opens line 38 to exhaust.

Control valve 37 is actuated by a pilot valve 43 which is hydraulically urged in one direction by pressure in a line 46, and in the opposite direction by an internal biasing spring 43'. Coupled to the pilot valve body is a follow up or back coupling linkage. This linkage includes a link 47 pivotally connected between the lever 33 and an arm 48. Arm 48 is constrained to pivot about a fixed point 50. Adjacent the arm is a part 51 which is directly connected to the pilot valve body and is urged toward the arm 48 by a spring 44. A roller 52 disposed in rolling contact with the arm determines its spacing from the part 51 by virtue of the fact that the roller is joined to the piston of a hydraulic actuator 53, the body of which is rigidly joined to the part 51. As will be explained more fully hereinafter, actuator 53 is connected by a line 56 to an orifice 57 located on the leading edge of one of the foils thereby to provide a pressure in the line 56 which is representative of the speed of the craft. Alternatively, the orifice can be located on the leading edge of one of the struts. A pair of additional orifices 58 and 59 are provided on the sides of one of the struts where no dynamic pressure is created under quiescent operating conditions. These are connected by lines 61 and 62 to respective bellows 63 and 64. As shown, the bellows are disposed in series so as to produce linear movement of a relief valve 66 for a chamber 67 in response to the average of the static pressure sensed at the orifices 58 and 59. A fluid such as oil under pressure is supplied to the inlet of the chamber 67 by way of a restriction or capillary passage 68. The outlet of the chamber is connected to the line 46 which leads to the pilot valve 43. To maintain the lines 61, 62 and line 56 free of water, there is provided an air pump 71. Pump 71 is connected to the bellows and to the actuator 53 through lines 72 and 73 respectively and creates a small flow of air out of the orifices 57-59. Alternatively, a different form of pump can be used and the lines kept full of sea water which is caused to flow into the orifices, but the former scheme is preferred in order to minimize the possibility of the orifices becoming fouled.

In operation, movement of the lever 33 as a result of a pressure change at one of the orifices, reacts upon the pilot valve 43 so that the latter is also caused to move. As a result, the control valve is returned to a neutral position which arrests the movement of the lever, causing the foils to take up a new angular position to compensate for the change in the level of flight of the craft which was responsible for the orifice pressure change in the first place. Should the depth of one or more of the foils increase because of a shift in the passenger load, for example, the average of the static pressures sensed by the orifices 58, 59 also increases. As a result, the bellows 63, 64 cooperate to produce an increased amount of force on the valve 66 so as to close it more, and thereby raise the pressure in the chamber 67 and the line 46 leading to the pilot valve. This causes the pilot valve piston to assume a more advanced position and enables the valve 37 to admit fluid under pressure to the upper end of the cylinder 36 by way of line 39. The piston and hence the lever 33 then move to increase the angle of attack of the corresponding foil, movement of which is arrested subsequent to the adjustment by the action of the follow up mechanism. It is important to note in this regard that when the craft is travelling at high speed, roller 52 will be in a more advanced position which amplifies the effect of the follow up linkage. As a result, the pilot valve and hence the control valve 37 respond to arrest the movement of the lever more quickly, before the lever has undergone as great an excursion as it would if the craft were travelling more slowly. This is as it should be since the greater is the speed of the craft, the smaller are the corrections in the angle of attack of the foils which are required to produce a given change in lift, the lift being proportional

to the square of the craft speed. The reason for employing two orifices 58 and 59 and two bellows is to neutralize the effect of waves and changes in the direction of the craft which increase the pressure in one of the lines 61 and 62 and decrease it in the other.

A more refined control mechanism for controlling the fluid pressure in the supply line 46 leading to the pilot valve 43 is illustrated in FIG. 6. With reference now to FIG. 6, it will be observed that the refinements comprise additional bellows 76 and 77 which are connected in series with the depth responsive bellows 63 and 64, so as to form a vertical stack. Bellows 76 is disposed above the depth sensing bellows so that its effect is additive. Its function is to provide an adjustable biasing force which reflects the desired level of flight of the craft. Thus, the inlet to the bellows 76 is connected to a source of pressure fluid by way of a line 78 which includes a needle valve 79. Downstream from the needle valve, there is connected a drain line 82 with a restriction in it. The rate of flow from the drain line is determined by the settling of the needle valve. This rate of flow, in turn, determines the pressure of the fluid which is supplied to the bellows 76. Therefore, the level of flight of the craft can be readily increased by opening the valve and decreased by closing the valve.

By virtue of its position in the stack below the valve 66, bellows 77 opposes the effects of bellows 63, 64 and 76. In other words, the effect of the bellows 77 is subtractive with respect thereto. To actuate the bellows 77, one end of a line 83 is connected thereto and the other end of the line is connected to a device which is responsive to vertical accelerations of the corresponding foil for the purpose of partially overcoming the depth controls under circumstances where constant depth would be undesirable, as where there is rapid wave action. This device is seen to comprise a vertical cylinder 84 partly filled with a fluid such as oil in which is suspended a slug or weight 86. The slug is supported by a spring 87 and is free to move vertically when the device experiences vertical acceleration. In consequence, the pressure of the fluid in the container is increased or decreased depending upon the direction of acceleration which the slug experiences. If the diametrical clearance between the slug and the inside cylinder wall is made relatively small, and the static length of the spring is long in comparison with the amount of deflection it undergoes when the slug experiences acceleration, then the static pressure of the fluid in the container will have superimposed thereon a term which is very nearly proportional to the acceleration of the foil.

As in FIG. 5, relief valve 66 controls the fluid pressure supplied to the pilot valve. In FIG. 6, however, a more elaborate form of pressure-multiplying device is employed in association with the valve. Communicating with the valve 66 by means of a line 88 is a chamber 89 within which there is mounted a bellows 91. Bellows 91 acts upon a valve 92 located at the inlet to the chamber which is supplied with high pressure fluid by a line 93 with a restriction in it. The line 46 to the pilot piston is connected to an outlet from the chamber and there is a small tube 94 which at one end projects into the outlet passage. The opposite end of the tube communicates with the interior of the bellows 91. When the flow to the pilot valve by way of the line 46 is cut off, the internal and external pressures on the bellows 91 are substantially equal. Under these conditions, the supply valve 92 is set to permit only a small flow of fluid into the chamber which then escapes by way of the main relief valve 66. However, when the flow of fluid to the pilot valve is appreciable, the pressure in the bellows 91 is decreased by reason of the negative pressure to which the tube 94 is subjected. The bellows then contracts, opening the supply valve more and insuring that the pilot piston's increased need for fluid is adequately met. Conversely, when, when flow occurs out of the pilot piston, as a result of the main relief valve assuming a more open position, then the pressure in the

chamber decreases, causing the valve 92 to assume a more nearly closed position. It follows that the advantage of the pressure multiplying device of FIG. 6 over that of FIG. 5 is that the former requires less oil to operate.

An example of the manner in which the inertial sensor and its associated bellows 77 controls the angle of attack of a foil will now be described. In this example, it will be assumed that the foil is caused to undergo a vertical component of acceleration in the upward direction which increases the fluid pressure in the sensor. As a result, the force on the main relief valve 66 decreases, permitting the valve to assume a more open position. This causes the chamber pressure to decrease and the pilot piston to assume a less advanced position. In response to this change in position of the pilot valve piston, the angle of attack of the foil is decreased, which reduces the amount of lift produced by the foil and arrests its upward acceleration. The net effect of this control is to increase the apparent inertia of the craft so that it responds to vertical forces as though it had a much greater mass than it actually has. This is especially important in a seaway where vertical excursions of the craft would otherwise become dangerously large. The effect can be made very powerful by provision of a bellows 77 having a relatively large effective area in relation to the area of the depth responsive bellows 63 and 64.

The foregoing operations may also be explained as follows: From the foregoing description it is apparent that the depth-sensing means involves a control loop, including the orifices 58, 59, the bellows 63, 64, the pilot valve 43, the actuator 36 and the foil shaft 26 by which the angle of attack is varied. In the absence of any other signals this loop operates to control the angle of attack in a manner to maintain the depth substantially constant.

A second control loop is constituted by the accelerometer 84, which is immediately responsive to vertical accelerations, the second loop acting through the bellows 77 in a direction to change the angle of attack in a sense to prevent the craft from undergoing the full vertical excursions called for by the depth control. Since the slug 86 is immediately responsive to accelerations, the response time of this second loop is shorter than that of the first loop, which responds only to changes in position of the entire craft relative to the actual surface of the water.

In FIG. 7 there is illustrated a complete hydraulic system including the refinements of FIG. 6 together with certain other refinements whereby control of the craft according to the invention is effected in a preferred manner. As shown in FIG. 7, three additional bellows 101, 102, and 115 are added to the stack of four bellows 63, 64, 76, 77 which were described in connection with FIG. 6. The sense of bellows 101 is seen to be the same as that of bellows 63, 64 and 76 while the senses of bellows 102 and 115 are opposite. In this embodiment, it is assumed that the stack of bellows illustrated is located at a central station amidships as are the three other stacks for control of the other three foils. A primary function of bellows 101 and 102 is to compensate for the effect of heel of the craft and acceleration in a horizontal plane as it affects the pressure of the fluid in the lines leading to the depth control bellows 63, 64 and the inertial control bellows 77. To this end, the bellows 101 is physically constructed in like manner as bellows 77 and is adapted to be connected by way of a valve 103 and a line 104 to a short vertical standpipe 106 wherein the vertical inertial effect of the fluid is small. The standpipe 106 is located directly above the foil with which the stack is associated, one of the bow foils it will be assumed, and the line 104 leads from the central station, where the valve is located, forward and athwartships to the standpipe. The function of the valve 103 is to interchange hydraulic input signals to the bellows 101 and 77, and to this end, the bellows 101 is alternatively adapted to be connected by the valve 103 to a line 107 leading to an inertial sensing device such as that described in connection with FIG. 6. In fact,

in this preferred embodiment, there are provided several inertial control sensors of differing sensitivities (designated I.C. #1, I.C. #2 and I.C. #3) which are adapted to be selectively connected to the line 107 by a selector 108.

The bellows 102, which is adapted to compensate for the effect of horizontal acceleration and heel of the craft upon the depth signals applied to the bellows 63 and 64, is connected by means of a line 109 to another standpipe 111. Standpipe 111 is located forward and athwartships of the central station at the same location as the standpipe 106. A third standpipe 112 is located directly athwartships of the control station, on the same side of the craft as the foil with which it is associated, and is connected to a bellows 115 at the central station through a line 113 and a valve 114 in the line. As will be described in detail, bellows 115 functions during a turn to produce banking or heeling of the craft in response to the pressure of the fluid in the line 113.

Finally, there is provided in the embodiment of FIG. 7, a bow tilt control which is particularly useful on take-off and landing. For purposes of level control alone, the pressure in the bellows 76 of each stack is adapted to be controlled by a single needle valve. Thus, it will be observed from FIG. 7 that the needle valve 116 is located in the main input line from the source of high pressure fluid. A chamber 117 with a restricted inlet 125 and a restricted opening 120 to exhaust is provided on the downstream side of the valve 116. The lines leading to the bellows 76 for control of the level of the stern foils are connected directly to chamber 117. However, the lines leading to the bellows 76 for control of the level of the bow foils, such as the line 78, are connected to one outlet from a chamber 121 which has its inlet connected to the downstream side of the valve 116 through a restriction 120'. Another outlet from the chamber 121 leads to exhaust by way of a restricted passage 122. A bypass line around restriction 120' leading from the pressure fluid source to the inlet of chamber 121, and a needle valve 124, to control the flow rate in the bypass line complete the arrangement for bow tilt control. As in FIG. 6, the stack of bellows operates upon relief valve 66 which, through the medium of a pressure multiplier, such as that described in FIG. 6, determines the amount of pressure supplied to the pilot piston.

In operation, it is desirable to produce a positive tilt, that is to raise the bow slightly with respect to the stern, both on take-off and setdown. Also, it is desirable to reduce the drag of the foils as much as possible while the craft is being brought up to take-off speed. To accomplish these ends, the valves 116 and 124 are both set to zero or to a low pressure setting such that the angle of attack of the foils is very small. As the craft approaches take-off speed, the valve 116 is adjusted to provide an increased amount of pressure to each bellows 76, thereby substantially increasing the angle of attack of each foil. By way of example, the lift coefficient established at this time may be in order of eight to ten times that which is established once the craft is in flight at cruising speed. Preferably, the foils are not set to produce maximum lift at this time, however, in order that control adjustments of both a positive and a negative sense can be initiated, if need be, even during take-off.

When the craft first begins to rise, valve 124 is opened, thereby increasing the pressure supplied to the bow bellows 76 and raising the bow slightly with respect to the stern. As the hull rises more and more out of the water, the drag of the hull decreases and the craft rapidly picks up speed. The foil angles will then begin to decrease automatically as required to terminate the upward movement of the hull at the desired level. The valve 124 can then be closed again to eliminate the upward tilt of the bow, and the valve 116 can be trimmed to establish precisely the desired level of flight for cruising speed. A similar procedure can be followed during setdown at which time

it is likewise desirable to introduce a small upward tilt of the bow. In this way, the hull is adapted to settle more smoothly in the water.

With the craft operating at cruising speed and the valves 103, 114 in the positions shown, let it be assumed now that a turn is initiated. During the turn, the liquid in the lines 104 and 109 is subject to the acceleration of the craft in a horizontal plane which causes a change of pressure within the bellows 101 and 63, 64. However, the liquid in the lines leading to bellows 77 and 102, respectively, are subject to the same acceleration and therefore, pressure changes occur in these bellows as well. The resulting changes in the forces produced by bellows 101 and 77 will be equal and opposite if the line 104 is filled with liquid of a like nature as the oil or other liquid in line 107. By the same token, the forces produced by bellows 63, 64 on the one hand, and bellows 102 on the other, can be made equal and opposite by the use of a more powerful bellows 102 or a heavier fluid such as water in the line 109 leading to bellows 102. This will compensate for the fact that the line 109 is shorter than the lines leading to the bellows 63, 64 and also the fact that the forces produced by bellows 63, 64 acting in series are additive. Under these conditions there will be no net force acting on the relief valve 66 due to horizontal accelerations as in a turn.

In the foregoing description, the valve 103 was set to connect the inertial sensor to the bellows 77 while the compensating line 104 was connected to the bellows 101. At times, it is desirable to reverse the roles played by the bellows 101 and 77 which has the effect of simulating inertia, but in a negative sense. The reason this mode of control may be desirable has to do with the effect of waves whose crest to trough height is greater than the vertical distance between the foils and the bottom of the hull. In a sea of this kind, the waves are quite long, typically 20 to 30 times greater than their height in deep water. In order for the craft to be able to negotiate this kind of a sea, it must "ride" it, that is rise and fall with the waves themselves. This can be accomplished more readily if the effect of the inertial control is diminished, or in very long seas, reversed altogether by a change in the setting of the valve 103. This connects the inertial sensor to the bellows 101, and the standpipe 106 to the bellows 77. As a result, the normal tendency of the craft to rise and fall with the waves is enhanced and it is made to perform as though it had less mass than it actually has, thereby insuring that the foils remain submerged at all times.

As described thus far, the craft is adapted to make turns on a level keel which is desirable for rough seas in order to avoid exposure of the foils. However, for sharp turns in relatively smooth seas, it is advantageous to cause the craft to bank. Not only are banking turns more comfortable to negotiate, but excessive side thrust on the struts is eliminated. To enable the craft to bank, valve 114 is set to connect the bellows 115 to the standpipe 112. It will be recalled that standpipe 112 is located athwartships of the central control but is not displaced longitudinally with respect thereto. Accordingly, during a turn, pressure is created in the bellows 115 due to the effect of centrifugal force upon the fluid in the line 113. For example, if the turn is to port, a positive pressure is created in the bellows 115 associated with the port foils causing the angle of attack of the port foils to decrease. Conversely, a negative pressure is created in the bellows 115 associated with the starboard foils which causes the angle of attack of these foils to increase. The net result, therefore, is that the craft starts to bank. The greater the amount of bank, however, the greater will be the effect of gravity upon the fluid in the lines 113, the resultant of the force of gravity and centrifugal force being determinative of the net pressure created in the bellows 115. Since there would be no net pressure with the standpipe 112 perpendicular to the direction of this

resultant force, it follows that the angle of the bank approaches this condition but never reaches it.

At the same time as the bellows 115 is causing the craft to bank the depth control bellows is tending to cause the craft to fly on a level with the standpipe 112 oriented vertically. Therefore, the relative sensitivities of the depth and banking controls will be determinative of how steep the angle of the bank is, the more powerful being the heel control, the more closely will the angle of the bank approach the optimum. The effect of bellows 115 can be made more powerful if its area is relatively large in comparison to the other bellows or alternatively a high density liquid such as mercury can be used in the lines 113.

It should be noted that the bellows 115 also acts to correct for heeling of the craft. For example, should the craft heel to starboard due to a shift in weight, a positive pressure will be produced in the bellows 115 for the port foils, tending to decrease their angle of attack. Also a negative pressure will be created in the bellows 115 associated with the starboard foils, tending to increase their angle of attack. The net effect is to increase the tendency of the craft to fly on a level in aid of the operation of the depth control bellows.

It can be shown that the net force on the main relief valve due to a change in pressure in any one of the bellows in the stack is equivalent to

$$A\Delta p \frac{S_1}{S_1 + S_2 + \dots + S_6}$$

where A is the area of the bellows, Δp is the change in pressure therein, and S_1 through S_6 represent the spring constants of the respective bellows. This assumes that whenever the pressure in one of the bellows changes, the resulting expansion or contraction thereof does not change the pressure in the other bellows appreciably, even though it acts to alter their volume.

Although the invention has been described in terms of moving the entire foils to make changes in the attack angle of the foils to change their lift coefficients, flaps can also be provided for this purpose. These can be built into the foils in like manner as the steering flaps are employed on the struts. One form of foil with flap controls for changing the lift is shown in FIG. 8. The foil 130 is provided with a tail flap 132 hinged to the main body of the foil by a suitable connection, as in the form of a thin metal sheet 134. A cover piece 136 attached to the flap is adapted to ride over the rear surface of the body 130 as the flap 132 pivots about its hinge. A bag 138 of flexible material of general horseshoe cross-section is received in a similarly shaped recess at the rear of the body 130. A metal bar 140 is received within the re-entrant portion of the bag and at its rear edge is received in a slot 141 in the flap. The bag 138 is anchored or otherwise secured to the body 130 throughout its outer surface. A pressure line 142 connects to the interior of the bag. This pressure connection can come from the line 46 shown in FIG. 5 so that the pressure in this line is used to expand the bag 138 enough to tilt the flap into a position for increased lift. The water pressure on the flap tends to move it toward the position of low lift and hence it is necessary only to provide for motion of the flap 132 downwardly under the pressure in the bag. The mechanism consisting of the pilot valve 43, the actuator 36, the arm 33 and associated parts shown in FIG. 5 may be omitted, in which case the flaps 132 will be relied on solely for lift control.

It is desirable also to provide for motion of the whole foils; thus limit switches may be provided to signal when the flaps have reached predetermined limits of angular movement. Thus as shown in FIG. 8a, a limit switch 143 operates when a sufficient quantity of fluid has passed through the line 142 to indicate that the flap 132 is near its maximum lift position. A normally closed valve 143 is in the line 46 leading from the chamber 67 to the pilot

valve 43, which controls the operation of the foil lift lever 33. When the valve 143' opens, the lever 33 then moves the entire foil. Upon reverse flow of fluid in the line 142, the limit switch may operate to allow the valve to remain open in a manner to restore the foil to its low-lift position. Under these circumstances the flaps are especially useful to compensate for the effect of small waves which necessitate a fast acting mode of control of lift coefficient in the nature of a vernier.

It will be understood, therefore, that the term foils as used in the claims hereinafter is intended to embrace such equivalent devices for influencing lift coefficient as foil sections or flaps.

While the combination of movable foils and movable flaps on the foils, as described above, may be desirable in larger hydrofoil craft, this arrangement is believed to be necessary in smaller craft. A relatively small craft will have a rate of change of attitude in response to change in conditions such as wave form and height, etc. which is substantially greater than that of the larger craft. Thus where the control system of this invention is employed in association with such smaller craft, it is necessary to provide variations in lift coefficient at a rate much greater than is necessary with larger craft. Accordingly, with the smaller hydrofoil craft the control of lift coefficient of the foils should preferably be accomplished through the utilization of adjustable flaps on the foils with the flaps being controlled, for example, as shown in FIG. 8. While the speed of flap movement can be made to be sufficiently large to obtain the desired degree of control in smaller craft, the extent of change in lift coefficient of the foils, by means of the flaps, is limited and may not be sufficient to compensate for all conditions. Accordingly, suitable means for moving the entire foil structure may still be necessary. However, the foil movement will be necessary only when a large change in lift coefficient is required. As appears from FIG. 8a, the same central control system could be employed for both the foils and the flaps. The movement of the entire foil structure would thus provide a rough control of the attitude of the craft while a fine control of faster response would be provided by the flaps.

In the parts thus far described, the operating controls which are dependent on the effects of several signals obtained by the use of series-connected bellows, it has been found in some cases that a parallel pressure cell construction is preferred. In FIG. 9 there is shown a bar 144 pivoted at 146 and substantially balanced to avoid effects of gravity. Pressure cells 148 connected to various signal sources act on the bar through rods 150. The preferred cell construction is shown at FIG. 10. It comprises a body 152 carrying a membrane 154, preferably a thin sheet of neoprene impregnated nylon fabric clamped at the edges of the body 152. The rod 150 is hinged to a plate on the membrane. The rod 150 is also hinged to the bar 144, preferably by means of a short section of flexible plastic tubing.

Leading into each cell is a pressure line 156 corresponding to the lines 61, 62 of FIG. 5, 109, 113 and 104 of FIG. 7, etc. The cells are spaced along the bar to produce clockwise or counterclockwise motion, that is, for either addition or subtraction of signals depending on the desired composition of signals under the same circumstances as in the series connected bellows of the previous figures.

A spring 158 is provided to urge the bar 144 in one direction. An adjusting nut 160 may be used to adjust the spring factor.

Near one end of the bar is an air gage indicated generally at 162 fed from a constant pressure source 164 through a suitable restriction as is well known in the construction of air gages. The orifice at the end of the gage 162 directs the flow of air against a plate 166. The pressure within the valve 162 varies in accordance with the distance of the plate 166 from the stationary valve

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member, and changes of this pressure are utilized through a multiplier to control the foil 12 in FIG. 5 or the flaps 132 of the type shown in FIG. 8. The plate 166 is required to move only a few thousandths of an inch and the inertia of the bar is negligible; hence the forces applied by the cells are small.

A preferred form of multiplier is shown in FIG. 11, to be used in place of the devices shown at 67 and 91. The multiplier comprises a body 170 enclosing a chamber within which is a control valve having a seat 172 and a movable valve member 174. The member 174 is mounted on a stem 176 connected to two diaphragms 178 and 180, the stem being urged by a spring 181 to a position to close the valve 174 on its seat 172. The edges of the diaphragms 178 and 180 are suitably clamped to enclose an inlet chamber 182 between them. The signal, as from the tube 88 in FIG. 6, leads into an input fitting 184 and thence into the chamber 182.

Also enclosed within the body 170 is a movable valve member 186 adapted to close against a valve seat 188 through the medium of a flexible diaphragm 190, the valve member 186 being urged toward its seat by a spring 192. The chamber 194 in back of the diaphragm is connected by a passage 196 with the inlet chamber 182 which lies between the previously described diaphragms 178 and 180.

A source of constant pressure is supplied to an inlet fitting 198, which connects to the passage 200 within the valve seat 172. When the valve 174 is open this pressure is communicated to an outlet chamber 202 leading to an output line 204. This line 204 is the line leading to the operating elements typified by the tube 46 in FIGS. 5 and 6.

The chamber 206 in back of the diaphragm 180 is connected with the outlet chamber 202 through a passage 208. The chamber 209 interior of the valve seat 188 is connected by a passage 210 with the outlet chamber. Thus the chambers 202, 206 and 209 are subjected to outlet pressure while the signal input pressure appears in chambers 182 and 194.

The operation of the device is such as to repeat the signal pressure so that the constant pressure source 198 can supply fluid to the operating mechanisms. The signal pressure is unable to sustain a sufficiently large flow for the operating mechanisms but the necessary flow can be sustained from the source 198. Thus the device operates as a current amplifier.

The operation of the multiplier is as follows: Assume first that there is zero pressure on the inlet 88 and also on the outlet 204. Under these conditions the spring 181 holds the valve 174 closed. There is no pressure tending to open valve 186. If now the pressure in the signal line 88 increases, a signal is sent to the multiplier to cause the pressure in chamber 182 to increase. There is no substantial flow since chambers 182 and 194 are closed. The area of diaphragm 180, as shown in FIG. 11, is greater than that of diaphragm 178. This tends to cause valve 174 to open and there is a fluid flow from the source 198 into the outlet chamber 202. When the pressure in the outlet chamber 202 builds up to equal that on the inlet, the pressures on both sides of diaphragms 178 and 180 are equal, and the spring 181 then closes valve 174. Thus as the inlet pressure rises the outlet pressure will rise to equal it, and this will occur with very little time lag. Under these circumstances, since the outlet and inlet pressures rise practically simultaneously valve 186 will not open.

If there is a fall in signal pressure, the valve 186 operates in the following manner: The valve 174 is held even more tightly closed than under the static pressure condition. However, the balance on diaphragm 190 is disturbed in the direction to cause valve 186 to open, since the reduced signal pressure is communicated through the port 196 to the chamber 194. The chamber 211, which is separated from chamber 209 by the valve 186, is

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vented to atmosphere through the port 212. Since chambers 202 and 209 are connected together the outlet pressure will drop until it again nearly equals the inlet pressure.

Therefore, in case of either a rise or fall of pressure, there will be a substantial flow of fluid in one direction or the other through output line 204 until the signal pressure and the output pressure are equalized. The flow that takes place during the equalization process is utilized to operate the mechanisms controlling the lift of the foils.

An alternative form of inertial sensor that can be employed is a standpipe filled with liquid and open at the top in like manner as standpipes 106, 111 and 112 but of greater length. It is also contemplated that gages can and preferably should be provided to reflect the pressures in the various bellows from which an indication of the attitude of the craft can be readily obtained. Certain of these gages can be common to the control systems for all of the foils.

In the operating system shown in FIG. 5, the operating devices for the foil 12 are controlled by sensors associated only with the foil itself. The refinements shown in FIG. 7 contemplate that a foil will respond to the effect of signals originating at different points in the craft. A further improvement is shown in FIG. 12, wherein each foil is actuated not only in accordance with signals originating in its own sensors but also in accordance with a signal dependent on an averaging of the depth signals derived from all of the struts. The purpose of this is to stabilize the craft in a seaway; for example, in a quartering sea, if one foil suddenly finds itself over a trough, that foil does not react to drop that corner of the craft.

In the preferred embodiment, the pressure lines 61 and 62 of the foil 12 are connected by lines 261 and 262 with a pressure averaging chamber 264, into which run lines 61' and 62' from the depth sensors of one or more of the other foils. A pressure line 266 runs to bellows 268 which is stacked with the bellows 63 and 64 of FIG. 5. Thus the control signals for the foil 12 comprise local signals from depth sensors 58, 59 together with a signal through line 266 corresponding to the average of signals from two or more foils. The relative effects of these signals may be adjusted by suitable orifices in the several lines. Thus with small orifices in the lines leading to the bellows 63 and 64 the averaged signal will predominate over the local signals; in fact, the bellows 63 and 64 may be omitted altogether, in which case each foil will respond only to the average of the depth controls; or the orifices may be made adjustable so that the composition of local and averaged signals may be varied by the operator in accordance with the sea conditions. In any event, the depth signals may be combined with the other signals introduced by the devices shown in FIGS. 6 and 7 for controlling operation of the craft under the conditions described in connection therewith.

It will be understood that the composition of signals from several points may be accomplished by use of parallel pressure cells of the general structure of FIG. 9 as well as by the series bellows arrangement shown diagrammatically in FIG. 12.

The use of fluid controls constitutes one of the important features of the present invention, since such controls afford a simple and reliable means of adding signals algebraically, and also amplifying or multiplying the flows whereby the operation of the control surfaces may be effected with adequate power and yet with speed and accuracy.

It should be understood that in the foregoing description and appended claims the term bellows is intended to include other structures such as diaphragms and piston-cylinder arrangements whereby an expansible chamber is provided. Accordingly, the terms bellows and expansible chamber may be used interchangeably. Various such details of construction and modifications of the preferred

embodiment that are within the spirit and scope of the invention will no doubt occur to those skilled in the art. Therefore, the invention should not be deemed to be limited to the details of what has been described herein by way of illustration, but rather it should be deemed to be limited only to the scope of the appended claims.

This application is a continuation-in-part of my co-pending application Serial No. 111,575, filed May 22, 1961.

What is claimed is:

1. In a submerged hydrofoil craft, the combination including completely submerged depth sensing means and means to sense vertical accelerations of at least one foil, means to supply fluid under pressures determined by depth and by vertical accelerations of said one foil, control mechanisms to vary the lift coefficients of said one foil, means to actuate said mechanisms in response to fluid pressure variations resulting from depth variations and vertical accelerations of said one foil, and means to cause outward fluid flow through the depth sensing means to prevent fouling thereof.

2. In a hydrofoil craft, the combination including means to sense vertical acceleration of at least one foil, means to supply fluid under a pressure determined by vertical acceleration of said one foil, an expandable chamber responsive to the pressure of the fluid, drive means operatively connected to said one foil, a control valve to control the operation of said drive means, a source of pressure fluid, a pressure multiplier including a relief valve to vary the pressure of the fluid from said source, said chamber being operatively connected to said relief valve, and a pilot piston responsive to the variable pressure fluid from said pressure multiplier, said piston being operatively connected to said control valve to change the setting thereof and thereby cause said drive means to change the lift coefficient of said one foil when the foil undergoes vertical acceleration.

3. In a hydrofoil craft, apparatus for controlling the lift coefficient of at least one foil, said apparatus including means to mount said one foil for pivotal movement about a generally horizontally disposed axis, depth sensing means to sense the depth of said one foil and to supply fluid under a pressure determined by the depth of said one foil, a first bellows responsive to the pressure of the fluid representing the depth of said one foil, inertial sensing means to sense vertical acceleration of said one foil and to supply fluid under a pressure determined by the magnitude and sense of such acceleration, a second bellows responsive to the pressure of the fluid representing the vertical acceleration of said one foil, means to mount said bellows in series relation, drive means operatively connected to said one foil, and means responsive to the net force produced by said bellows to control the operation of said drive means.

4. Apparatus according to claim 3 wherein said inertial sensing means includes a pressure transducer to supply fluid under pressure as a function of vertical acceleration of said one foil, said pressure transducer being located at a distance horizontally from said second bellows, and an interconnecting line between said transducer and said second bellows to transmit said pressure fluid.

5. Apparatus according to claim 4 including a third bellows disposed in series relation to said second bellows, a source of static pressure, and an interconnecting line between said static pressure source and said third bellows, said line extending in a horizontal direction with respect to said third bellows so that when the craft undergoes horizontal acceleration the pressure in said third bellows is caused to change thereby to compensate for the effect of the horizontal acceleration upon the line interconnecting said transducer and said second bellows.

6. Apparatus according to claim 5 including valve means selectively to interchange the lines leading to said second and third bellows.

7. In a hydrofoil craft having a pair of bow foils and

a pair of stern foils, apparatus for controlling the lift of coefficient of each foil, said apparatus including means to mount the foil for pivotal movement about a generally horizontally disposed axis, depth sensing means to sense the depth of the foil and to supply fluid under a pressure determined by the depth of the foil, a first bellows responsive to the pressure of the fluid representing the depth of the foil, a second bellows, manual means to adjust the pressure in said second bellows, means to mount said bellows in series relation, drive means operatively connected to the foil, and means responsive to the net force produced by said bellows to control the operation of said drive means.

8. In a hydrofoil craft apparatus for controlling the lift coefficient of each foil, said apparatus including means to mount the foil for pivotal movement about a generally horizontally disposed axis, depth sensing means to sense the depth of the foil and to supply fluid under pressure determined by the depth of the foil, a first bellows responsive to the pressure of the fluid representing the depth of the foil, inertial sensing means to sense vertical acceleration of the foil and to supply fluid under a pressure determined by the magnitude and sense of such acceleration, a second bellows responsive to the pressure of the fluid representing the vertical acceleration of the foil, a third bellows, manual means to apply a selected pressure to said third bellows, means to mount said bellows in a stack with said first and third bellows opposing said second bellows, a fluid actuator operatively connected to the foil, and means responsive to the net force produced by said bellows to control the operation of said actuator, said control means including a follow up linkage, means to produce signals representative of the speed of the craft, and means to modify said follow up linkage in response to said speed signals thereby to modify the response of said actuator to changes in the net force produced by said bellows.

9. In a hydrofoil craft apparatus for controlling the lift coefficient of each foil, said apparatus including means to mount the foil for pivotal movement about a generally horizontally disposed axis, depth sensing means to sense the depth of the foil and to supply fluid under a pressure determined by the depth of the foil, a first bellows responsive to the pressure of the fluid representing the depth of the foil, inertial sensing means to sense vertical acceleration of the foil and to supply fluid under a pressure determined by the magnitude and sense of such acceleration, a second bellows responsive to the pressure of the fluid representing the vertical acceleration of the foil, said depth and inertial sensing means being located at a distance horizontally of said first and second bellows, a third bellows, manual means to apply a selected pressure to said third bellows, fourth and fifth bellows, means to pressurize said fourth and fifth bellows in response to acceleration of the craft in a horizontal plane, means to mount said bellows in a stack with said first and third bellows opposing said second bellows, said fourth and fifth bellows opposing said first and second bellows, respectively, to compensate for the effect of horizontal acceleration of the craft on the pressures in said first and second bellows, a fluid actuator operatively connected to the foil, and means responsive to the net force produced by said bellows to control the operation of said actuator, said control means including a follow up linkage, means to produce signals representative of the speed of the craft, and means to modify said follow up linkage in response to said speed signals thereby to modify the response of said actuator to changes in the net force produced by said bellows.

10. In a hydrofoil craft having a plurality of submerged foils with means for varying the lift coefficients thereof, completely submerged depth-sensing means, fluid pressure means for generating a signal from said depth-sensing means, fluid pressure means to generate signals from vertical accelerations of the craft, means connected

with said foils for applying fluid pressure to effect variations in the lift coefficients thereof, means for causing outward flow of fluid through the depth sensing means to prevent fouling thereof, and means for combining said signals to produce fluid pressures for the several foils in accordance with the aggregate of said signals for the several foils.

11. In a hydrofoil craft as defined in claim 10, the provision of bellows arranged in series and independently connected to said fluid pressure means to combine said signals for each foil to vary the lift coefficient thereof.

12. In a submerged hydrofoil craft having a plurality of foils, at least one foil having a movable part to vary the lift coefficient thereof, completely submerged depth sensing means, linear inertial sensing means to detect vertical accelerations of said foil, a first fluid pressure means controlled by the depth sensing means, means for causing outward flow of fluid through the depth sensing means to prevent fouling thereof, a second fluid pressure means controlled by the inertial sensing means, and devices controlled by changes in said fluid pressures to operate said movable part to vary the lift coefficient.

13. In a submerged hydrofoil craft having a plurality of foils, at least one foil having a movable part to vary the lift coefficient thereof, depth sensing means, linear inertial sensing means to detect vertical accelerations of said foil, a first fluid pressure means controlled by the depth sensing means, a second fluid pressure means controlled by the inertial sensing means, individual expandable chambers operated by changes in said fluid pressures, and means jointly controlled by said chambers to operate said movable part to vary the lift coefficient.

14. In a submerged hydrofoil craft having a plurality of foils, at least one foil having a movable part to vary the lift coefficient thereof, completely submerged depth sensing means, linear inertial sensing means to detect vertical accelerations of said foil, means jointly controlled by said depth sensing means and said inertial sensing means to operate said movable part to vary the lift coefficient, means for causing outward flow of fluid through the depth sensing means to prevent fouling thereof, and means controlled by the speed of the craft for diminishing the motion of the movable part under the influence of the depth sensing and inertial sensing means as the speed increases.

15. In a submerged hydrofoil craft having port and starboard foils, each having a movable part to vary the lift coefficient thereof, completely submerged depth sensing means for the foils, linear inertial sensing means to detect vertical accelerations of the foils, fluid pressure means jointly controlled by the depth sensing means and the inertial sensing means to operate the movable parts of said foils, means for causing outward flow of fluid through the depth sensing means to prevent fouling thereof, and compensating means acting on said fluid pressure means to compensate for changes in the lift coefficients of the port and starboard foils due to horizontal accelerations occurring in a turn.

16. In a submerged hydrofoil craft having a plurality of foils, at least one foil having a movable part to vary the lift coefficient thereof, completely submerged depth sensing means, a slug to detect vertical accelerations of the craft, means controlled by said depth sensing means to control said movable part in a manner tending to maintain the depth constant, and means controlled by vertical motions of the slug relative to the craft to operate said movable part to vary the lift coefficient in a manner to resist vertical movement of the craft, the provision of individual fluid pressure means controlled by said depth sensing means and by said slug, means for causing outward flow of fluid through the depth sensing means to prevent fouling thereof, and expandable chambers to operate the movable part of said foil under changes in the pressures in said chambers.

17. In a submerged hydrofoil craft having a plurality of foils, at least one foil having a movable part to vary the lift coefficient thereof, completely submerged depth sensing means, connections from the depth sensing means to said movable part to vary the lift coefficient in a manner tending to maintain a constant depth of the foils below the surface, linear inertial sensing means to detect vertical accelerations of the craft in response to wave motion, means for causing outward flow of fluid through the depth sensing means to prevent fouling thereof, and means controlled by the inertial sensing means to operate on said movable part in a direction to reduce vertical accelerations.

18. In a submerged hydrofoil craft having a plurality of foils, at least one foil having a movable part to vary the lift coefficient thereof, completely submerged depth sensing means, a first signal loop from the depth sensing means to said movable part to operate the latter in a manner, in the absence of other signals, to maintain a constant depth below the surface, means for causing outward flow of fluid through the depth sensing means to prevent fouling thereof, an accelerometer to detect vertical accelerations of the craft and a second signal loop including the accelerometer and said movable part to operate the latter in a manner to reduce vertical accelerations.

19. A submerged hydrofoil craft as defined in claim 18, in which the second signal loop has a shorter response time than the first loop.

20. In a submerged hydrofoil craft, a completely submerged foil having a body and a movable flap, completely submerged depth sensing means for the foil, means for mounting the foil for movement of the foil as a whole to vary its angle of attack, additional means for operating the flap to vary its lift coefficient and limit-control means actuated upon motion of the flap near the limit of its movement to cause motion of the foil as a whole.

21. In a submerged hydrofoil craft having a plurality of foils, means for controlling the lift coefficient of at least one foil, depth sensing means to sense the depth of said one foil and to supply fluid under a pressure determined by the depth of said one foil, a first pressure sensing means responsive to the pressure of the fluid representing the depth of said one foil, second sensing means for supplying fluid under a pressure representing another characteristic of the motion of the craft, a parallel connection for combining the effects of the sensing means, and means for operating the means for controlling the lift coefficient in accordance with the operation of said parallel connection, each sensing means being a pressure cell, and there being provided a pivoted bar to which the several pressure cells are connected in parallel for combining the effects of the cells.

22. In a submerged hydrofoil craft as defined in claim 21, the combination of an air gage to sense movements of the bar, a multiplier, and connections from the air gage through the multiplier to vary the lift coefficient.

23. In a submerged hydrofoil craft having a plurality of foils, at least one foil having means for varying its lift coefficient, means for sensing depth of said one foil, means to supply fluid under a signal pressure determined by said depth, a multiplier having an inlet chamber in which the signal pressure is applied, a source of pressure and an outlet chamber, a valve between the source and the outlet chamber, pressure responsive means operable upon a difference of pressure between the inlet chamber and the outlet chamber to control operation of the valve, and means operated by flow through said valve to operate said means for controlling the lift coefficient.

24. In a submerged hydrofoil craft having a plurality of foils, at least one foil having means for varying its lift coefficient, means for sensing depth of said one foil, means to supply fluid under a signal pressure determined by said depth, a multiplier having two independent inlet chambers in which the signal pressure is applied, a source

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of pressure and an outlet chamber, a first valve between the source and the outlet chamber, means controlled by an excess of pressure in one inlet chamber over that in the outlet chamber to open said first valve to cause a flow of fluid to effect equalization of said inlet and outlet pressures, a vent, a second valve between the outlet chamber and the vent, means controlled by excess of pressure in the outlet chamber over that in the other inlet chamber to operate said second valve to cause a flow from the outlet chamber through the vent, and means operated by flow of fluid through the outlet chamber to control the means for varying the lift coefficient.

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