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SUBMARINE HOVERING SYSTEM

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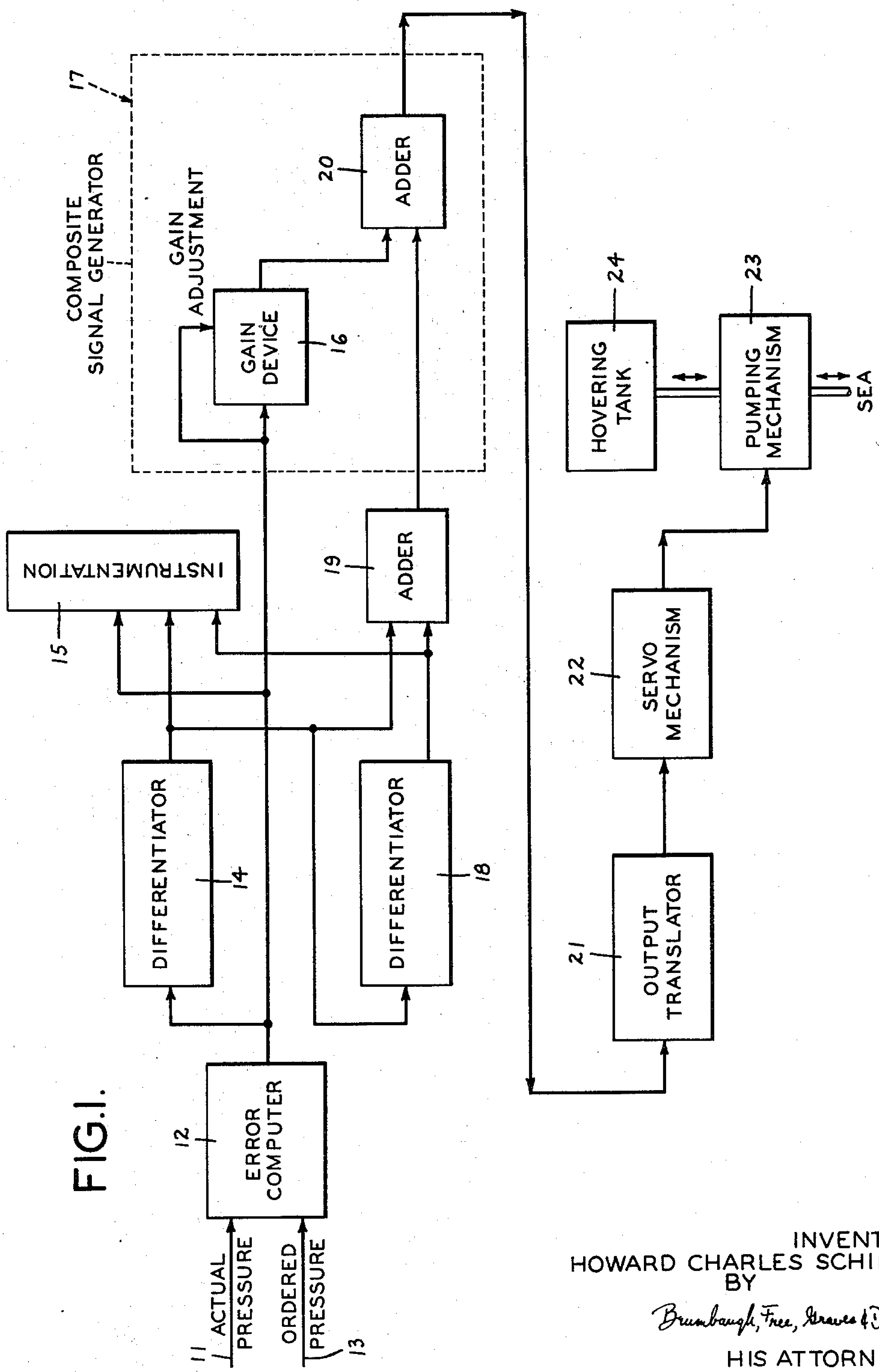

FIG. 1.

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FIG. 2A.

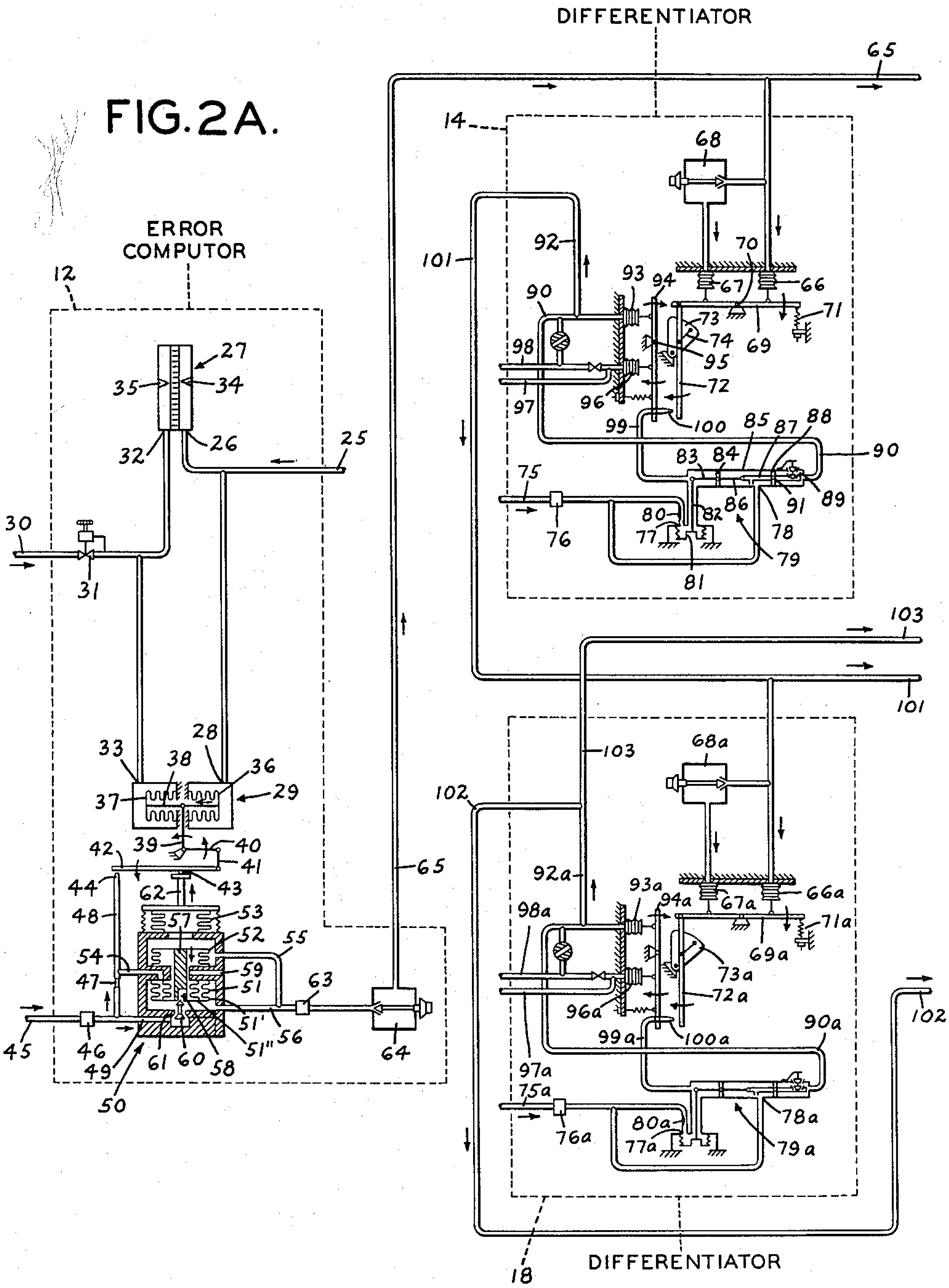

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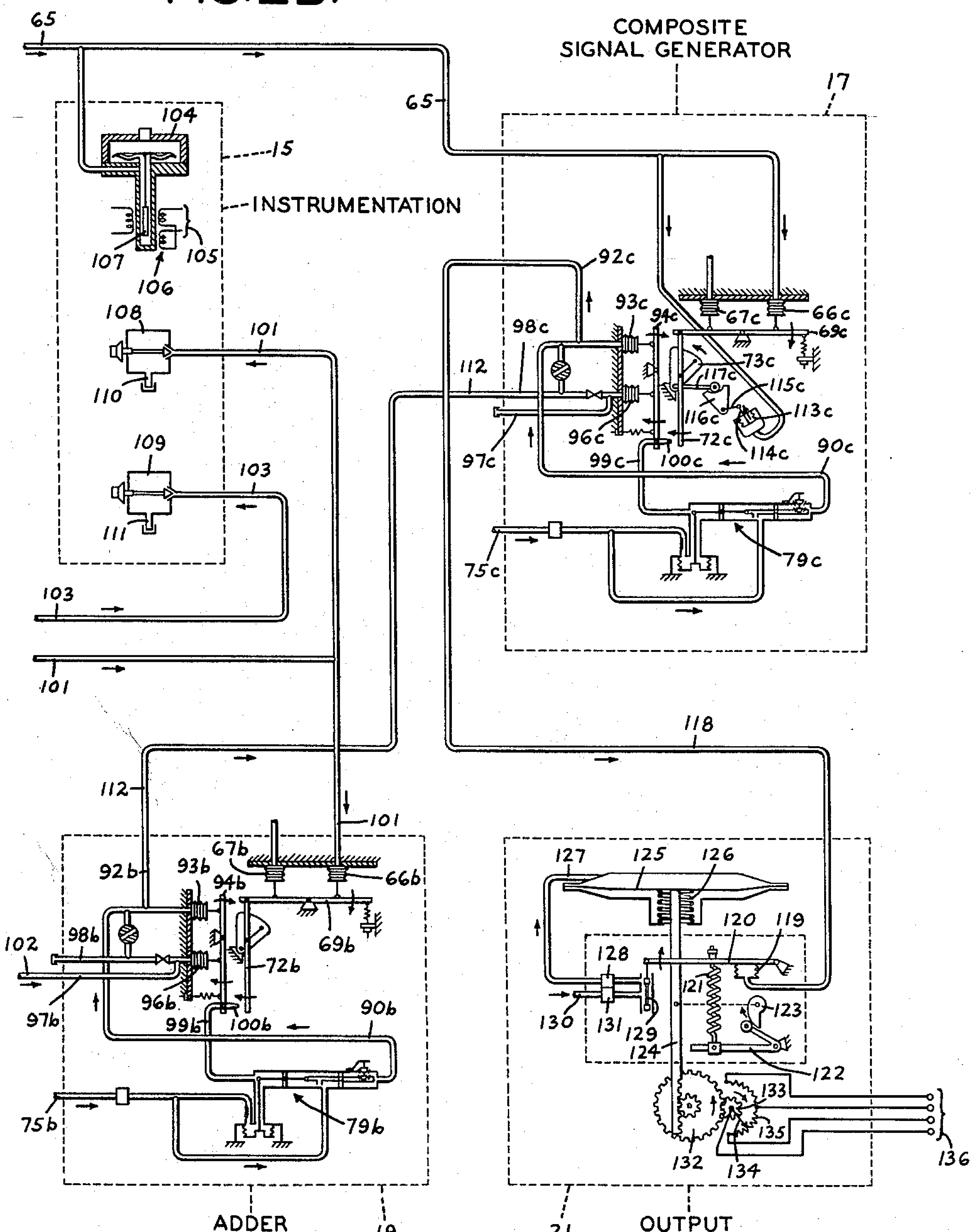
FIG. 2B.



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SUBMARINE HOVERING SYSTEM

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5 Claims. (Cl. 114—25)

This invention relates to a submarine hovering system and, more particularly, to a system that automatically positions a submarine accurately at a predetermined depth.

A submarine is oftentimes required to assume a given depth in the ocean which theoretically requires a condition of neutral buoyancy. For a number of reasons, including the temperature gradient of the water, the salinity of the water, underwater currents, and the like, it is impossible to maintain a true condition of neutral buoyancy. Therefore, the state of neutral buoyancy is approached by alternately flooding and exhausting water tanks in the boat.

During flooding and pumping operations, the boat momentarily achieves a state of neutral buoyancy, and then, depending on whether it is receiving or exhausting water, becomes either heavier or lighter than the volume of water it displaces. When the submarine takes on sufficient water so that its density exceeds that of the volume of water it displaces, the boat sinks. Due to increasing water pressure as it sinks, the submarine's hull contracts, thereby further increasing its density and downward velocity. The converse is true when the boat becomes positively buoyant; i.e., its upward velocity increases as the depth decreases.

Prior systems employed to position submarines at predetermined depths have generally taken into account one or more factors that include the water pressure at the level actually assumed by the boat, the water pressure at the desired depth, and the rate of change in depth of the submarine. These factors were then combined in various fashions to provide a single or a number of control signals to change the buoyancy of the submarine. However, none of the prior art systems has been successful in varying the buoyancy of a submarine to position it rapidly and accurately at a desired depth without substantial undesirable hunting.

In the present invention an error signal, indicative of the difference between a depth actually assumed by a submarine and a desired depth, and its first and second time derivatives are combined after being suitably weighted in accordance with the magnitude of the error signal to result in the production of a single control signal that is used to reposition the submarine. In this fashion, a given difference between a depth assumed and a depth desired results in a more than proportionately larger control signal than that produced by a smaller difference, and the depth correction of the submarine is made much more rapid as the "error" increases. This ensures that large errors are rapidly reduced, thereby increasing the effectiveness of the automatic control system.

Although the invention has been described generally above, a better understanding of it may be obtained by consulting the following detailed description of an exemplary embodiment thereof, when taken in conjunction with the appended drawings in which:

FIGURE 1 is a block diagram of an exemplary control system embodying the principles of the present invention for use in submarines; and

FIGURES 2A and 2B are detailed diagrams of selected ones of the blocks of FIGURE 1.

Referring to FIGURE 1, an exemplary automatic control system for the hovering of a submarine at a predetermined depth within the sea is shown. A signal indicative of the actual pressure exerted by the sea water at the depth actually assumed by the submarine is applied via an input line 11 to an error computer 12. A signal indicative of the pressure exerted by the sea water at the depth at which it is desired to position the submarine is applied to the error computer via an input line 13. The error computer generates an output signal equal to the difference between the two applied signals, i.e., the output signal is representative of the difference between the actual and ordered depths of the submarine, hereinafter referred to as the "depth error."

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The output signal from the error computer 12 is applied to a differentiator 14, to an instrumentation block 15, and to a gain device 16 located within a composite signal generator 17. Within the differentiator 14, the error signal is differentiated with respect to time to produce what may be termed a "velocity" signal. That is, when the ordered pressure signal applied on line 13 to the error computer 12 remains constant, the output signal from the differentiator 14 is equal to the vertical velocity of the submarine, i.e., the rate of change in the submarine's depth. When the ordered pressure signal is changing, however, to call for a changing depth, such as a constantly increasing depth, for example, the signal from the differentiator 14 is not indicative of the rate of change in the depth of the submarine. Thus, while the output signal from the differentiator 14 is herein termed a velocity signal, the true nature of the signal should be kept in mind at all times, and it should be remembered that the signal represents the rate of change, with respect to time, of the output signal from the error computer 12.

The output signal from the differentiator 14 is applied to the instrumentation block 15, to a differentiator 18, and to one input of an adder 19. Within the differentiator 18, the output signal from the differentiator 14 is differentiated with respect to time to produce a signal equal to the second derivative of the depth error signal from the error computer 12. This second derivative signal may be termed an "acceleration" signal; however, like the velocity signal, the acceleration signal only represents the vertical acceleration of the submarine if the ordered pressure signal applied to the error computer remains constant.

The output signal from the differentiator 18 is applied to the instrumentation block 15 and to the adder 19. The instrumentation block, which has applied thereto the depth error, velocity, and acceleration signals, comprises any number of test instruments located at a central location or at varied locations within the submarine to facilitate monitoring the signals from the error computer and the differentiators.

Within the adder 19 the signals from the differentiators 14 and 18 are summed together to produce a single output signal which is applied to one input of an adder 20 located within the composite signal generator 17. Applied to the other input of the adder 20 is the output signal from the gain device 16. This latter signal is equal to the signal from the error computer 12 modified in magnitude in accordance with the magnitude of the error signal itself. This modification is such as to increase proportionally the magnitude of the error signal by a larger amount when the error signal is large than when the error signal is small.

The output signal from the adder 20, i.e., the output signal from the composite signal generator 17, thus is equal to the sum of the velocity, acceleration, and the modified error signals. This output signal may be expressed by the following equation:

$$C=\frac{dE}{dt}+\frac{d^2E}{dt^2}+KE \qquad (1)$$

where C is the output signal from the composite signal generator 17, E is the depth error signal, K is a proportionality factor determined by the magnitude of the depth error signal itself, t is time, and d is the differential operator.

The output signal from the composite signal generator takes all pertinent factors properly into consideration. By adding to the velocity and acceleration signals a modified depth error signal, a greater correction is provided when a greater depth error obtains. Furthermore, rapid changes in the depth error signal are reflected in the velocity and acceleration components of the composite signal, and thus changes in the depth of the submarine are more quickly instituted when warranted by rapidly changing conditions.

The output signal from the composite signal generator 17 is applied to an output translator 21 which serves to transform the signal into a signal of any desired parameter. Thus, for example, if the signal from the composite signal generator is pneumatic or hydraulic, the output translator 21 translates such a signal into an electrical signal if so desired. Output signal translation is optional, however, and the control system may deal entirely with signals of a single parameter.

The signal from the output translator 21 is applied to a servomechanism 22 which in turn controls a pumping mechanism 23. The pumping mechanism pumps sea water both away from and into a hovering tank 24 used to control the buoyancy of the submarine. Thus, for example, when the depth error is positive, i.e., when the submarine is at a greater depth than that which is ordered, sea water is pumped out of the hovering tank into the sea in order to lighten the submarine. On the other hand, when the depth error is negative, i.e., when the submarine is at a depth less than that ordered, sea water is pumped by the pumping mechanism into the hovering tank to add weight to the submarine.

Turning now to FIGURES 2A and 2B, a detailed description of exemplary apparatus incorporated in selected ones of the blocks of FIGURE 1 will be given. This apparatus is suitable for an automatic control system in a submarine, and, as shown, basically comprises a pneumatic system.

Error computer

In FIGURE 2A, sea water obtained from an input port on the side of a submarine (not shown), or a pneumatic pressure corresponding to the pressure exerted by the sea water at the depth actually assumed by the submarine, is applied on an input line 25 to the error computer 12. Within the computer the input line 25 is applied to one input 26 of a gage 27 and to one input 28 of a sensing bellows 29.

Pneumatic pressure from a source of reference pressure (not shown) is applied on an input line 30 to the error computer 12. Within the computer, the pressure is adjusted by a pressure adjusting valve 31 to provide an output pressure which is indicative of the depth at which it is desired to position the submarine. This output pressure is applied to an input 32 of the gage 27 and to an input 33 of the sensing bellows 29.

In the gage 27, the relative positions of two pointers 34 and 35 are indicative of the difference between the depth at which it is desired to position the submarine and the actual depth assumed by the submarine. For example, as shown in the figure, the pointer 34 is higher than the pointer 35, and thus the submarine is at a greater depth than that at which it is to be positioned. On the other hand, if the pointer 35 is higher on the gage than the pointer 34, the submarine is above the depth at which it is to be positioned. In this fashion, the gage gives a visual indication of the depth error, and the gage may be located at any convenient point in the submarine for a quick visual inspection.

Within the sensing bellows 29 of the error computer 12, the two pneumatic pressures applied to the inputs 28 and 33 operate against each other through two bellows sections 36 and 37. A rod 38 that couples together the two sections thus is forced either to the right in the figure or to the left depending upon which of the pressures in the input lines 28 and 33 is increasing relative to the other. For example, movement of the arm to the left indicates that the pressure applied to the input 28 is increasing relative to the pressure applied to the input 33. If the magnitude of the pressure applied to the input 28 is greater than the magnitude of the pressure applied to the input 33 at this time, this would indicate that the submarine is at a depth greater than that ordered and that the depth error is increasing.

The right and left movement of the rod 38 is translated by linkages 39, 40 and 41 into a pivotal movement of a nozzle regulating vane 42 about a pivot point 43. One end of the vane is positioned above a nozzle 44 that exhausts air supplied thereto from a source of reference air pressure (not shown) that is supplied upon an input line 45 to the error computer 12. The air pressure from the input line is first applied to a filter 46 from which it passes to the nozzle 44 through a restriction 47 in nozzle tube 48. The air pressure from the filter 46 is also applied to an input 49 of a booster section 50.

The booster section 50 consists of three bellows sections 51, 52, and 53. The lower bellows section 51 is itself formed from two separate sections: an outer section 51′ and an inner section 51″. The outer bellows section 51′ is coupled to an input line 54 that is connected to the nozzle tube 48 just above the restriction 47. The middle bellows section 52 and the upper bellows section 53 are both controlled by air pressure supplied thereto by a pressure line 55 that is coupled to an output line 56 of the booster section.

A connecting member 57 joins the middle and lower bellows sections 52 and 51, and within the connecting member 57 a passage 58 permits a flow of air therethrough to the inner bellows section 51″ that is discharged through a discharge port 59. A valve member 60 is situated below the passage 58, and regulates the flow of air therethrough as well as the flow of air from the line 49 through a passage 61. A base platform 62 is coupled to the upper bellows section 53 and serves as a rest upon which the pivot 43 is positioned.

The operation of the error computer is as follows. Assume that the submarine is at a greater depth than that which is ordered and that the actual depth is increasing. In this instance, the rod 38 within the sensing bellows 29 moves to the left as shown by the arrow, and the movements of the linkages 39, 40, and 41, and the nozzle regulating vane 42 are as shown by their associated arrows. The movement of the end of the nozzle regulating vane thus is toward the nozzle 44. This restricts the flow of air from the nozzle, thereby increasing the air pressure therein.

The increased air pressure within the nozzle 44 is communicated to the lower, outer bellows section 51′ through the line 54, and the section 51 along with the connecting member 57 are moved downward. As the connecting member is moved downward, it contacts the valve 60 pushing the valve downward. This action closes off the passage 58 within the connecting member and opens up the passage 61 to allow the flow of additional air to the chamber surrounding the lower bellows section 51 and to the chamber between the bellows sections 52 and 53 through lines 56 and 55. Since bellows sections 51 and 52 are substantially equal in diameter, the degree of opening of the passage 61 is not influenced by this pressure change. The increase in pressure, however, causes the upper section 53 to be urged upward. The support platform 62 is accordingly raised upward, moving the end of the regulating vane 42 away from the nozzle 44, thereby decreasing the pressure in the nozzle. This reduces the downward movement of the bellows section 51 and reduces the flow of air through the passage 61 to the output line 56.

The entire effect of the booster section 50 is to create a rapid and large change in the output pressure from the section when warranted by a changing depth error. By the use of feed back, the rapid and large change is tapered off somewhat so that a balance condition is achieved, and the output pressure from the booster section, i.e., the depth error signal, is made to be exactly that as called for by the particular depth error. In this respect it should be noted that the output pressure varies about some fixed pressure that corresponds to zero depth error.

Differentiator 14

The pneumatic depth error signal, after first passing through a filter 63 and an adjustable pulsation dampener 64, is applied via an output line 65 to the differentiator 14, to the instrumentation block 15, and to the composite signal generator 17. (See FIGURE 2B.) Within the differentiator 14, the depth error signal is applied directly to a bellows 66 and indirectly to a bellows 67 after first passing through a pressure dampening device 68. Because of the action of the pressure dampening device, for a changing depth error signal the pressure in the bellows 67 lags the change in pressure in the bellows 66.

The bellows 66 and 67 are coupled to a rod 69 which pivots in seesaw fashion about a fixed point 70. The rest position of the rod is set by a set point adjuster 71 that is coupled to one of the ends of the rod 69. A nozzle regulating vane 72 is coupled to the other end of the rod 69, and a portion of the vane in turn is coupled to a cam-type proportional band sector 73 by a linkage 74.

Air pressure is applied from a source of reference pressure (not shown) via an input line 75 to the differentiator 14. Within the differentiator the input air pressure passes through a filter 76 to a pair of inputs 77 and 78 of a diaphragm booster unit 79. A small restriction 80 is located in the input line 77 and restricts the flow of air into bellows section 81.

The diaphragm booster unit 79 comprises a lower bellows section 81 that is connected to the input line 77. A pair of linkages 82 and 83 mechanically couple the bellows section 81 to a flexible diaphragm 84 attached to the sides of an outer tube 85. The diaphragm 84 is, in turn, coupled by a linkage 86 to an inner tube 87 located within the outer tube 85. The inner tube 87 passes through and is pivotally coupled to a second flexible diaphragm 88 attached to the sides of the outer tube 85. The inner tube 87 has air pressure admitted thereto via the input line 78. A valve assembly 89 controls the flow of air from the inner tube, and air flows into an output line 90 only when the inner tube is pivoted about a pivot point 91 in the diaphragm 88 to open the valve.

Air flow from the diaphragm booster unit 79 proceeds upon the line 90 to an output line 92 of the differentiating unit 14 and to an upper bellows 93. The upper bellows is coupled to one end of a nozzle control arm 94 that pivots about a pivot point 95. A lower bellows 96 is coupled to the nozzle control arm on the other side of the pivot point 95, and the bellows is freely exhausted to the outside atmosphere by virtue of two exhaust lines 97 and 98. Attached to one end of the nozzle control arm 94 is a tube 99 containing a nozzle 100 at the tip thereof. The tube 99 is coupled to the diaphragm booster unit 79 and receives air pressure applied thereto from the input line 77.

The operation of the differentiator 14 is as follows. Assume that the depth error signal applied on the line 65 is increasing. The increasing pressure is communicated to the bellows 66 before it is communicated to the bellows 67. Thus, the rod 69 pivots about the point 70 as shown by the arrow, thereby forcing the nozzle regulating vane 72 toward the nozzle 100. This increases the pressure within the nozzle tube 99, which is communicated back to the diaphragm booster unit 79, and results in a downward motion of bellows section 81 which results in corresponding motion of linkages 82, 83 and 86 through pivotal diaphragm 84. Consequently, motion of inner

tube 87 results in the opening of valve 89. Accordingly, an increase in air pressure occurs in the line 90 which is directly coupled to the output line 92 of the differentiator.

Since the increased output pressure in the line 90 is also applied to the upper bellows 93, the nozzle control rod 94 pivots about the point 95, as shown by the arrows, thereby forcing the nozzle 100 away from the end of the nozzle regulating vane 72. This results in a decrease in pressure within the nozzle tube 99, giving a feed back action similar to that encountered in the booster section 50 of the error computer 12 and a consequent rapid response of the output signal. Thus, because of the lagging action of the bellows 67, the output pressure from the differentiator 14 is equal to the rate of change, with respect to time, of the depth error signal.

As may be noted, when the depth error signal is constant and is not changing, the pressures applied to the bellows 66 and 67 are equal, and the nozzle regulating vane 72 assumes a rest position with respect to the nozzle 100. In the rest position, the output pressure from the differentiator 14 is constant at a fixed value which corresponds to no rate of change of the depth error signal.

Differentiator 18

The output pressure from the differentiator 14, which is indicative of the rate of change of the depth error signal, is applied via an output line 101 to the differentiator 18, to the adder 19, and to the instrumentation block 15. The differentiator 18 has the same internal components as are included in the differentiator 14, and for this reason similar numerical designations for like components have been used in FIGURE 2A.

The output signal from the differentiator 18 thus is equal to the first time derivative of the output signal from the differentiator 14, i.e., the second time derivative of the depth error signal. This output signal is applied via output lines 102 and 103 to the adder 19 and to the instrumentation block 15, respectively.

Instrumentation block

As may be noted, the signals applied to the instrumentation block 15 are the depth error signal (line 65) and its first and second time derivatives (lines 101 and 103, respectively). Within the block, the depth error signal is applied to a depth error transducer 104 which serves to transform the pneumatic depth error signal into an electrical signal, e.g., if such a transformation is desired for convenience. The electrical depth error signal appears upon a pair of secondary leads 105 of a transformer 106 whose core 107 is positioned in accordance with the pressure applied to the transducer. These secondary windings in turn may be coupled to any standard electrical meter (not shown) to give an indication of the depth error signal.

Within the instrumentation block 15 the first and second derivative signals are applied to a pair of associated adjustable pulsation dampeners 108 and 109, respectively, whose outputs on lines 110 and 111 may be coupled to pneumatic test instruments (not shown).

The instrumentation block 15 is provided for monitoring the essential signals that form the ultimate control signal used to position the submarine. Thus, the test instruments located therein may be mounted either on a single panel, at some convenient central location, or at various separate locations within the submarine.

Adder

The adder 19 has virtually the same internal components as does the differentiator 14 described above, and for this reason similar numerical designations for like components have been used. Changes in the connections of the components of the adder, however, are as follows. Bellows *67b* is completely vented, input line *98b* is completely closed off, and input line *97b* within the adder is coupled directly to the line 102 from the differentiator 18. With these modifications, the adder sums together the input signals applied thereto from the differentiators 14 and 18. This is apparent since the signal from the differentiator 14 is coupled only to the bellows *66b*, providing the sole force on the nozzle regulating vane *72b*, while the signal from the differentiator 18 is coupled directly and only to bellows *96b*, which moves the nozzle tube *99b*. Venting the bellows *67b* eliminates the differentiating feature of the unit.

Composite signal generator

The sum of the first and second derivatives of the depth error signal is applied via an output line 112 from the adder 19 to input line *98c* within the composite signal generator 17. Like the other units of the control system, the internal components of the composite signal generator are similar to those included in the differentiator 14, and for this reason similar numerical designations for like components have been used. The following changes, however, have been made. Input line *97c* is completely closed off, bellows *67c* is vented, and the depth error signal, applied to the composite signal generator on line 65, passes to bellows *66c* and to another bellows *113c*. A pair of linkages *114c* and *115c* couple the diaphragm *113c* to a secondary cam *116c* whose movement actuates an arm *117c* that swings the primary cam *73c* about its pivot point. Movement of the primary cam *73c* swings the end of the nozzle regulating vane *72c* toward or away from the nozzle *100c*.

With the changes described, the output signal from the composite signal generator appearing on the line *92c* within the generator is equal to the sum of the signal from the adder 19 and a modified depth error signal. This output signal is expressed by Equation 1 given above. That the composite signal generator generates such a signal is apparent from an examination of the generator itself. That is, the input signal from the adder 19 is applied directly to the bellows *96c* which controls the movement of the nozzle control arm *94c*. This accounts for the first two factors of Equation 1, namely, the first derivative and second derivative depth error signals. Applying the depth error signal to the bellows *66c* and *113c*, both of which control the movement of the nozzle regulating vane *72c*, results in the addition of the third and final factor of Equation 1. Without the bellows *113c* the depth error signal would be added directly to the signal from the adder 19; however, the bellows *113c* modifies the depth error signal by a proportionality factor given as K in Equation 1.

Because it is the depth error signal that is applied to the bellows *113c*, the proportionality factor K is a variable which is a function of the depth error signal. The variation in K with the depth error may be chosen to be linear or non-linear, to give any desired type of response, i.e., one which is either positive or negative with respect to the depth error. In the present application of this invention to submarine hovering, it is desirable that K increases as the magnitude of the depth error itself increases.

The output signal from the composite signal generator, which is a weighted signal taking into account the depth error signal and its first and second time derivatives, may be used in its pneumatic form to actuate suitable control equipment for changing the depth of the submarine. However, at times it may be desirable to effect a translation of the control signal from its pneumatic form into another form, such as an electrical control signal. Apparatus to effect such a translation is shown in FIGURE 2B as the output translator 21, and a description of this follows.

Output translator

The output signal from the composite signal generator 17 is applied on a line 118 to the output translator 21. Within the translator the pneumatic input signal is applied to a bellows 119 which actuates a movable bar 120. The bar 120 is urged downward by a spring 121 coupled between the bar 120 and another bar 122. The movement of the bar 122 is determined by the movement of a cam 123 that is mechanically coupled to a vertical gear rod 124. The gear rod 124 is in turn coupled at the top thereof to a diaphragm 125 that is urged downward against the restraining force of a spring 126 by a source of air pressure supplied to the diaphragm from an input line 127. The input line 127 is coupled to a filter 128 which receives air pressure through a valve 129 that is actuated by the movable bar 120. The valve 129 receives air pressure from a source of reference pressure (not shown) that is applied via an input line 130 through a filter 131.

To understand the operation of the output translator, assume that the signal from the composite signal generator 17 is increasing. In this event, the movement of the movable bar 120 is upward as shown in the figure, resulting in the delivery of a greater supply of air to the diaphragm 125 and a consequent downward movement of the vertical gear rod 124. Downward movement of the gear rod results in counterclockwise movement of a gear 132 and clockwise movement of a gear 133. The clockwise movement of the gear 133 in turn moves an arm 134 on a rheostat 135, thus changing the values of the resistances "seen" looking into output terminals 136 connected to the rheostat. The terminals 136 may be coupled to any well-known electrical gain device (not shown) whose gain depends upon the magnitudes of associated resistances, and in this fashion the output translator effects a translation of a pneumatic control signal into an electrical control signal. Such a gain device, e.g., would normally be incorporated in the servomechanism 22 of FIGURE 1.

Although the submarine hovering system described in detail above its a pneumatic-electric control system, the invention is not in any way limited thereto. Such a control system could be entirely pneumatic, hydraulic, or electrical, for example, or portions of the system might involve any one or more of these parameters. This is illustrative of one of the ways in which the invention might be modified without constituting a departure from the spirit of the invention. Such modifications and changes as these, and other immaterial changes, should all be deemed to lie well within the scope of the following claims which are set forth as follows to define this invention.

I claim:

1. The method of positioning a submarine at a predetermined depth comprising the steps of generating an error signal representative of the difference between the depth assumed by the submarine and the predetermined depth, differentiating the error signal to generate a first derivative signal, differentiating the first derivative signal to generate a second derivative signal, multiplying the error signal by a factor substantially equal to the error signal raised to a power equal to at least one, and combining the multiplied error signal, the first derivative signal and the second derivative signal to generate a composite control signal, whereby the composite control signal may be utilized to reposition the submarine.

2. In a control system in which a signal is generated for positioning a vehicle at a predetermined level in a fluid, means for multiplying the signal by a factor substantially equal to the difference between the level assumed by the vehicle in the fluid and the predetermined level, thereby to generate a weighted signal.

3. In apparatus for positioning a vehicle at a predetermined level within a fluid, means for generating a single control signal usable to actuate apparatus for repositioning the vehicle within said fluid, comprising means for generating an error signal substantially equal to the difference in pressure exerted by said fluid at said predetermined level and the level then assumed by said vehicle, means for generating a velocity signal and an

acceleration signal from said error signal, means for multiplying the magnitude of said error signal by a factor proportional to its unadjusted magnitude with respect to a reference magnitude which is equal to at least one, and means for combining said velocity, said acceleration and said multiplied error signals thereby to generate a single control signal.

4. In a control system in which an error signal and at least one time differentiated error signal are utilized to position a vehicle within a fluid, means for generating a composite control signal comprising means for multiplying said error signal by a factor proportional to its magnitude which is equal to at least one, and means for adding together said multiplied error signal and said time differentiated error signal to produce a composite control signal.

5. Apparatus to position a submarine at a predetermined depth comprising means for generating an error signal representative of the difference between the water pressure at the depth actually assumed by the submarine and a reference pressure representative of the water pressure at said predetermined depth, means for differentiating said error signal with respect to time to generate a first derivative signal, means for differentiating said first derivative signal with respect to time to generate a second derivative signal, means for adding said first and said second derivative signals to generate a first sum signal, means for multiplying the magnitude of said error signal by a factor substantially equal to the error signal raised to a power equal to at least one, means for adding said first sum signal and said multiplied error signal to generate a correction signal, and means responsive to said correction signal to reposition the submarine.

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