

Aug. 16, 1966

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3,266,380

PNEUMATIC OPERATIONAL AMPLIFIER SYSTEM

Filed Nov. 26, 1963

2 Sheets-Sheet 1

Fig. 1

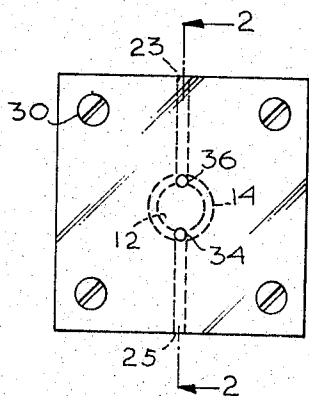


Fig. 2

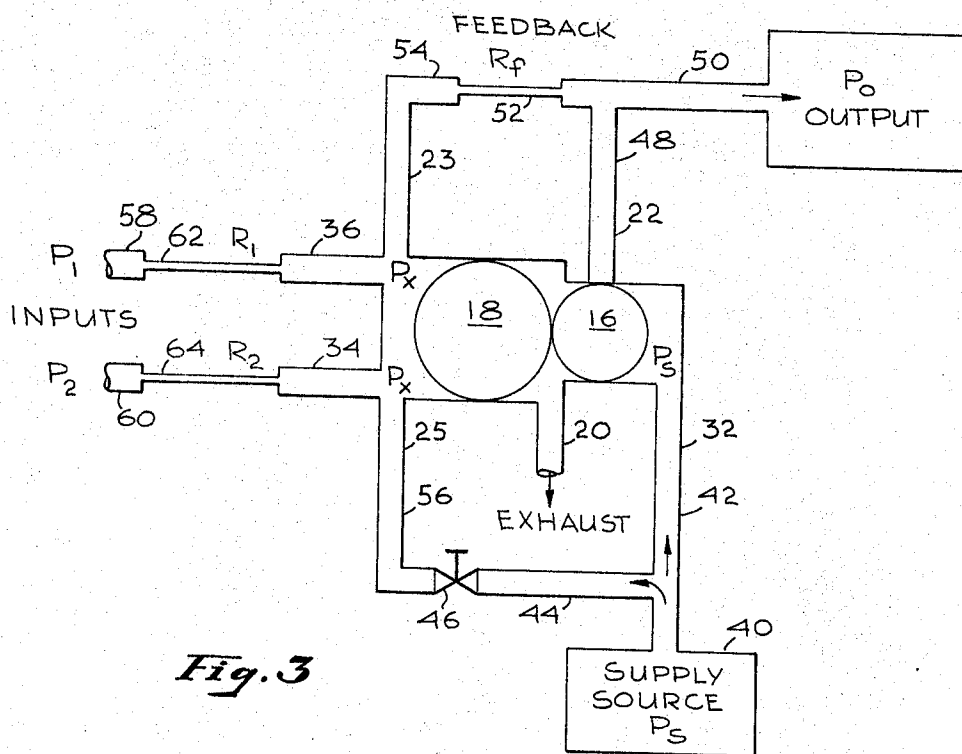
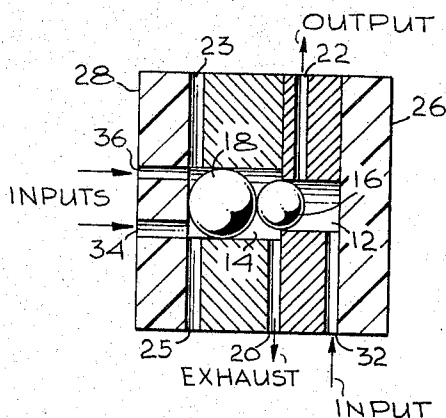


Fig. 3

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2 Sheets-Sheet 2

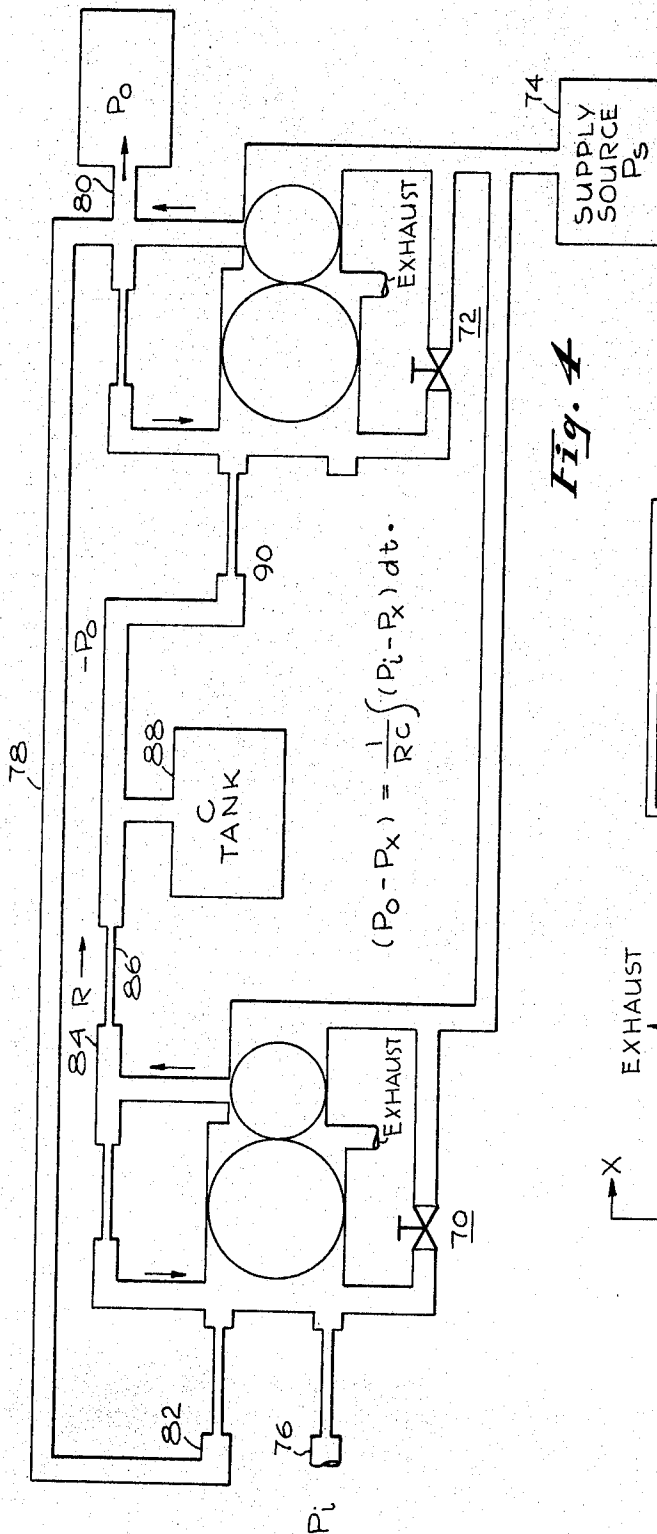


Fig. 4

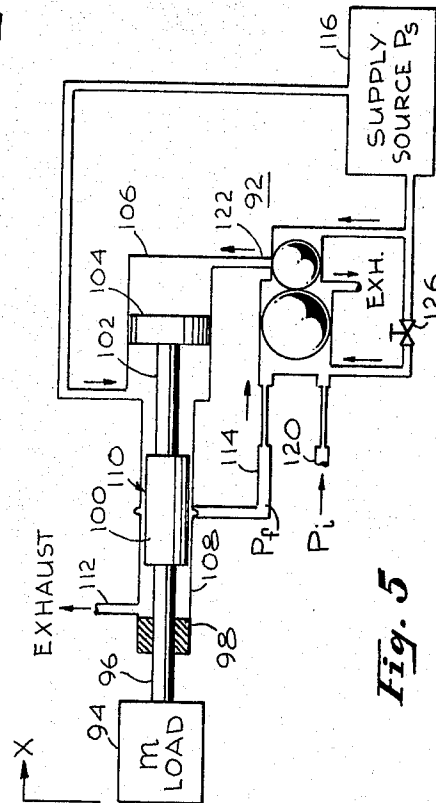


Fig. 5

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PNEUMATIC OPERATIONAL AMPLIFIER SYSTEM
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8 Claims. (Cl. 91-388)

This invention relates to fluid-actuated structures for performing logical operations and more particularly to improvements therein.

In an application for patent for fluid logic structures filed May 31, 1963 and having Serial No. 284,725, now abandoned, there is described a fluid-actuated logical element which is employed for performing digital logic. The utility of the invention is in environments in which the electronic components normally used for performing digital logic are not suitable. In such environments, provided that results are not required at the speeds of electronic components, fluid-actuated logical elements may be employed. Besides digital operations, it is also necessary to perform analog operations in such environments.

Accordingly, an object of this invention is the provision of a fluid-actuated element which may be employed for analog operations.

Yet another object of this invention is the provision of a unique fluid-actuated operational amplifier.

Still another object of the present invention is the provision of a simple and reliable fluid-actuated analog control element.

These and other objects of the present invention are achieved by a structure having two different-size aligned passages in which two different-size balls may move or slide. Very little clearance is provided for the balls in these passages. Openings are provided in the walls of these passages to permit air to be applied to the smaller ball to move it against the larger ball and to permit air to be applied to the larger ball to move it against the smaller ball. Some of the latter openings may be used for the application of input pressures to be summed by the device. In addition, openings are provided in the side walls of these passages whereby, when the smaller ball assumes one position, it cuts off or blocks an output aperture and as it is moved toward a second position, it permits the air which pushes it toward the larger ball to exit through that output aperture to an extent determined by its location between the two positions. In addition, air is fed from the output aperture back to a side of the larger ball to urge the larger ball toward the smaller ball. Furthermore, supply air is fed not only against the side of the smaller ball to urge it toward the larger ball but also through a control or bias valve to an opening in the passage adjacent the larger ball which permits this air also to urge the larger ball against the smaller ball, compensating exactly for the constant leakage flow around the large ball.

The structure briefly described comprises an operational amplifier, which those skilled in the art will readily recognize as being a basic unit in analog computation.

The novel features that are considered characteristic of this invention are set forth with particularity in the appended claims. The invention itself, both as to its organization and method of operation, as well as additional objects and advantages thereof, will best be understood from the following description, when read in connection with the accompanying drawings, in which:

FIGURE 1 shows the appearance of one end of a two-ball element which is employed in the analog element of this invention;

FIGURE 2 is a cross-section through FIGURE 1 along the lines 22, illustrating the internal appearance of the element;

FIGURE 3 is a schematic drawing of an embodiment of this invention;

FIGURE 4 is a schematic drawing illustrating how the embodiment of this invention may be employed for performing integration;

FIGURE 5 is a schematic drawing showing how the embodiment of this invention may be performed for performing position control functions.

FIGURES 1 and 2 of the drawing respectively show an end and cross sectional view of what may be termed a "two-ball arrangement" of a fluid-actuated logic structure. These two drawings are substantially identical with FIGURES 1 and 2 of the drawing shown in the previously mentioned application, Serial No. 284,725, which is assigned to a common assignee. However, some modification has been made of the basic element, as is shown in FIGURE 2, for the purpose of its being utilized as an analog device.

In FIGURE 2, the basic block of material 10 has drilled therethrough with aligned centers, a smaller passageway 12 and a larger passageway 14. A smaller ball 16, and a larger ball 18, sized to provide a running fit in these passageways, are respectively inserted therein. An opening 20 is milled in the block 10 extending from the larger passageway at its junction with the smaller passageway. This opening is known as the exhaust opening. Another hole 22 is drilled through the block 10 on the opposite side thereof from the exhaust opening 20 and opening into the smaller passageway 12, displaced from the junction thereof with the larger passageway. This is known as the output opening 22. Two more oppositely extending openings respectively 23 and 25 are milled in the block 10 to afford access into the larger passageway 14 on the side of the larger ball 18 which is farthest away from the smaller ball 14.

End pieces respectively 26, 28 are attached to the central block 10 by any suitable means such as screws 30. The end pieces 26, 28 serve to close off the smaller and larger passageways respectively 12, 14, except that an input aperture 32 is milled through the block 10 to afford input to the side of the smaller passageway and two input apertures respectively 34, 36, are drilled through the end plate 28 to afford access to the outer side of the larger ball.

As previously indicated, the two balls 16, 18 slide in concentric holes with very little clearance or leakage. With the two balls in the position shown in FIGURE 2, air which is applied at the opening 32 will flow through the passageway 12 and through the output aperture 22. The ball 16 prevents any air from moving into the passageway 14. Upon the application of the air to any one or combination of the openings 23, 34, 36, 25, the ball 18 slides to the left moving the ball 16 therewith, whereupon opening 22 is blocked. The exhaust aperture 20 is provided to exhaust any air which may pass by the ball 18 and to exhaust any air that may remain in the output opening when it is connected to the apparatus. Upon removal of the air which is maintaining the ball 18 in pressing contact against the ball 16 such that opening 22 is blocked, the smaller ball 16 will move the larger ball 18 to the right, whereupon an output will occur through the opening 22.

The arrangement shown provides gain. That is, the results of the same input pressure applied to the larger ball and to the smaller ball will always result in the balls moving to the position with the opening 22 being blocked. The amount of this gain is largely determined by the ratio of the ball diameters.

FIGURE 3 is a schematic arrangement of an embodiment of the invention. Therein, the balls 16, 18 are represented with lines on either side thereof representing the passageways in which these balls slide and the re-

spective openings 20, 22, 23, 25 and 32, 34, 36 affording access to these passageways in the manner previously described. It will be seen that a constant pressure supply source 40 is coupled by appropriate tubing 42, 44 respectively, to the opening 32 and to a control valve 46. The output opening 22 is coupled by appropriate tubing 48 to an output tube 50 which also connects through a linear flow resistance 52, designated as R_t , through tubing 54 back to an input opening 23. The control valve 46 connects through tubing 56 back to input opening 25.

Inputs to openings 34, 36 are applied through tubes respectively 58, 60 which connect to these openings through linear flow resistances respectively 62, 64. Assume now that the input to tube 58 is designated as P_1 , the input to tube 60 is designated as P_2 , the output pressure is designated as P_0 . P_s is the pressure in the passageway on the side of the small ball farthest away from the larger ball. Let P_x equal the fluid pressure on the side of the larger ball farthest away from the smaller ball.

If the cross-sectional area of the smaller ball is, for example, one-half that of the larger ball, then the two balls will be in static equilibrium only when P_x equals one-half P_s . But since P_s is a fixed reference pressure, then P_x will also be a fixed known pressure level (except for transient disturbances). This P_x corresponds to the "virtual ground" at the summing junction of an electronic summing amplifier. The input signals are represented by the pressure differentials $(P_1 - P_x)$ and $(P_2 - P_x)$, and can therefore be positive or negative (with respect to "computer ground," P_x).

R_1 , R_2 , and R_t as previously indicated are linear flow resistances, such as capillaries or porous plugs. Resistance here has the units of pressure drop divided by volume flow rate. The valve 46 can be adjusted so as to balance out the effect of leakage past the large ball, thus eliminating zero offset of the output.

A summation of flow rates into the P_x chamber will show that the output is the negative weighted sum of the inputs as follows:

$$(P_0 - P_x) = -\frac{R_t}{R_1}(P_1 - P_x) - \frac{R_t}{R_2}(P_2 - P_x)$$

Note that P_1 and P_2 are assumed to be pressure sources of low internal resistance compared to R_1 and R_2 . They must be able to put out or to accept some flow at constant pressure. This invention is such a device, and therefore units can be cascaded in networks.

It should be appreciated that the embodiment of the invention schematically represented in FIGURE 3 comprises an operational amplifier that is connected to give the inverted sum of two input pressure signals.

The usual way to integrate a function with respect to time using an operational amplifier is to feed back around the amplifier through a coupling capacitor. The fluid analogy to a coupling capacitor is two chambers separated by a spring-loaded partition or compliant membrane. For applications where these springy elements are not desired, there is another system for integrating that is based upon the fact that a rigid tank containing a compressible fluid, such as air, is analogous to a capacitor with one end tied to ground. Electronically, a current source feeding such a capacitor would generate a voltage at the capacitor proportional to the integral of the current. The current could be controlled by monitoring the drop across a resistor.

FIGURE 4 illustrates the pneumatic analog, in accordance with this invention, of an integrating system. The arrows associated with the schematic drawing show information flow and not necessarily air flow direction. It will be seen that the integrator in FIGURE 4 includes two of the summing amplifiers shown in FIGURE 3 respectively designated by reference numerals 70 and 72.

A single supply source 74 at a pressure P_s is provided for the system. The input, at a pressure P_1 which is to be integrated is applied to one input 76 of the first summing device 70. The summing device 72, as will become clear with further discussion, is used as an inverter.

A feedback coupling is made by a pipe 78 from the output 80 of the second device 72 back to the second input 82 of the first summing device 70. The output hose 84 from the first summing device 70 is connected through a capillary or linear resistance 86 to a tank 88 and also to an input 90 of the second summing device 72. The second input to the second summing device 72 is blocked. All unmarked capillaries are of equal resistance.

An analysis of the arrangement shown in FIGURE 4 indicates that an output $(P_0 - P_x)$ is achieved at the pipe 80 which is equal to

$$\frac{1}{RC} \int (P_1 - P_x) dt$$

where R is equal to the capillary 86, C is the "pneumatic capacitance" of the air tank, P_1 is the input pressure and P_x has the same meaning as was given in FIGURE 3. Since R , C , and P_x are constants, effectively, the output of the arrangement shown in FIGURE 4 is the integral of the input with respect to time.

The basic two-ball element in accordance with this invention can also be used as a high-gain amplifier for control as well as for computing. An arrangement illustrating this is shown in FIGURE 5. This shows a fluid servomechanism for positioning a variable load in continuous response to a low-power pressure signal. The advantage of this arrangement is that there are no springs or diaphragms to creep or deteriorate at high temperatures. The element corresponding to the one shown in FIGURE 3 is designated by the reference numeral 92. A load 94 is to be positioned using a pneumatic piston arrangement. The load is held on a piston rod 96 which rides in a bearing 98. The piston rod has an enlarged portion 100 and thereafter a reduced portion 102 which terminates in the piston head 104. The piston head has twice the cross-sectional area of the enlarged portion 100 and operates in a piston chamber 106. The enlarged portion 100 of the piston rod slides within a pipe 108 which provides a capillary gap 110 of resistance much less than that at input 114. It will be seen that the pipe 108 is closed with the piston chamber 106 at one end and has an exhaust opening 112 at the other end. The capillary gap 110 around the enlarged portion of the piston rod acts as a pressure divider, providing a feedback pressure $(P_f - P_x)$ to one input 114 of the device 92, which is proportional to the position of the load 94. It should also be noted that the one supply source 116 at pressure P_s supplies the pressure required for operation of the summing amplifier device 92 and the pressure applied to the interior of the piston and pipe chamber.

The load displacement " x " will be proportional to $(P_f - P_x)$ where P_f is the pressure of the fluid applied to one input 120 of the device 92. As pointed out, the pressure signal from the capillary divider is proportional to the position of the load. The resulting flow summation at the amplifier input causes the balls to shift and this serves to cause fluid to flow, or not, through the output 122 of the device 92 back into the head end of the cylinder until an equilibrium position is reached which corresponds to the input signal. Thus, the load displacement is proportional to the input pressure. The zero position of the load may be set using the valve 126.

There has accordingly been described and shown herein a novel, useful and unique pneumatic analog device which can perform a multiplicity of analog operations.

What is claimed is:

1. A fluid-actuated logical element comprising a body of material having a first input aperture, an output aper-

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ture, a first passage therein affording communication between said first input aperture and said output aperture, first ball means in said first passage movable therein between a first position for blocking communication between said first input aperture and said output aperture, and a second position wherein said communication is afforded, a second passage in said body of material aligned with said first passage and in communication therewith, said second passage being larger than said first passage, a second ball means in said second passage movable in said second passage to a first position whereby it moves said first ball means to its first position and to a second position whereby said ball means may be moved to its second position, the extent of communication between said input and output apertures being determined by the location of said first ball means relative to said first and second positions, second, third, fourth, and fifth input apertures in said body of material communicating with said second passage at the side of said second ball means which is farthest away from said first ball means, means coupling said output aperture with said second input aperture, means coupling said first input aperture with said third input aperture, first means for applying fluid under pressure to said first and third input apertures for establishing a reference pressure level within said first and second passages, and means for applying fluids under pressures to said fourth and fifth input apertures whereby the output pressure at said output aperture is the negative weighted sum of the inputs.

2. A fluid-actuated logical element as recited in claim 1 wherein said means coupling said output aperture to said first input aperture includes a linear flow resistance.

3. A fluid-actuated logical element as recited in claim 1 wherein said means coupling said first and third input apertures includes a valve to provide a bias flow into the input side of said large passageway to compensate for leakage flow around the larger ball.

4. A fluid-actuated logical element as recited in claim 1 wherein said third and fourth input apertures each include a linear flow resistance.

5. A fluid-actuated logical element comprising a body of material having a first input aperture and an output aperture, a first passage therein for affording communication between said first input aperture and said output aperture, first ball means in said first passage movable from a first position wherein it blocks communication between said first input aperture and said output aperture to a second position wherein communication is completely afforded, the extent of communication between said input and output apertures being determined by the location of the first ball means relative to its first and second positions, a second passage in said body of material which communicates with said first passage and is coaxial therewith, said second passage being larger than said first passage and including a second ball means slidably movable in said second passage to a first position for moving said first ball means to its first position and to a second position for permitting said first ball means to return to its second position, second, third, fourth, and fifth input apertures communicating with said second passage at a location adjacent said second ball means which is on the side farthest away from said first ball means, an exhaust aperture communicating with the passageway region between said first and second ball means when said first ball means is in its second position, a feedback coupling including a flow resistance device connecting said output aperture with said second input aperture, a feed coupling including a fluid flow-control device connecting said first input aperture with said third input aperture, first means for applying fluid at a reference pressure to said first input aperture, and means for applying fluids at pressures which it is desired to sum to said fourth and fifth input apertures.

6. A fluid-actuated integrating system comprising a first

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and second fluid-actuated device each including a body of material having a first input aperture and an output aperture, a first passage therein for affording communication between said first input aperture and said output aperture, first ball means in said first passage movable therein between a first position for blocking communication between said first input aperture and said output aperture and a second position wherein said communication is afforded, the location of said ball means between said first and second positions determining the extent of communication between said first input and output apertures, a second passage in said body of material concentric with said first passage and in communication therewith, said second passage being larger than said first passage, a second ball means in said second passage movable in said second passage to a first position whereby it moves said first ball means to its first position and to a second position whereby said first ball means may be moved to its second position, second, third and fourth input apertures in said body of material communicating with said second passage at the side of said second ball means which is farthest away from said first ball means, a feedback coupling between said output aperture and said second input aperture, a flow control coupling between said first input aperture and said third input aperture, a second feedback coupling between the output aperture of said second fluid-actuated device and the fourth input aperture of said first fluid-actuated device, forward coupling means coupling the output of said first fluid-actuated device to the fourth input of said second fluid-actuated device, a fluid holding tank coupled to said forward coupling means, means for applying fluid at a predetermined pressure to the first inputs of said first and second fluid-actuated devices, a fifth input aperture in said first fluid-actuated device communicating with said second passage at the side of said second ball means which is farthest away from said first ball means, means for applying fluid under pressure which is to be integrated to said fifth input aperture, and means to derive an output from the output aperture of said second fluid-actuated means.

7. The structure of claim 6 wherein the feedback means of said first and second fluid-actuated devices include linear flow resistances therein, said forward feed means includes a linear resistance, and there is a linear resistance in each of said fourth inputs in said fifth input apertures.

8. A fluid-actuated control device for controlling a fluid-operated device composed of a body of material having a first input aperture and an output aperture therein, a first passage therein affording communication between said first input aperture and said output aperture, first ball means in said first passage movable therein between a first position for blocking communication between said first input aperture and said output aperture and a second position wherein said communication is afforded, the location of said first ball means between said first and second positions determining the extent of communication between said first input aperture and said output aperture, a second passage in said body of material concentric with said first passage and in communication therewith, said second passage being larger than said first passage, second ball means in said second passage movable in said second passage to a first position whereby it moves said first ball means to its first position and to a second position whereby said first ball means may be moved to its second position, second, third, fourth and fifth input apertures in said body of material communicating with said second passage at the side of said second ball means which is farthest away from said first ball means, flow-control means coupling said first input aperture with said fifth input aperture, means for applying fluid at a reference pressure to said first input aperture, means in said fluid-actuated device to be controlled for providing fluid at a pressure representative of the

controlled state of said apparatus, means for applying said fluid at a pressure representative of the controlled state of said apparatus to said third input aperture, control means for applying fluid with a pressure representative of the desired control to said fourth input aperture, and means to apply output from said output aperture to said fluid control device to effectuate control thereof.

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5 WILLIAM F. O'DEA, *Primary Examiner*.

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