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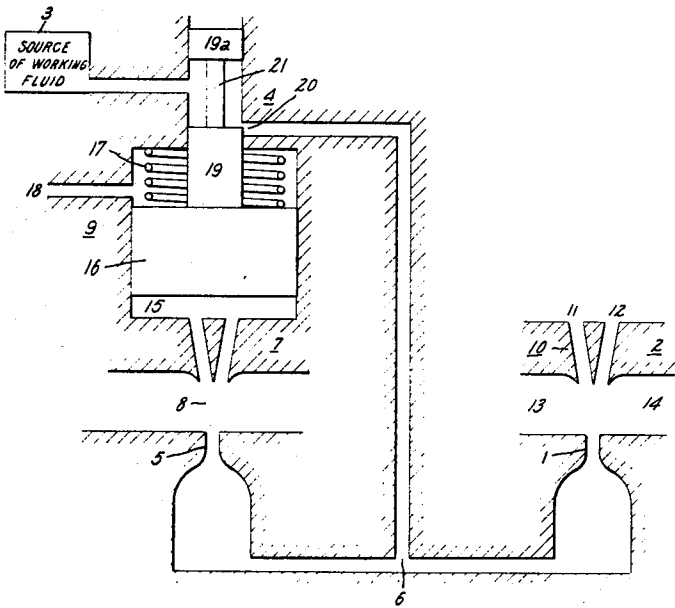
[54] METHOD AND APPARATUS FOR REYNOLDS
NUMBER COMPENSATION OF WORKING FLUID
SUPPLIED TO FLUID AMPLIFIER
13 Claims, 6 Drawing Figs.

[52] U.S. Cl..... 137/81.5
[51] Int. Cl..... F15c 3/02
[50] Field of Search..... 137/81.5

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ABSTRACT: A variable area valve is interposed between a source of working fluid and the power nozzle of a hydraulic fluid amplifier, and its flow area is controlled in inverse response to pressure changes detected in a fluid jet issuing from a reference nozzle. The reference nozzle is substantially identical to, and is connected in fluid parallel with, the power nozzle of the fluid amplifier. Fluctuations in the Reynolds Number or viscosity associated with the working fluid are directly manifested in pressure changes in the jet issuing from the power nozzle and thus in gain changes in the fluid amplifier. Pressure changes detected in the reference jet are directly related to any pressure changes which occur in the power jet of the fluid amplifier and serve to compensate for the latter by moving the variable area valve so as to increase or decrease the pressure of the working fluid supplied to the fluid amplifier.



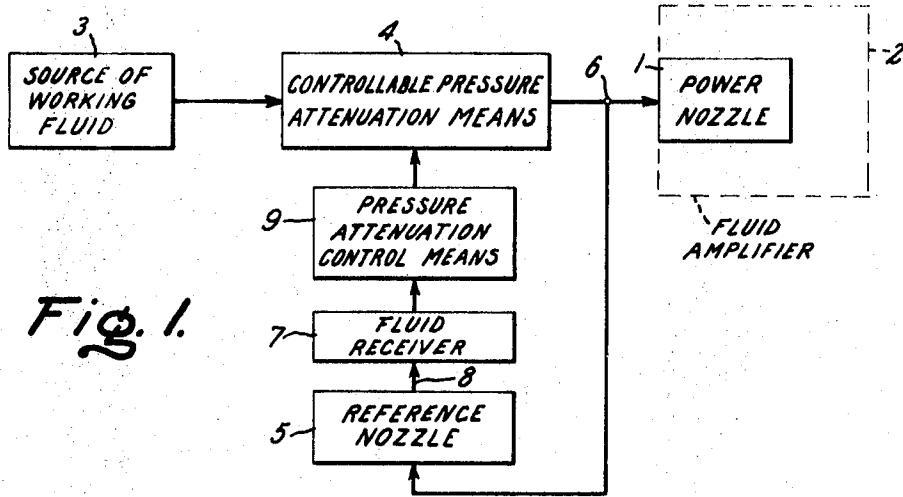


Fig. 1.

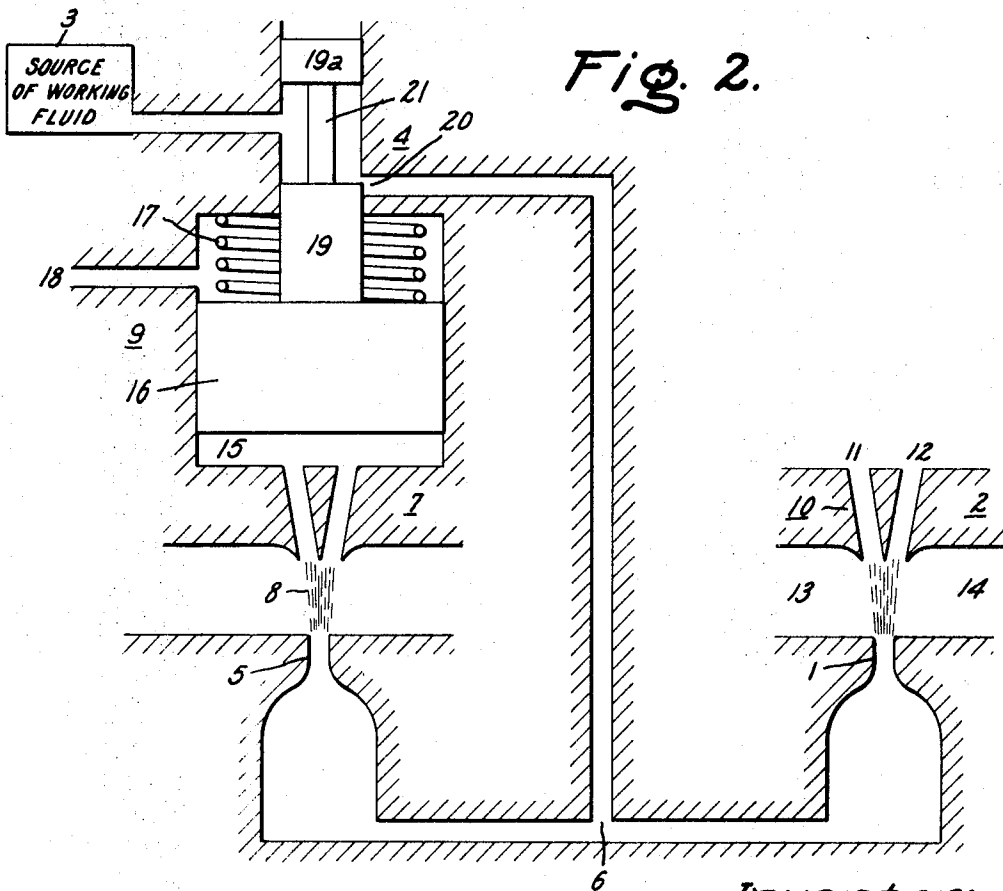
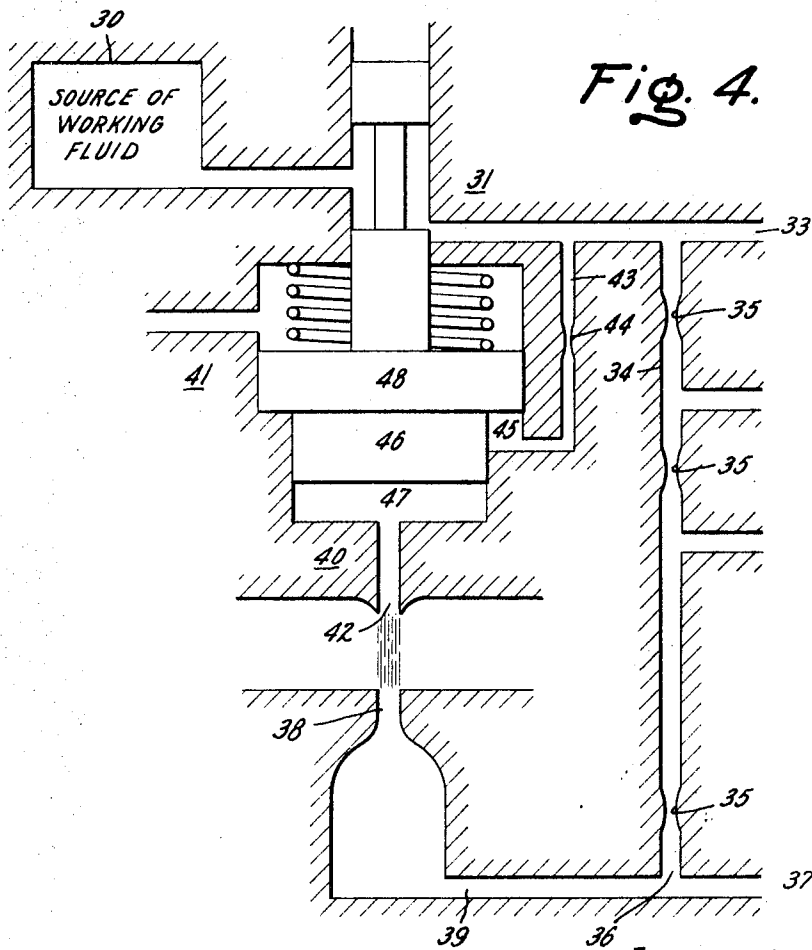
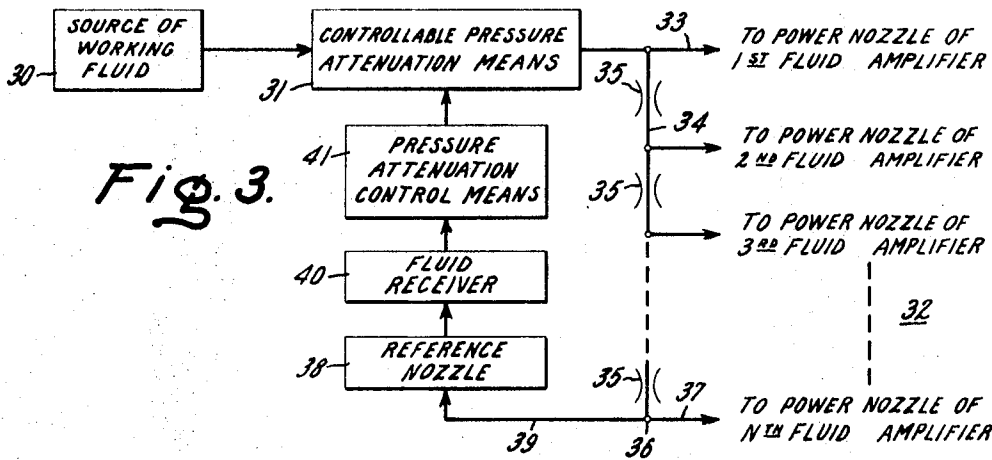


Fig. 2.

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Fig. 5.

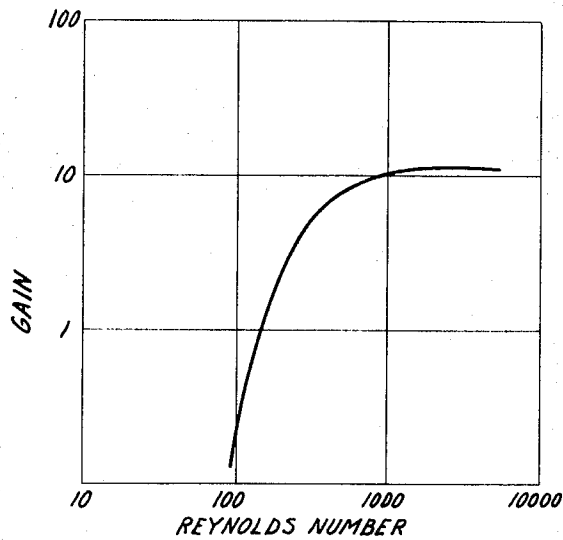
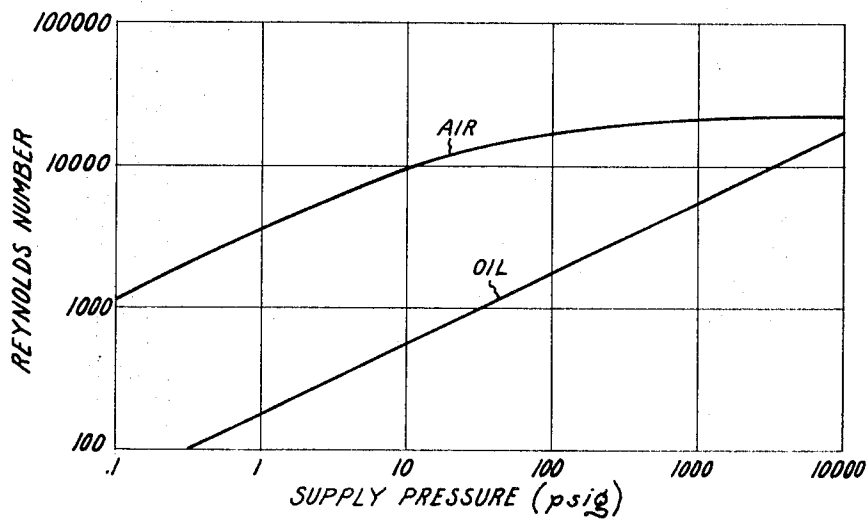


Fig. 6.



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METHOD AND APPARATUS FOR REYNOLDS NUMBER COMPENSATION OF WORKING FLUID SUPPLIED TO FLUID AMPLIFIER

This invention relates to fluid operated control devices and, more particularly, to a fluid operated gain control device for maintaining at a substantially constant value the Reynolds Number associated with a working fluid supplied to fluid amplifiers.

A vast majority of prior art fluidic devices and fluidic systems have been strictly pneumatic in nature, designed to incorporate air or some other gas as a working fluid. However, many of the military and industrial applications suited to fluidic control employ hydraulic rather than pneumatic actuators for the final control elements.

Two fundamental design approaches are available to the fluidic engineer restrained to the use of hydraulic actuators as ultimate control elements. The first is to provide a pneumatic control system, i.e., a system of fluidic elements which utilize a gaseous working fluid, and to couple the outputs from this pneumatic control system through pneumo/hydraulic valve interfaces to hydraulic actuators. The second approach is to provide an integrated system wherein both the fluidic control elements and the final actuators operate on a common hydraulic working fluid, such as oil or, where feasible, water. The integrated hydraulic approach is clearly preferable in high-power applications, since costly and often unreliable pneumo/hydraulic interfaces may be eliminated and fluidic control circuitry may be accordingly simplified.

Although many of the basic concepts of fluidics are equally applicable to both gas and liquid operation, there are also important differences between the two modes of operation due to the radically different physical properties which characterize the fluids involved. The typical liquid used in hydraulic fluidic systems, e.g., MIL-H-5606 red oil, compared with air, is of higher density and viscosity but of much lower compressibility. Table I (below) summarizes the key physical characteristics of these two fluids at 40° C.:

TABLE I

Fluid property	Air	Oil (MIL-H-5606)
ρ = Density, lb./in. ³	4.0×10^{-5}	3.1×10^{-2}
μ = Viscosity, lb./in.-sec.	9.2×10^{-7}	6.7×10^{-4}
$C_r = \frac{\mu}{\sqrt{\rho}}$ Reynolds coefficient,		
(in.-lb.) ^{1/2} /sec.	1.5×10^{-4}	3.7×10^{-3}
B = Bulk modulus (p.s.i.)	127.6	25×10^4

¹ At 5 p.s.i.g. adiabatic compression.

Table II (below) summarizes the direction in which various parameters associated with a hydraulic system, including proportional fluid amplifier gain, vary in relation to each other when other parameters are held constant.

TABLE II

Characteristic	Pressure	Temperature	Reynolds Number
Viscosity	Relatively independent.	Inverse	Inverse.
Reynolds Number	Direct	Direct	
Amplifier gain	do*	do*	Direct.*

*Up to a limit beyond which there is little effect (see FIGURE 5).

It has been found that one of the most critical factors in the operation of proportional fluid amplifiers of the hydraulic type is Reynolds Number variation. The gain of any particular hydraulic fluid amplifier, operating in the lower range of supply pressures, is far more sensitive to Reynolds Number changes than is an equivalent device which incorporates air as a working fluid.

In many hydraulic systems, the hydraulic oil is exposed to a wide range of temperatures. Accordingly, the viscosity and Reynolds Number of the oil will, unlike air, vary drastically at normal operating pressures. If an amplifier is operated at a fixed supply pressure, this means that Reynolds Number, and thus gain, will decrease as the oil temperature drops. If a supply pressure is set at a sufficiently high value to avoid this Reynolds Number problem at low temperatures, then, during normal operation at higher temperatures, power consumption

will be excessive and the noise level may be raised to a prohibitive level.

While it would be possible to correct for the temperature sensitivity of hydraulic fluid amplifiers by controlling the temperature of the hydraulic oil, such an approach would be both difficult and expensive to implement and could be used only for a single hydraulic fluid.

Rather than compensating for temperature changes in hydraulic oil, the present invention detects and compensates for pressure recovery changes as they occur in hydraulic fluid amplifiers. By increasing (or decreasing) the supply pressure to an amplifier in response to a lowering (or raising) of the Reynolds Number of the hydraulic oil, the gain of the amplifier may be maintained at a substantially constant level, even though operated over a wide range of temperatures and at relatively low supply pressures.

Accordingly, it is a primary object of this invention to provide a device for automatically regulating the supply pressure to a fluid amplifier in order to compensate for gain changes caused by increases or decreases in the pressure, viscosity, or Reynolds Number associated with the working fluid.

Another object of this invention is to provide a device for automatically pressure regulating the gain of a fluid amplifier, which device will be operative in various hydraulic systems incorporating many different kinds of working fluids.

Another object of this invention is to provide a device for automatically regulating the gain of a fluid amplifier which device is capable of being set to maintain a desired gain level.

Another object of this invention is to provide a device for automatically regulating the gain of a plurality of fluid amplifiers, which device is responsive to Reynolds Number related gain changes occurring in the most sensitive amplifier in the plurality of amplifiers.

In one embodiment of the invention a variable area valve is connected between a source of working fluid and the power nozzle of a proportional fluid amplifier. The gate of the variable area valve is moved in direct response to pressure changes detected in a fluid jet issuing from a reference nozzle which is physically identical to the power nozzle of the fluid amplifier and which is connected in fluid parallel therewith. Any increase or decrease in the Reynolds Number, viscosity, or pressure of the hydraulic fluid supplied to the power nozzle of the fluid amplifier will result in a corresponding change in the gain of the fluid amplifier. Because the reference nozzle is identical to, and connected in fluid parallel with, the power nozzle of the fluid amplifier, pressure changes detected in the reference jet are directly indicative of any increase or decrease in amplifier gain and serve as a precise source of fluid control signals for the regulation of the variable area valve and thus the pressure of the hydraulic fluid which is supplied to, and determines the gain of, the fluid amplifier.

The invention is pointed out with particularity in the appended claims; however, other objects and advantages, together with the operation of the invention may be better understood by reference to the following detailed description taken in conjunction with the drawings wherein:

FIG. 1 shows a generalized block diagram illustrating the basic interrelationship of various elements comprising a first embodiment of the invention.

FIG. 2 shows in detail the various elements comprising the embodiment of the invention shown generally in FIG. 1.

FIG. 3 shows a generalized block diagram illustrating the basic interrelationship of various elements comprising a second embodiment of the invention.

FIG. 4 shows in detail the various elements comprising the second embodiment of the invention.

FIG. 5 shows the relationship between the Reynolds

Number associated with a hydraulic working fluid and the gain of a proportional fluid amplifier.

FIG. 6 shows the relationship between the Reynolds Number associated with a hydraulic working fluid and the pressure under which the hydraulic working fluid is supplied to a proportional fluid amplifier.

Referring to FIG. 1, the power nozzle 1 of a fluid amplifier 2 is supplied with pressurized working fluid from a source of working fluid 3 through a controllable pressure attenuation means 4. For the purpose of the embodiments set forth herein, it will be assumed that the working fluid is a hydraulic oil, such as MIL-H-5606 red oil, although any other suitable working fluid might be used. A reference nozzle 5 is connected so as to receive a supply of working fluid from a point 6 which is in common fluid communication with power nozzle 1. The reference nozzle 5 has physical characteristics substantially identical to the physical characteristics of power nozzle 1. It is important that the physical characteristics of the two nozzles be as closely identical as possible since it has been found that, due to the different frictional forces associated with unlike nozzle geometries, the recovery pressures associated with fluid jets issuing from substantially different nozzles tend to vary as different functions of Reynolds Number and viscosity.

Fluid receiver 7 intercepts fluid jet 8 after it has issued from reference nozzle 5, and directs the flow thereof into pressure attenuation control means 9. Pressure attenuation control means 9 provides control signals directly related to the recovery pressure associated with fluid jet 8, as detected at the output of fluid receiver 7. These control signals are supplied to controllable pressure attenuation means 4. Controllable pressure attenuation means 4 varies the ratio (output/input) between the pressure of the working fluid as supplied to point 6 fluid and the pressure of the working fluid as received from the source of working fluid 3 in inverse response to the magnitude of the control signals received from pressure attenuation control means 9.

Because the reference nozzle 5 directly simulates any pressure changes, and thus gain changes, which may occur in fluid amplifier 2, the recovery pressure at the output of fluid receiver 7 is directly related to the recovery pressure of fluid amplifier 2. Thus, for example, when the ambient temperature drops, causing the Reynolds Number associated with the working fluid to decrease, the gain of fluid amplifier 2 will also decrease, as indicated in FIG. 5. This decrease in gain is manifested in a proportionately lower recovery pressure at the output of fluid amplifier 2 and, accordingly, at the output of fluid receiver 7. By virtue of this lower pressure detected by pressure attenuation control means 9 at the output of fluid receiver 7, control signals are supplied to controllable controllable pressure attenuation means 4, which, in response thereto, increases the pressure of the working fluid supplied to point 6, thus increasing the Reynolds Number associated with the working fluid as supplied to fluid amplifier 2 (see FIG. 6) and thus the gain of the fluid amplifier 2 (see FIG. 5).

The nozzle dimension of the particular proportional amplifier which forms the basis for graphs of FIGS. 5 and 6 was 0.020×0.020 inch and the hydraulic fluid employed was MIL-H-5606. As may be seen in FIG. 5, the gain of the proportional fluid amplifier starts to decrease below Reynolds Numbers of approximately 1,000, and becomes unity at a Reynolds Number of approximately 150. The amplifier is actually an attenuator of signals when operated at Reynolds Numbers below 150. The amplifier data for FIG. 5 was obtained under blocked load conditions.

Referring to FIG. 6 it can be seen that it would be necessary to operate such an amplifier at supply pressures in excess of 30 p.s.i.g. in order to maintain a Reynolds Number of at least 1,000 which is the minimum value at which operation independent of Reynolds Number may be achieved (see FIG. 5). FIG. 6 also illustrates the Reynolds Number versus supply pressure characteristics for perfectly expanded air, i.e., the characteristics of a pneumatic amplifier.

Since element 4 is a pressure attenuator, the pressure sup-

plied to the power nozzle 1 of fluid amplifier 2 (i.e., the pressure at point 6) can never be higher than the pressure of the working fluid source 3. Assuming the sources of working fluid 3 to be at a substantially constant pressure, increasing the pressure of the working fluid at point 6 increases the output/input ratio associated with the controllable pressure attenuation means 4. Conversely, decreasing the pressure of the working fluid at point 6 serves to decrease this output/input ratio. While the magnitude of the control signals from pressure attenuation control means 9 varies directly as the recovery pressure detected at the output of fluid receiver 7 (and thus the gain of fluid amplifier 2), it is necessary that controllable pressure attenuation means 4 vary the magnitude of the pressure associated with the working fluid at point 6 in inverse response to the magnitude of the control signals.

In FIG. 2, the fluid amplifier 2 is shown to be comprised of power nozzle 1, fluid receiver 10, output ports 11 and 12, and drains 13 and 14. The gain of fluid amplifier 2 is obtained in any conventional manner such as by the use of opposed control nozzles (not shown) for issuing control jets of fluid for deflecting the fluid jet issuing from nozzle 1 relative to ports 11 and 12. The reference nozzle 5 is shown to be substantially identical to the power nozzle of fluid amplifier 2. No control nozzles are associated with reference nozzle 5. The fluid jet 8 is shown issuing from reference nozzle 5 to fluid receiver 7, which has a geometry substantially the same as fluid receiver 10 of fluid amplifier 2. The recovery pressure at the output of fluid receiver 7, that is, passages thereof shown in FIG. 2, is detected in chamber 15 by pressure attenuation control means 9. Pressure attenuation control means 9 comprises chamber 15, piston 16, bias spring 17, and drain 18. Motion induced in piston 16 by changes in recovery pressure in chamber 15 is translated via a rigid mechanical linkage, or piston, 19 to controllable pressure attenuation means 4.

In this embodiment of the invention, controllable pressure attenuation means 4 operates as a variable area fluid valve. Movement of the upper edge of piston 19 upwardly across output port 20 as a result of increased pressure detected by the pressure attenuation control means 9 serves to decrease the effective area through which the working fluid may flow from source 3 to point 6, thus decreasing the pressure at point 6 and decreasing the output/input pressure ratio between the pressure of the source of working fluid 3.

Since the pressure at point 6 may in no case exceed the pressure of source 3, it is desirable to bias the piston 19 so that some intermediate valve area will correspond to the desired gain level to be achieved in fluid amplifier 2. In FIG. 2, bias spring 17 is shown as a means for biasing piston 19 to this desired position. It will be obvious to one skilled in the art that the biasing force exerted by spring 17 against the upper portion of piston 16 may be adjusted by a control screw (not shown) or some equivalent device, thereby providing an adjustment for determining the gain level of fluid amplifier 2.

A loss of gain in fluid amplifier 2 (which may be related to a change in the Reynolds Number or viscosity of the working fluid) will be directly reflected in a lowering of the recovery pressure at output ports 11 and 12 of receiver 10, and correspondingly, in a lowering of the recovery pressure detected in chamber 15 at the output of fluid receiver 7. As the recovery pressure in chamber 15 drops, the force exerted by piston 16 against bias spring 17 is proportionately decreased, causing downward motion in the piston 16. This motion is directly transmitted to controllable pressure attenuation means 4 via piston 19. The effective area at output port 20 is increased in proportion to the downward movement of pistons 16 and 19, thus causing an increase in the pressure of the working fluid at point 6 and thus an increase in the gain of fluid amplifier 2 sufficient to compensate for the Reynolds Number or viscosity related to the loss of gain.

Conversely, when the gain of fluid amplifier 2 increases due to changes in the Reynolds Number or viscosity of the working fluid, the recovery pressure in chamber 15 is correspondingly increased, by virtue of the structural identity between power nozzle 1 and reference nozzle 5. With the increased pressure

in chamber 15, piston 16 moves upwardly against the force of bias spring 17, causing the upper edge of piston 19 to move proportionately across output port 20, thereby decreasing the effective area of output port 20. As the effective area at output port 20 decreases, so does the pressure of the working fluid at point 6 and the gain of fluid amplifier 2. When the gain of fluid amplifier 2 has been returned to its desired value, the recovery pressure in chamber 15, acting on piston 16 and thus against bias spring 17, will have returned the pressure attenuation control means 9 to its predetermined position of equilibrium.

It will be realized that by connecting a piston 19a, having a cross-sectional area identical to that of piston 19, to piston 19 by means of a rod 21, any downward force exerted on piston 19 by the working fluid passing from source 3 will be counteracted by an identical force acting upward on piston 19a.

In the embodiment of the invention shown in FIG. 3, a source of working fluid 30 supplies a hydraulic oil (such as MIL-H-5606) through a controllable pressure attenuation means 31 to the power nozzles of a plurality of fluid amplifiers 32. The power nozzle of a first fluid amplifier is connected to the output of the controllable pressure attenuation means via fluid line 33. The power nozzle of a second fluid amplifier, whose desired gain level is lower than that of the first fluid amplifier, is connected to the output of controllable pressure attenuation means 31 through conduit 34 which includes a restrictor 35. Similarly, any number of progressively lower gain amplifiers or groups thereof may be connected to controllable pressure attenuation means 31 through a continuation of conduit 34 containing additional series restrictors, a restrictor 35 being disposed between each adjacent pair of fluid amplifiers.

In FIG. 3 the power nozzle of the Nth fluid amplifier is coupled to a common point 36 via a fluid passage 37. Since the power nozzle of the Nth fluid amplifier is coupled to the output of controllable pressure attenuation means through a total of N-1 restrictors, its gain will be the lowest of any of the amplifiers in the plurality of amplifiers 32. Accordingly, as can be seen from FIG. 5, the gain of the Nth fluid amplifier will be more sensitive to changes in the Reynolds Number of the working fluid than any other of the fluid amplifiers in the plurality of fluid amplifier 32. For this reason, the input to reference nozzle 38 is connected via fluid line 39 to common point 36. Reference nozzle 38 is constructed to have physical characteristics substantially identical to the physical characteristics of the power nozzle of the Nth fluid amplifier, so that pressure changes in the fluid jet issuing from the power nozzle of the Nth fluid amplifier will be simulated by pressure changes in the fluid jet issuing from the reference nozzle. Furthermore, the recovery pressure detected at the output of fluid receiver 40 will correspond directly to the recovery pressure at the output ports of the Nth fluid amplifier.

In the embodiment of the invention shown in FIG. 3, pressure attenuation control means 41 detects changes in the recovery pressure at the output of fluid receiver 40 and produces control signals related thereto for transmission to controllable pressure attenuation means 31, substantially in the manner described in conjunction with the embodiment of the invention shown in FIG. 1.

As is evident from FIG. 4, the operation of this embodiment of the invention is identical to the operation of the invention as shown in FIG. 2, except that the input to the critical Nth fluid fluid amplifier is separated from the output of controllable pressure attenuation means 31 by a plurality of restrictors 35. The input 42 to fluid receiver 40 is of a somewhat different configuration from the input to fluid receiver 7 in FIG. 2, indicating that a variety of configurations might be incorporated so long as the frictional forces, to which the fluid jet issuing from the reference nozzle is exposed, are substantially the same as the frictional forces to which the fluid jet issuing from the power nozzle of the critical fluid amplifier is exposed. Also in FIG. 4, a feedback conduit 43 containing restrictor 44 is shown connecting the output of controllable pressure attenuation means 31 to a second chamber 45, which is separated by

piston 46 from recovery pressure chamber 47. By properly selecting restrictor 44, the pressure exerted on piston 48 by the working fluid fed back to chamber 45 will serve to damp out transient effects and will provide for a faster response in the case of severe or radical changes in the physical properties of the working fluid as supplied to the plurality of fluid amplifiers. It will also serve to close off attenuation means 31 when pressure 33 exceeds limits established by spring preload and area of chamber 45.

While specific embodiments of this invention have been shown and described, it is not intended that the invention be limited to the particular forms shown and described. It is intended, by the appended claims, to cover all modifications within the spirit and scope of this invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

I claim:

1. A fluid operated gain control device arranged for connection to a source of working fluid comprising:
 - a pure fluid amplifier including a power nozzle;
 - a reference nozzle having physical characteristics substantially identical to the physical characteristics of said power nozzle;
 - said nozzles being connected to receive a common supply of the working fluid; and
 - means responsive to changes in pressure of fluid discharged from said reference nozzle for varying inversely the pressure of the fluid supplied to said fluid amplifier.
2. The device of claim 1 wherein said working fluid is a liquid.
3. The device of claim 1 wherein said means comprises controllable pressure attenuation means having an input port in fluid communication with the source of working fluid and an output port in fluid communication with said power nozzle, said controllable pressure attenuation means being actuated in response to changes in pressure at said reference nozzle to vary inversely the pressure at said output port.
4. The device of claim 2 wherein said controllable pressure attenuation means comprises a variable area fluid valve.
5. A fluid operated gain control device arranged for connection to a source of working fluid comprising:
 - a pure fluid amplifier including a power nozzle;
 - a reference nozzle having physical characteristics substantially identical to the physical characteristics of said power nozzle;
 - said nozzles being connected to receive a common supply of the working fluid;
 - fluid receiving means for intercepting the fluid jet issuing from said reference nozzle and directing the flow thereof through an output passage;
 - control means for detecting pressure changes at said output passage and generating control signals directly related to said pressure changes; and
 - controllable pressure attenuation means having an input port in fluid communication with the source of working fluid, and an output port in fluid communication with said power nozzle and said reference nozzle, said pressure attenuation means receiving said control signals to vary the pressure at said output port inversely to the pressure changes at said output passage.
6. The device of claim 5 wherein:
 - said control means includes a chamber connected to said output passage, a first piston movable in said chamber in response to changes in pressure at said output passage; and
 - said controllable pressure attenuation means includes a second piston movable by said first piston for varying the size of said output port.
7. A fluid operated gain control device for controllably regulating the pressure of working fluid supplied to a plurality of fluid amplifiers from a source of working fluid comprising:
 - a plurality of pure fluid amplifiers, each of said amplifiers having a power nozzle;
 - a reference nozzle having physical characteristics substan-

tially identical to the physical characteristics of the power nozzle of a selected one of said fluid amplifiers;
said reference nozzle and said power nozzle of said selected fluid amplifier being connected to receive a common supply of working fluid; and

means responsive to changes in pressure of fluid discharged from said reference nozzle for varying inversely the pressure of the fluid supplied to said fluid amplifiers.

8. The device of claim 7 wherein said means comprises controllable pressure attenuation means having an input port in fluid communication with the source of working fluid and an output port in fluid communication with said plurality of fluid amplifiers and with said reference nozzle, said controllable pressure attenuation means being actuated in response to changes in pressure at said reference nozzle to vary inversely the pressure at said output port.

9. The device of claim 8 wherein said controllable pressure attenuation means comprises a variable area fluid valve.

10. The device of claim 8 and further including:

a conduit providing communication from said output port to said fluid amplifiers, said fluid amplifiers being connected to said conduit at intervals therealong;

said conduit including a plurality of restrictors, one of said restrictors being disposed between each adjacent pair of said fluid amplifiers whereby the pressure at each successive fluid amplifier is less than that of the preceding fluid amplifier; and

said selected fluid amplifier being the last of said successive fluid amplifiers whereby said selected fluid amplifier is operated at the lowest pressure of all of said fluid amplifiers.

11. A fluid operated gain control device for controllably regulating the pressure of a working fluid supplied to a plurality of fluid amplifiers from a source of working fluid comprising:

a plurality of pure fluid amplifiers, each of said fluid amplifiers having a power nozzle;

a reference nozzle having physical characteristics substantially identical to the physical characteristics of the power nozzle of a selected one of said amplifiers;

said reference nozzle and the power nozzle of said selected fluid amplifier being connected to receive a common supply of working fluid;

fluid receiving means for intercepting the fluid jet issuing from said reference nozzle and directing the flow thereof

through an output passage;

control means for detecting pressure changes at said output passage and generating control signals directly related to said pressure changes;

controllable pressure attenuation means having an input port in fluid communication with the source of working fluid and an output port in fluid communication with said fluid amplifiers and with said reference nozzle, said pressure attenuation means receiving said control signals to vary the pressure at said output port inversely to the pressure changes at said output passage;

a conduit providing communication from said output port to said fluid amplifiers, said fluid amplifiers being connected to said conduit at intervals therealong, said conduit including a plurality of restrictors, one of said restrictors being disposed between each adjacent pair of said fluid amplifiers whereby the pressure of each successive fluid amplifier is less than that of the preceding fluid amplifier; and

said selected fluid amplifier being the last of said successive fluid amplifiers whereby said selected fluid amplifier is operated at the lowest pressure of all of said fluid amplifiers.

12. The device of claim 11 wherein:

said control means includes a chamber connected to said output passage, a first piston movable in said chamber in response to changes in pressure at said output passage;

said controllable attenuation means includes a second piston movable by said first piston for varying the size of said output port;

said control means further includes a second chamber and a third piston connected to said first piston and movable in said second chamber; and

a feedback conduit having a restrictor therein and providing fluid communication between said output port and said second chamber for damping transient effects.

13. A method for Reynolds Number Compensation of working fluid supplied to a pure fluid amplifier comprising:

connecting a variable area valve between a source of working fluid and the power nozzle of a hydraulic fluid amplifier; and

controlling the flow area of the valve in inverse response to pressure changes detected in a fluid jet issuing from a reference nozzle connected in fluid parallel with the power nozzle.

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