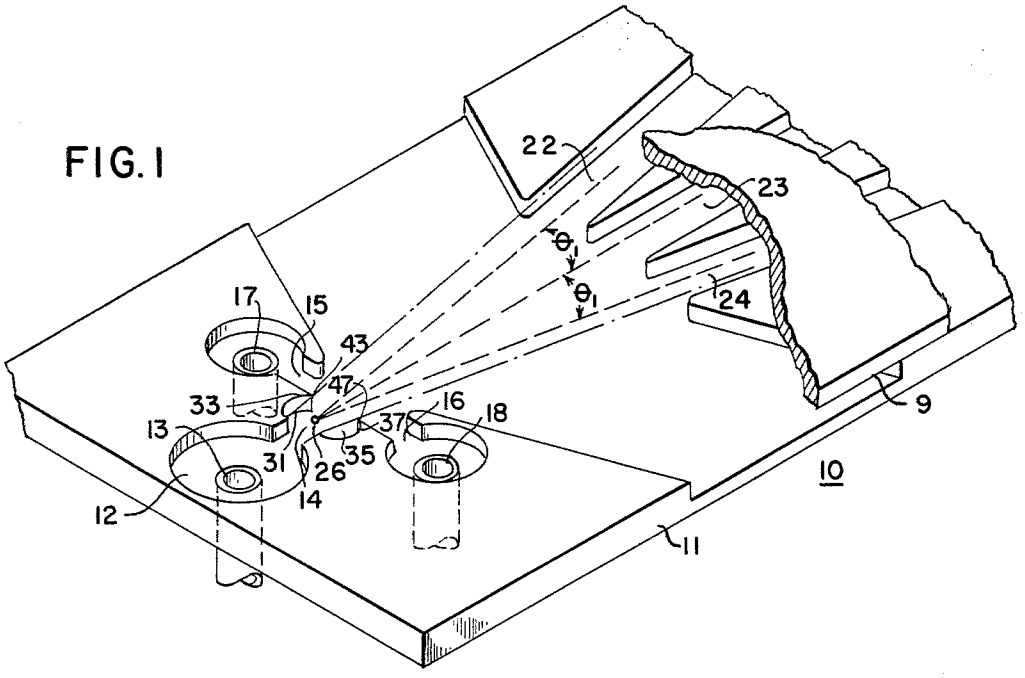
March 15, 1966 C. H. T. PAN 3,240,221

FLUID AMPLIFIERS

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FIG. 1



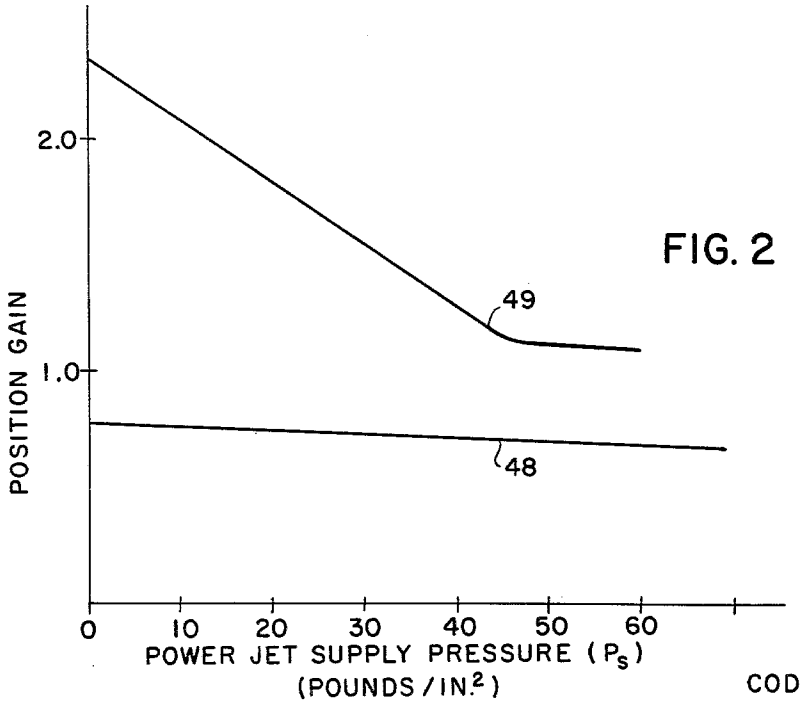




FIG. 2


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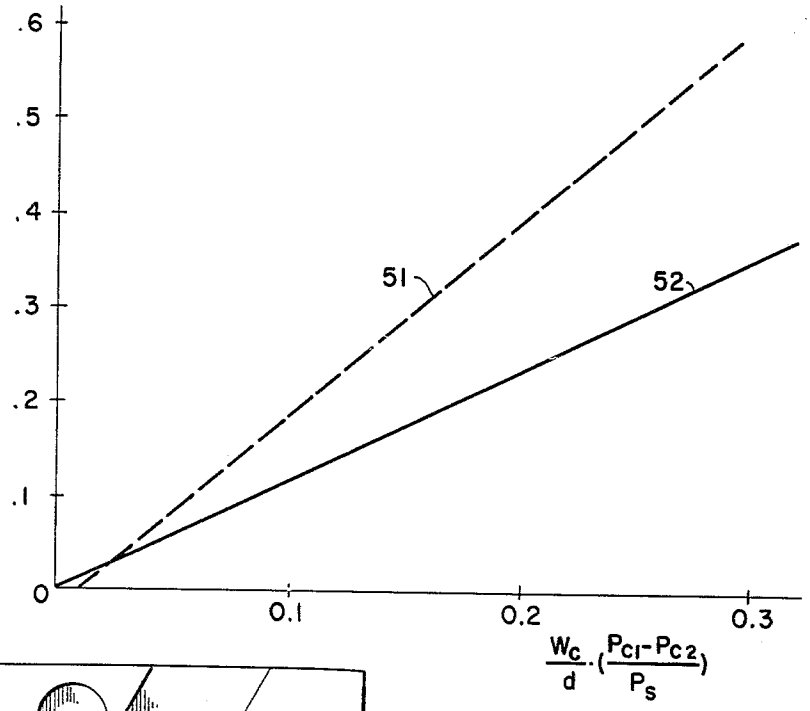
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FLUID AMPLIFIERS

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FIG. 3



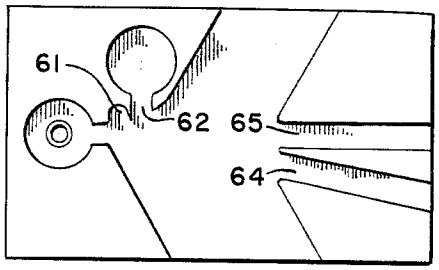
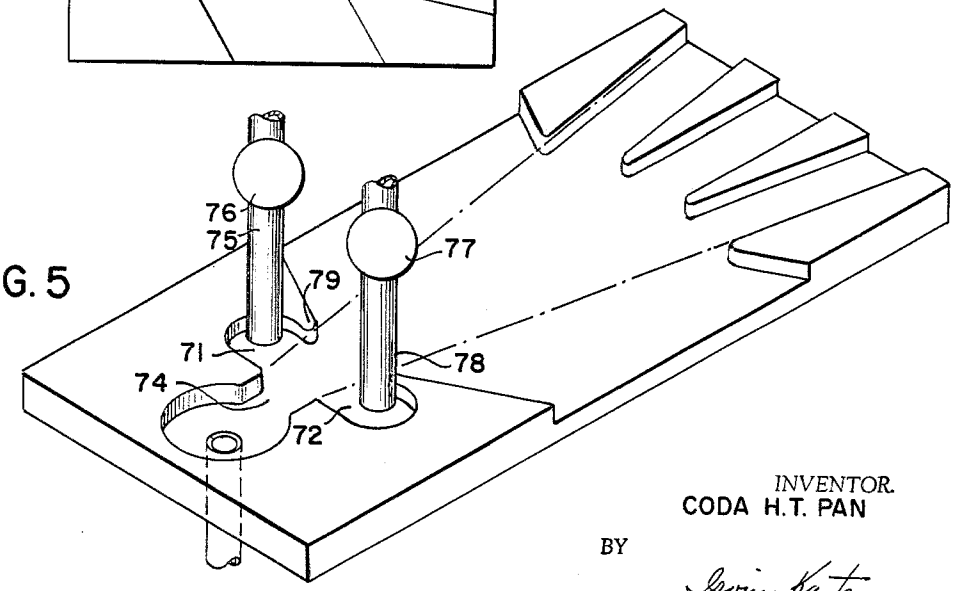




FIG. 4

FIG. 5




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United States Patent Office 3,240,221
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3,240,221

# FLUID AMPLIFIERS

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Filed May 8, 1963, Ser. No. 278,887
10 Claims. (Cl. 137—81.5)

This invention relates to fluid control devices and has particular relation to digital and analog type fluid amplifiers.

Fluid amplifiers have the potential for wide application in various fields due primarily to their reliability, temperature insensitivity, shock resistance, and ease of fabrication. These devices may be employed as digital and analog computing elements and also as power devices to operate valves and the like. Fluid amplifiers may be operated as pneumatic devices employing a compressible fluid, such as gas or air, or as hydraulic devices utilizing an incompressible fluid, such as water or oil.

One of the two basic types of fluid amplifiers is of the momentum exchange type wherein a main or power fluid jet is deflected by one or more control jets directed laterally at the power jet from opposite sides thereof. The power jet is normally directed midway between two fluid receivers, channels or apertures, and is deflected relative to the receivers by an amount proportional to the net sideways momentum of the control jets. This device is therefore often referred to as a proportional or analog device.

In the case of the analog fluid amplifier, the amount of amplification is determined by the magnitude of angular deflection of the power jet from its central position, and the gain of the amplifier is a function of the ratio of this angular deflection to the differential momentum provided by the difference in pressure between the two control jets. It follows, therefore, that the greater the angular deflection of the power jet for a fixed amount of differential momentum, the greater the gain.

It is, therefore, an object of the present invention to provide a fluid amplifier embodying improved means for the control thereof.

It is an important object of the present invention to provide an analog type fluid amplifier providing greater gain than has heretofore been possible in such analog devices.

It is another object of this invention to provide an analog fluid amplifier with enhanced gain obtained in a fluid amplifier having a simple structural geometry.

The above objects are accomplished in accordance with the principles of the invention by providing a cavity, chamber or recess in the side wall located between the source of the power jet and the control jet port. The cavity or recess, at one end thereof, provides a partition or cusp formed by the juncture of the wall of the control port and the wall of the cavity or recess, the cavity itself being concave toward the region of power jet flow.

With a cavity of this type on each side of the power jet flow and between the control jet ports and the power jet source, there is provided effective means for enhancing the angular deflection of the power jet with the application of a puressure differential between control jets. In the neutral or null position wherein the pressure of the two control jets is the same, the power jet continues along its centrally directed path. With increased pressure from one of either side, the power jet is deflected toward the other side and commences forming a vacuum in the cavity on that side. The decrease in pressure in this cavity tends to pull the power jet even closer, thereby increasing the angular deflection of the power jet over what would have been the case had the cavity not been present.

In the prior art analog fluid amplifiers, the angular deflection bears a desirably linear relationship to the differential in momentum between the control jets. It is an important feature of this invention, that this linear relationship is maintained over a wide operating range, even though the gain provided in accordance with the principles of the invention is greatly increased over that of the prior art. Thus, in accordance with the invention, desirable operating characteristics of the analog fluid amplifier of the prior art are not disturbed, while gain is enhanced.



In the analog fluid amplifier, when the cavity is positioned sufficiently close to the path of the power jet, the application of a control jet differential pressure sufficiently great to deflect the power jet by a large angle may result in providing a vacuum sufficiently great in the cavity to cause the jet to latch to that side. Thus, when the pressure differential is removed, the power jet may stay deflected to that side, due solely to the cavity vacuum. Therefore, by a proper relationship between cavity and power jet parameters in the analog fluid amplifier, a latching action at a particular threshold of control jet differential may be obtained.

The analog fluid amplifier previously mentioned is a dual polarity type device in that deflection from the center to one side may be considered a positive signal, while deflection to the other side may be considered a negative signal. In another embodiment of the invention, a single polarity analog fluid amplifier is provided with a control jet and a cavity solely on one side. In such an arrangement, the cavity provides the salutary effect of more quickly restoring the deflected signal to its central or null position upon the removal of the control jet signal.

The second of the two basic types of fluid amplifiers is of the boundary layer effect type. In this device power jet deflection is effected by the side walls of an interaction chamber which are shaped in such a way that the power jet will attach to one or the other of the side walls but not to both side walls. This is brought about by the entrainment action of the power jet wherein the power jet tends to entrain air trapped between it and an adjacent side wall, the entrainment becoming more effective as the power jet approaches the adjacent side wall. This type of amplifier is basically a two position device and for this reason is generally referred to as a digital device. The binary fluid amplifier of the prior art therefore requires the use of one or more control jets to obtain the binary digital switching action.

In another embodiment digital switching is provided without control jets by employing a digital fluid amplifier having a power jet source and two side recesses or cavities similar to the ones previously mentioned with respect to the analog fluid amplifier. Thus, there is a cavity in each of the two walls on opposite sides of the power jet and concave towards the power jet, but the device has no control jet ports at all. Each of the cavities has a vent which may be either open or closed. With both cavity vents open, the power jet proceeds along its centrally directed path in its null or undeflected condition. This is because the vacuum type of action of the power jet relative to the cavities is nullified by flow out the vents from the two cavities. With one of the vents closed, however, a vacuum pump action takes place in that cavity, while the vented cavity does not have such an action. Accordingly, the vacuum built up in the cavity with the closed vent tends to draw the power jet toward it and provides a new type of latching action. Digital operation is thus provided by selectively opening and closing the vents to the cavities.

In the discussion hereinafter, the term "boost cavity" will be used for the cavities, recesses, or chambers which enhance the gain of the analog fluid amplifier or provide the latching action described for the digital device, in accordance with the principles of the invention.

The novel features believed to be characteristic of this invention are set forth with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings.

In the drawings:

FIG. 1 is a diagrammatic view in perspective illustrating a fluid amplifier including boost cavities in accordance with the principles of the invention;

FIGS. 2 and 3 are graphical representations of certain characteristics of the fluid amplifier of FIG. 1;

FIG. 4 is a plan view of a variant form of the fluid amplifier of FIG. 1; and

FIG. 5 is a diagrammatic view in perspective illustrating a digital fluid amplifier embodiment constructed according to the invention.

Referring now to the drawings in greater detail, there is illustrated in FIG. 1 an embodiment of the invention, given by way of example, in the form of an analog type fluid amplifier represented generally by the numeral **10**. The device **10** is diagrammatically shown in FIG. 1 as including a plate **11** formed of suitable material, such as metal, plastic or the like, which is slotted in a special configuration to provide passages for fluid. The various slots in the plate **11** may be formed in any suitable manner and may extend entirely through the plate or may be of lesser depth as desired. In the illustrated embodiment, the slots in the plate **11** are shown extending only partially therethrough.

The plate includes a main opening **12** into which extends a conduit or passage **13** which carries pressurized fluid into the opening **12**, it being understood that suitable enclosure such as a covering plate **9** is positioned on top side of plate **11** to confine fluid to the various slots of the plate **11**. The fluid utilized in the control device may assume a variety of forms. For example, the fluid may constitute a compressible fluid, such as air, to provide a pneumatic device. As a further example, the fluid may be incompressible, such as oil or water, to provide a hydraulic device.

Communicating with the opening **12** is a restricted slot **14** constituting a power nozzle from which issues a jet of fluid emanating from the conduit **13**. At a distance from the juncture of nozzle **14** and opening **12**, and on opposite sides of the centerline extension of nozzle **14**, are located a pair of slots **15** and **16** which may be designated control slots and into which extend conduits or passages **17** and **18** for introducing pressurized fluid into the control slots. The conduits **17** and **18** may be supplied with pressurized fluid in any suitable manner, such as from the same source which supplies the conduit **13** or from independent sources as desired. As is understood in the art, pressurized fluid in the control slots **15** and **16** cooperate upon a pressure differential basis to deflect the jet issuing from nozzle **14**.

In the illustrated embodiment, plate **11** is formed with two elongated diverging fluid receiving passages **22** and **24**, which selectively receive fluid of the power jet depending upon the direction and magnitude of angular deflection of the power jet. The passages or channels **22** and **24** are separated by a third channel **23**, whose centerline is a co-linear extension of that of nozzle **14**. The downstream end of receiver **23** may be vented to the atmosphere or may be employed to drive some useful load. A major portion of the power jet flow from nozzle **14** passes into and through receiver **23** when there is a null pressure differential between the control jets from slots **15** and **16**. When the pressure of the control jet from either of the two slots **15** or **16** is greater than that of the other, the power jet from nozzle **14** is deflected in the direction of the side wherein the control jet pressure is lower. The angular deflection $\theta$ of the power jet, with $\theta$ being measured from the centerline of slot **14** to the centerline of the deflected power jet, determines what portion of the power jet enters receiver **22** or **24** and what portion enters the null receiver **23**. When $\theta$ is at its magnitude $\theta_1$, there is alignment of the centerline of the jet with the centerline of receiver **22** or **24**, with little of the power jet exiting through the null receiver **23**. Thus, the portion of the power jet entering receiver **22** or **24** is a continuously variable analog signal proportional to the angle $\theta$, and therefore directly proportional to the control jet pressure differential.



The geometry and operating characteristics of the fluid amplifier of FIG. 1, as thus far described, is that of a conventional analog fluid amplifier. However, the amplifier of FIG. 1 is not conventional in the geometry of the walls between nozzle **14** and control slots **15** and **16**. Thus, directly between the constricted throat **14** and control port **15**, and forming the wall boundary therebetween, is a boost cavity **31**, or recess, having an arcuate configuration, which may be substantially semicircular, and oriented concave toward the path of the power jet. Cavity **31** formed in this manner is defined in part by a wall section **33** which constitutes a partition, septum or cusp formed between the walls of cavity **31** and control port **15**. Thus, the control jet issuing tion, septum or cusp formed between the walls of cavity **31**, or putting it another way, the cavity **31** is shielded from the effect of the control jet by septum **33**. On the other side of the power jet path the wall between control port **16** and throat **14** is similarly formed as a cavity or recess **35** with a similar septum **37**. The ends **43** and **47** of the septa **33** and **37** are spaced from each other and from the power jet boundary sufficiently so that the pressure in boost cavities **31** and **35** is approximately the same as the fluid pressure at the exit of control jet ports **15** and **16** when the power jet is in its null position and received mainly by null receiver **23**.

In operation, when the control jet pressure on one side is greater than that on the other, for example when the pressure from control port **15** is the greater, then the clearance between the boundary of the power jet on the right and cavity **35** is reduced. This results in a partial vacuum being created in boost cavity **35**, which in turn results in a larger effective control pressure differential, and therefore results in a larger deflection angle $\theta$ than would be the case had the boost cavity **35** not been there. Conversely, if the pressure from port **16** had been the greater, deflection would have been to the left toward boost cavity **31**, with a similar type of enhanced action in the opposite angular direction.

To more fully appreciate the gain enhancement provided by the boost cavities **31** and **35** in accordance with the principles of the invention, there are presented in FIG. 2 curves **48** and **49** which represent functions of the angular deflection for prior art fluid amplifiers and a fluid amplifier of the invention, respectively, at various power jet supply pressures. The ordinate of FIG. 2 is "position gain," which is a function of the power jet angular deflection normalized with respect to the variables of control pressure differential, and control port and power nozzle dimensions. More specifically, the ordinate is equal to:

$$\frac{\Delta \tan \theta}{\Delta[(P_{c1}-P_{c2})/P_s]\cdot\left(\frac{W_c}{d}\right)} \tag{1}$$

where $\theta$ is equal to power jet angular deflection, $P_{c1}$ and $P_{c2}$ are the control jet pressure, $P_s$ is power jet supply pressure, $W_c$ is the control jet port width, and $d$ is power jet nozzle width. The abscissa is power jet supply pressure. It may be seen from curve **49** that at supply pressure below 25 pounds per square inch, the gain of the fluid amplifier in accordance with the principles of the invention is more than twice the gain of the prior art analog fluid amplifiers. All pressures men-

tioned are gauge pressures, with the gauge reference being the pressure in the interaction chamber.

In FIG. 3, are shown curves **51** and **52** which represent the angular deflection obtained in a fluid amplifier in accordance with the invention, as a function of control jet pressure differential, and more specifically, as a function of:

$$\left(\frac{W_c}{d}\right)\cdot\frac{P_{c1}-P_{c2}}{P_s} \qquad (2)$$

Curves **51** and **52** are for power jets having supply pressure of 15 and 44 pounds per square inch, respectively. It may be noted that the relationship between angular deflection and control jet differential pressure is maintained substantially linear over a wide operating range.

In the construction of the fluid amplifier of FIG. 1, it is believed that certain relationships in the geometry of the amplifier should preferably be provided. Thus, for example, the distance of receivers **22**, **23** and **24** from the power jet nozzle **14** is preferably five to eight times the width $d$ of the power jet nozzle. The spacing of receivers **22** and **24** from the center line may be selected dependent upon whether pressure recovery or power recovery is of more importance. If pressure recovery is of main interest, then the idealized point location of the receiver from the power jet nozzle center line should be $0.6y_0$ where $y_0$ is the lateral distance from the jet axis to the point where the velocity of the power jet is half that of the velocity of the power jet at its center line. Where power recovery is of more interest, optimum power recovery is obtained with a receiver having a width equal to $2y_0$. Furthermore, with two receivers of this width spaced with each a distance $y_0$ from the center line, the resulting configuration provides the greatest power gain (but such an arrangement precludes a center receiver).

It may be noted from the curves of FIG. 2 that "position gain" is a function of power jet supply pressure, and that gain decreases with an increase in supply pressure. This is due in part to the fact that increased power jet supply pressure results in the pivot point **26** (FIG. 1), which effectively defines the point at which angular deflection $\theta$ commences, moving downstream. The greater the supply pressure, the greater the distance downstream that pivot point **26** is moved, and angular deflection decreases as a consequence.

In the analog fluid amplifier of FIG. 1, deflection of the power jet to the angle $\theta_1$ which provides a complete correspondence between the power jet and one of the receivers **22** or **24**, results in bringing the boundary of the power jet in intimate association with the boost cavity cusp. Accordingly, the vacuum within the boost cavity at that angular deflection is ordinarily sufficiently great such that when the pressure differential between the control jets is removed, the power jet remains fixed in its $\theta_1$ deflected position. Accordingly, the amplifier of FIG. 1 not only provides analog amplification but also provides a latching function in that when the control jet pressure differential reaches a particular threshold level, the jet remains latched to that side.

Referring to FIG. 4, there is shown a plan view of an analog type fluid amplifier of the same type as that of FIG. 1, except that solely one boost cavity **61** and control jet port **62** appear, and only one receiver **64** other than the null receiver **65** is provided. In the embodiment of FIG. 4, deflection is by a control jet from port **62** on the same side as the boost cavity **61** and accordingly, deflection of the power jet is away from boost cavity **61**. Removal of the control jet pressure results in the power jet resuming its null condition and exiting through receiver **65**. Due to the boost cavity **61** on the side toward which the deflected power jet returns, some vacuum is created in boost cavity **61** as the power jet is in the process of returning from its deflected position. This tends to increase the speed of return and tends to snap the jet back to the null position.

In the embodiment of FIG. 5, a digital fluid amplifier is represented in accordance with the principles of the invention. It may be noted that this digital device has a structure which varies from that of the analog device of FIGS. 1 and 4 in several respects. Thus, there are no control jet ports at all. The boost cavities **71** and **72** which are located adjacent the end of power jet nozzle **74** are substantially similar to those of FIG. 1. However, each of the boost cavities is ventable by a vent pipe as shown. Fluid flow through vent pipe **75** for cavity **71** is controlled by valve **76** which is preferably of the type that is normally fully open or closed and may be rapidly switched from one state to the other. A similar valve **77** is provided in the vent pipe **78** for the other boost cavity **72**.

In operation, closing of valve **76** while leaving valve **77** open results in vacuum pump action building up in cavity **71**, to thereby cause the power jet to deflect toward boost cavity **71**. This is a positive feedback type of action such that the deflection continues until the boundary layer of the power jet is in contact with the cusp **79** of boost cavity **71**. Accordingly, the power jet remains latched to that side. This provides one of the two binary switching positions for this binary type fluid amplifier. If it is desired to switch the power jet to the opposite side and therefore to the second of the binary positions, valve **76** for cavity **71** is opened while simultaneously, valve **77** for boost cavity **72** is closed. The conditions are thereby reversed. The vacuum that had been created in boost cavity **71** is broken, and pressure builds up, while vacuum pump action commences in boost cavity **72** because of the closed vent **77**. In this way, binary switching action is obtainable and flip-flop action is provided without the need for control jet ports and control jet supplies. Simple electromechanical switching means may be employed if desired for automatically actuating the vent valves for providing the desired switching action.

While the principles of the invention have now been made clear in illustrative embodiments, there will be immediately obvious to those skilled in the art many modifications in structure, arrangement, proportions, the elements, materials, and components, used in the practice of the invention, and otherwise, which are particularly adapted for specific environments and operating requirements, without departing from those principles. The appended claims are therefore intended to cover and embrace any such modifications, within the limits only of the true spirit and scope of the invention.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

**1.** A fluid amplifier comprising: a power jet nozzle for projecting a fluid power jet having a boundary layer; a plurality of fluid receiving means positioned downstream from said power jet nozzle; a control jet port adjacent said nozzle for directing a first fluid control jet at said power jet; and a concave recess in the wall formed between the wall forming said nozzle and the wall forming said port, the terminating points of said concave recess being positioned adjacent the boundary layer of said fluid power jet whereby a low pressure is formed in said concave recess to exert a force on said jet.

**2.** A fluid amplifier as recited in claim **1** wherein said recess is concave toward the path of said power jet.

**3.** A fluid amplifier as recited in claim **2** wherein the boundary forming said recess is arcuate in shape.

**4.** A fluid amplifier as recited in claim **2** wherein said concave recess has an end wall portion forming a cusp with an end wall portion of said control port.

**5.** A fluid amplifier as recited in claim **4** wherein said cusp is spaced a distance from the boundary layer of said power jet for all power jet supply pressures in the operating range of said fluid amplifier.

**6.** A fluid amplifier as recited in claim **1** including a

second control jet port on the opposite side of said power jet nozzle from said first control jet port; and a second concave recess in a wall formed between said nozzle and said second control jet port.

7. A fluid amplifier as recited in claim 6 wherein said second concave recess is concave toward the path of said power jet.

8. A fluid amplifier comprising: a power jet nozzle for projecting a fluid power jet having a boundary layer; a plurality of fluid receivers positioned downstream from said power jet nozzle; a control jet port adjacent said nozzle for directing a first fluid control jet at said power jet; and means comprising a cavity disposed between said nozzle and said port, said cavity having an opening adjacent to a portion of the boundary layer of said power jet for decreasing fluid pressure in a region contiguous to said portion of said boundary layer when said power jet is deflected from a given angular orientation.

9. A fluid amplifier comprising: a jet nozzle for projecting a jet of fluid along a path, said jet of fluid having a boundary layer; a plurality of fluid receiving means positioned downstream from said jet nozzle; and control means positioned adjacent said path and said boundary layer for varying the direction of said path, said control means comprising a control jet port adjacent said nozzle for directing a fluid control jet at said power jet and means defining a cavity having an opening adjacent said boundary layer, said cavity being positioned between said jet nozzle and said control jet port, said cavity producing, in response to the passage of said jet of fluid adjacent to said opening, a region of reduced fluid pressure contiguous to said boundary layer and including said cavity.

10. A fluid amplifier comprising: a jet nozzle for the projection of a jet of fluid along a path, said jet of fluid having a boundary layer; a plurality of fluid receiving means positioned downstream from said jet nozzle; and control means for changing the direction of said path, said control means comprising a control jet port adjacent said nozzle for directing a fluid control jet at said power jet and means defining at least one concave recess disposed adjacent the boundary layer of said jet of fluid for producing a reduction in fluid pressure in a region contiguous to said boundary layer and including said recess in response to the projection of said jet of fluid, said recess being positioned between said jet nozzle and said control jet port.

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