

March 17, 1970

O. L. WOOD

3,500,846

FLUID DEVICE

Filed Dec. 30, 1966

3 Sheets-Sheet 1

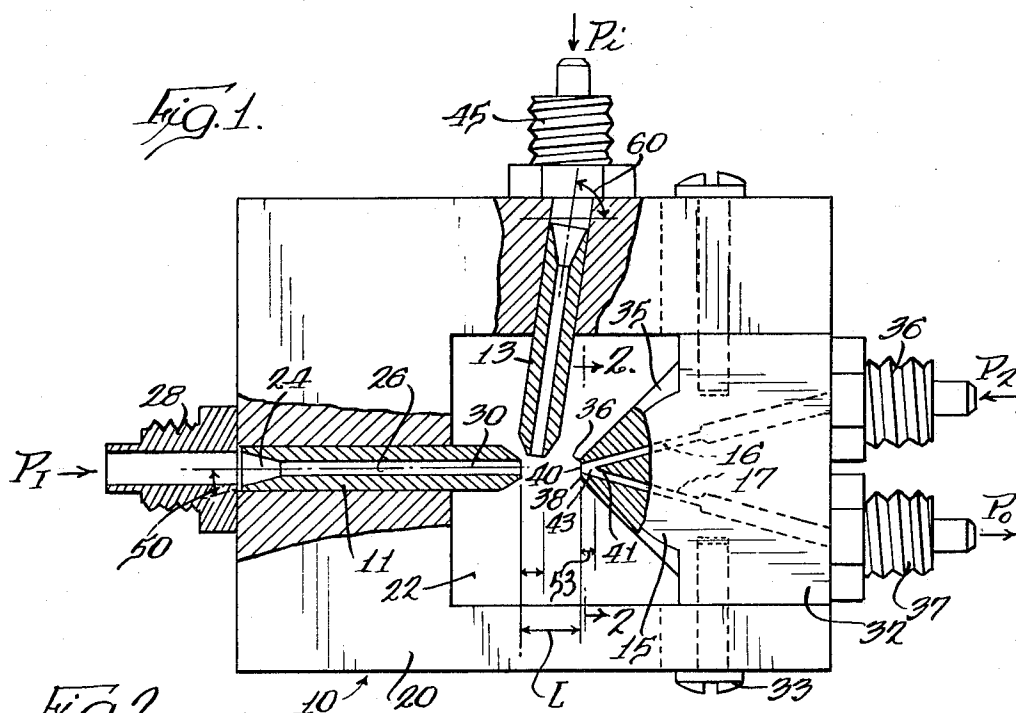
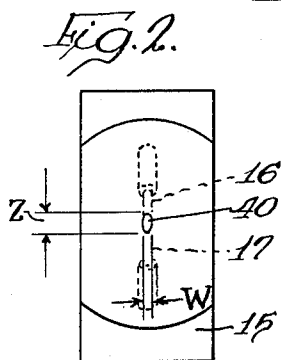
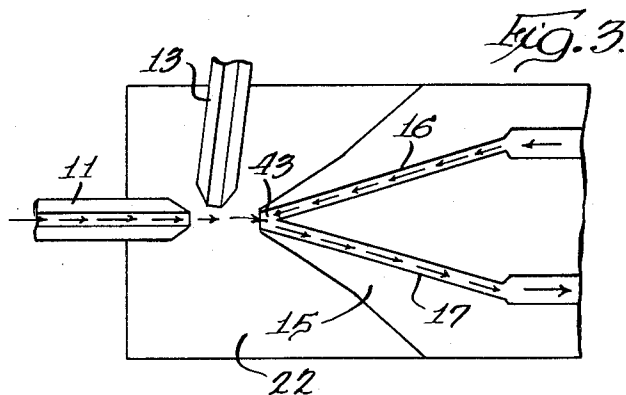
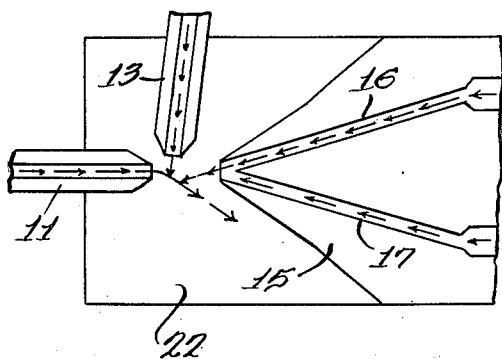


Fig. 4.

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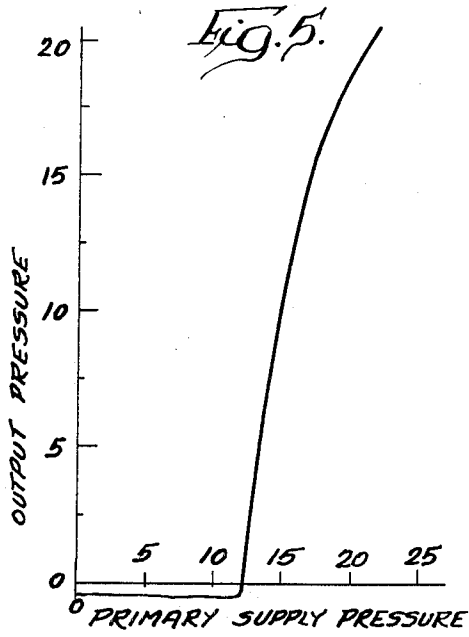
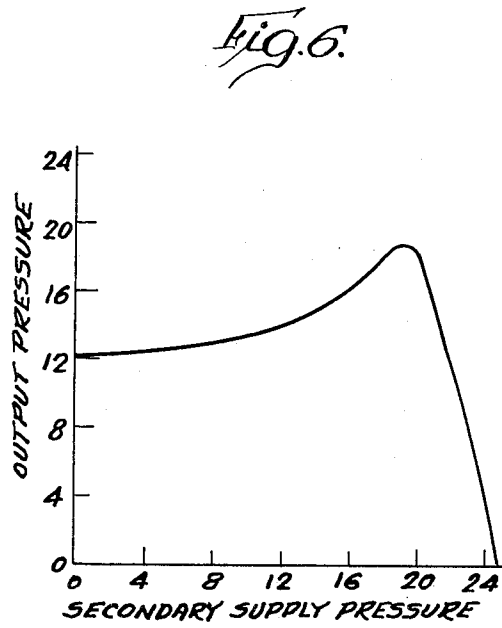
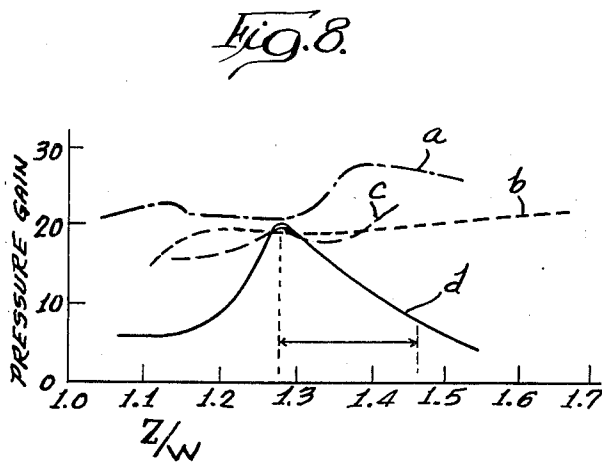
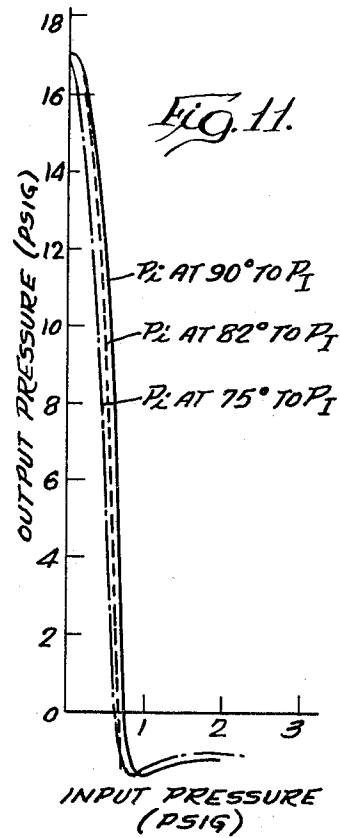
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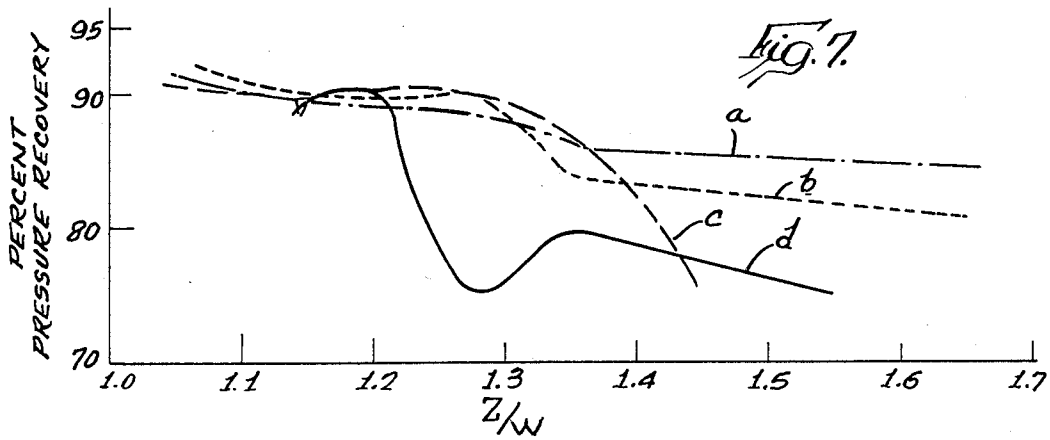
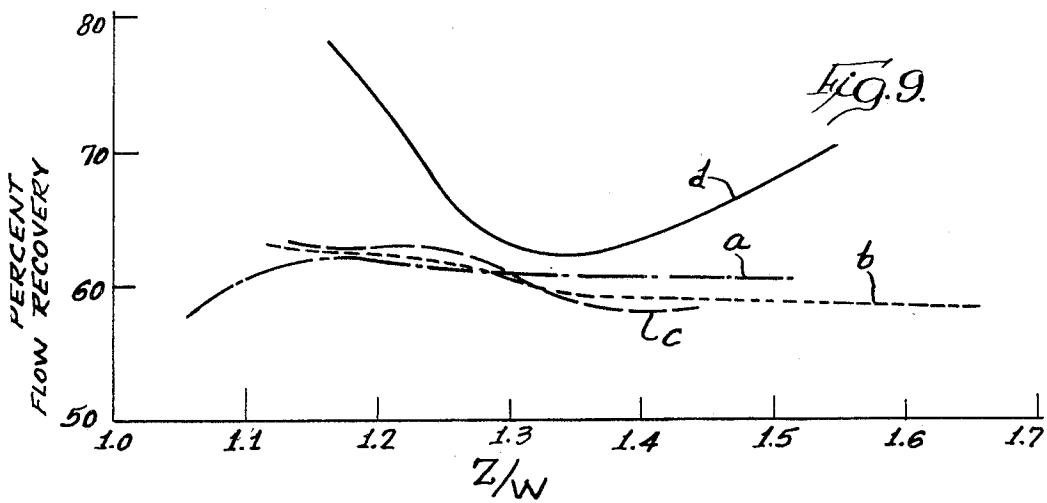
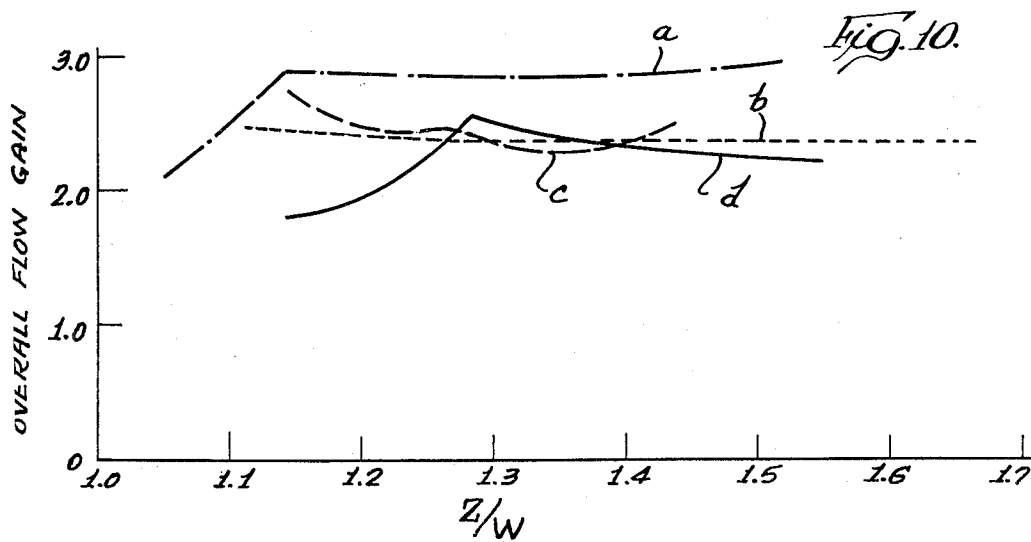
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FLUID DEVICE

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FLUID DEVICE

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24 Claims

ABSTRACT OF THE DISCLOSURE

A fluid amplifier having high gain and high pressure recovery characteristics including a supply nozzle for providing a first fluid stream into a low pressure region, a receiver positioned opposite the supply nozzle having a conical configuration with an orifice at the apex of the cone with a first passage in the receiver communicating with the orifice for supplying a second supply stream which impacts with the main supply stream adjacent the tip of the receiver, a discrete outlet fluid passage in the receiver also communicating directly with the orifice the latter being angularly aligned in one state with the resulting flow vector between the first and second supply streams, such that as the momentum flux of the first supply stream is varied the flow stream resulting from the interaction of the first and second streams will move away from the discrete outlet passage toward the low pressure region.

This invention relates generally to fluid devices and more particularly to a pure fluid device having high pressure recovery characteristics.

The recently developing technology of pure fluid devices involves the control of fluid power systems by devices in which the fluid itself is the working medium. Many fluid devices known today adopt the phenomena of wall attachment or stream interaction to perform control, sensing and logic functions. Fluid amplifiers, referred to in the art as "active" elements, have the capability of responding to small changes in a low energy fluid control signal to cause relatively great changes in a higher energy output signal, much like an electronic amplifier.

The presently known pure fluid devices include the jet deflection amplifier, vortex devices, the double leg elbow amplifier and the transverse impact modulator amplifier, these being merely exemplary. Although these devices are generally considered proportional elements, they may also be designed to permit digital or "on-off" response, if desired.

The operating performance of fluidic amplifiers may be evaluated in terms of pressure and flow recovery, pressure and flow gain, and signal to noise ratio, among other criteria. The pressure recovery of the device is defined as the proportion of output flow pressure to the supply flow pressure under maximum recovery conditions. Flow recovery is defined in the same way with respect to flow. Pressure or flow gain refers to the ratio of change of the output flow to the change of the control flow input with the power stream remaining unchanged. Lastly, the signal to noise ratio is the ratio of the maximum output signal to the maximum noise level experienced. It is, of course, desirable to design circuit devices which have a high signal output with very little noise and thus a high signal to noise ratio.

Prior known fluid amplifiers have had relatively low pressure recovery and low signal to noise characteristics. One such prior device, the impact modulator amplifier, and more particularly the transverse impact modulator, employs the concept of deflecting one of two aligned impacting power jets, the latter being maintained at constant supply pressures. The impacting jets produce a radial flow cone, the balance point of which is controlled by

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varying the momentum flux of one of the supply jets or by a transverse control jet. To capture this "flow cone" and produce an output, an annular collection chamber is provided normally aligned with the flow cone. By reducing the momentum flux with the application of a control signal, the balance point of the flow cone moves away from the annular collection chamber thereby providing an amplifier with negative gain characteristics. As the efficiency of the collection chamber is low, the pressure recovery of the transverse impact modulator is also relatively low and the noise level is quite high at low frequencies. In effect, the collection chamber serves as a noise generator.

In accordance with the present invention, a proportional fluid amplifier is provided which not only has high pressure recovery characteristics, but also a high signal to noise ratio. The device incorporates primary and secondary power jets flowing in generally opposite directions with the jets being angularly related. An outlet or receiving duct is positioned so that the momentum vector of the flow resulting from the interaction of the two power jets is aligned therewith. This alignment leads to a much higher pressure recovery than heretofore known in devices of this character. With the application of a control flow against one of the power jets, the momentum flux thereof is reduced so that the interaction region between the two power jets moves axially, and the angle of the momentum vector increases, thus reducing the flow in the output duct. The output flow varies in an inverse proportional manner with the control flow, and hence in the embodiment disclosed herein the amplifier is a negative gain proportional amplifier.

It is, therefore, a primary object of the present invention to provide a new and improved fluidic device.

Another object of the present invention is to provide a new and improved proportional amplifier having a higher pressure recovery characteristic than heretofore known in the prior art, with a low noise factor.

A more specific object of the present invention is to provide a fluidic device having two generally opposed angularly related power jets with the momentum vector of the flow resulting from the interaction of the two jets being aligned in at least one state with a discrete outlet passage or duct.

Another object of the present invention is to provide a new and improved fluid amplifier of the type described above having a receiver in the path of flow of one of the power jets with passages therein intersecting approximately at the tip of the receiver, one of the passages defining the other power jet and the other passage defining the output duct arranged so that the power jets interact at or within the tip of the receiver in one state and upon variation in the moment flux in one of the power jets the interaction of the two power jets will move out of or away from the receiver tip causing the momentum vector of the resulting flow of the two power jets to at least partially miss the output duct.

A still further object of the present invention is to provide a new and improved fluid amplifier of the type described immediately above in which the intersection of the two passages at the tip of the receiver defines a receiver orifice of generally elliptical shape with the dimension of the orifice being optimized to provide maximum pressure recovery and low noise.

Another object of the present invention is to provide a new and improved fluid amplifier of the type described above in which the axial distance between the primary one of the power jets and the receiver tip is optimized to provide maximum pressure recovery in the outlet duct.

It is a still further object of the present invention to provide a new and improved fluid amplifier of the type described above with a control jet for varying the mo-

mentum flux of one of the power jets with the dimensional location of the control jet with respect to the power jet or nozzle being optimized to provide a high pressure gain.

Another object of the present invention is to provide a new and improved fluid amplifier of the type described generally above having a supply jet nozzle which contributes greatly to a high pressure recovery device.

Other objects and advantages will be apparent from the following detailed description taken in connection with the accompanying drawings in which:

FIG. 1 is a top elevation, partially in cross-section, showing a fluid amplifier according to the present invention;

FIG. 2 is a subassembly view taken generally along line 2—2 of FIG. 1 showing the receiver tip;

FIGS. 3 and 4 are diagrammatic views illustrating the operation of the present device;

FIG. 5 is a curve showing the variation in output pressure as a function of the primary supply pressure;

FIG. 6 is a curve showing the variation in output pressure as a function of the secondary supply pressure;

FIG. 7 is a curve showing the pressure recovery as a function of the ratio of the major to minor orifice diameters for various receivers;

FIG. 8 is a curve showing the overall pressure gain as a function of the major to minor receiver orifice diameters for various receivers;

FIG. 9 is a curve showing the percent flow recovery as a function of the ratio of the major to minor orifice diameters for the various receivers;

FIG. 10 is a curve showing the overall flow gain as a function of the ratio of the major to minor orifice diameters for the various receivers; and

FIG. 11 is a curve showing the output pressure as a function of the control pressure for various control nozzle angles.

While I have shown and shall hereinafter describe one embodiment of the invention, it is to be understood that it is capable of many modifications. Changes, therefore, in the construction and arrangement may be made without departing from the spirit and scope of the invention as defined in the appended claims.

Referring to the drawings and particularly FIGS. 1 and 2, a fluid amplifier 10 according to the present invention is seen to consist generally of a primary supply nozzle 11, a control nozzle 13 and a receiver 15 having defined therein a secondary supply nozzle 16 and an outlet duct or passage 17.

More specifically, a generally U-shaped frame or fixture 20 is provided defining with the receiver 15 a low pressure central region 22. The primary supply nozzle 11 is mounted within the frame or fixture 20 and extends into the low pressure region 22. Nozzle 11 includes an upstream conical portion 24 and a reduced downstream exit portion 26. A suitable fitting 28 fixed to one side of the fixture 20 is adapted to be connected to a suitable source of supply (not shown) under pressure P_1 . Fluid device 10 will operate under either a gaseous or liquid fluid, although development of the device thus far has proceeded mainly with the use of gaseous fluid, such as air. As will appear hereinafter the axis 30 of the primary supply nozzle is employed as a reference for the location of the various other portions of the device.

The receiver 15 has a generally rectangular portion 32 mounted between the legs of the U-shaped frame member 20 by suitable threaded fasteners 33. Extending towards the primary supply nozzle 11 from the rectangular portion 32 is a generally conical portion 35 having a flat tip 36. A knife edge is provided at 38 for improving the operation of the device.

As shown in the drawings, the axes of the passages 16 and 17 define an included angle of approximately thirty degrees with the axis 30 of nozzle 11 bisecting this angle. However, this is only a preferred relationship

and the axis of passage 16 may define a lesser or greater angle with respect to the axis 30 as long as the angle is somewhat greater than zero. Furthermore, the axis of passage 17 may, if desired, define with the axis 30 an angle greater or less than the fifteen degrees shown.

Suitable fittings 36 and 37 fixed to the receiver 32 communicate respectively with the passages 16 and 17. Fitting 36 is adapted to be connected to the source for supplying fluid under pressure P_2 to the secondary supply duct 16. As will appear more clearly hereinbelow, it is usually desirable to provide a pressure drop between P_1 and P_2 , although in some instances under certain conditions they may be equal. A suitable dropping resistor may be provided between the fittings 28 and 36 for the former purpose. However, due to the non-linearities in a dropping resistor, the amplifier would not be optimally operable over a wide pressure range. One solution to this problem is to select the diameter of the secondary supply passage 16 smaller than the diameter of the nozzle passage 26 so that the momentum flux from the secondary supply jet 16 is less than that from nozzle 11 even though the fluid pressure in both is equal.

The outlet fitting 37 is adapted to connect the outlet passage to the load (not shown).

The axes of passages 16 and 17 intersect somewhat outside the receiver towards the nozzle 11 so that the passages open at the tip surface 36 defining therein a generally elliptical orifice 40. Further, the passages 16 and 17 define a splitter 41, and an area 43 within the receiver which is the interaction region for the primary and secondary jet flow. The axis 30 of the primary jet nozzle 11 preferably bisects the splitter 41. As will appear hereinafter the depth of the splitter 41, the size of the orifice 40 and the sizes of the various passages and outlets have a profound affect upon the performance characteristics of the present device.

For varying the momentum flux of the primary supply jet from nozzle 11, the control nozzle 13 is provided which communicates with a suitable fitting 45. Fitting 45 is adapted to be connected to a regulatable source of control fluid, at a pressure which is a small percentage of the primary and secondary supply pressure. Control flow from the nozzle 13 deflects the primary supply jet from nozzle 11 thus reducing the momentum flux of the primary stream and varying the output flow in duct 17.

The operation of the device as thus far described will be apparent from a reference to FIGS. 3 and 4. With fluid pressure P_1 applied to nozzle 11, e.g. 35 p.s.i.g. and fluid pressure P_2 applied to secondary supply jet passage 16, e.g. 32 p.s.i.g., the primary and secondary jets therefrom impinge on one another. The ratio of the primary supply jet pressure to the secondary supply jet pressure (P_1/P_2) is adjusted to give a maximum pressure recovery in the output passage 17. The output pressure can have an infinite number of values by setting the primary power pressure P_1 and then adjusting the secondary power pressure P_2 to obtain the proper ratio. If the primary power nozzle 11 is subsonic, a maximum output pressure can be obtained in duct 17 of approximately 50 p.s.i.a. Much higher output pressures can be obtained, however, if the primary power nozzle 11 is supersonic. With the proper selection of the ratio P_1/P_2 , the primary and secondary power jets will interact adjacent the region 43 and the momentum vector of the flow resulting from the interaction of the two power jets will be aligned with the output duct 15. This alignment contributes to a high pressure recovery characteristic.

With control flow present in control nozzle 13, as shown in FIG. 4, the control fluid stream strikes the primary jet stream from nozzle 11 in the low pressure region 22. This reduces the momentum flux of the primary power jet or stream and deflects it so that it no longer interacts with the secondary power jet in region 43. Instead, the two power jets interact in low pressure region 22 and the momentum vector of the flow resulting from the interaction of the two power jets increases its angular relationship with duct 17 and is no longer directed to and aligned with

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respect to the output duct. In this situation no output flow is captured by the output duct 17 and in fact flow may actually be entrained through the output duct. Of course, as this is a proportional amplifier, the momentum flux of the primary power jet may be reduced or deflected a lesser amount resulting only in a reduced flow through the output duct 17. The output flow varies in an inverse proportional manner with the control flow, and the control flow through nozzle 13, required to modulate the output flow, is low compared to the output flow. Hence, the present amplifier is a negative gain proportional fluid amplifier.

The control nozzle 13 is coplanar with the primary supply nozzle 11 and passages 16 and 17 to provide the optimum pressure and flow gain. Once the control flow from nozzle 13 has deflected the primary supply flow from nozzle 11, the secondary supply flow from passage 16 aids in further deflection of the primary supply flow away from the receiver tip 36. This characteristic enhances the pressure and flow gain of the present device.

The pressure gains in several devices constructed in accordance with the present invention have been found to be about thirty to one with gains as high as sixty to one in selected portions of curves illustrating the output pressure as a function of control pressure with the device driving an infinite impedance.

The control jet 13 is only a preferable means for varying the momentum flux of the primary jet from nozzle 11 and other means may be provided in place of this to deflect, constrict, or in some other manner disturb the primary jet. Such means may include electrophoresis devices, an electromagnetic device with ionized supply flow, devices which restrict the primary power flow with an annular concentric control flow, etc.

Shown in FIG. 5 is a curve showing the variation in dead-ended output pressure for the present amplifier, plotted as a function of the primary supply pressure P_1 with the secondary supply pressure P_2 constant, and adjusted to give maximum pressure recovery when the primary supply pressure is 20 p.s.i.g. Note that the pressure recovery, i.e., the proportion of output pressure to primary supply pressure, is in excess of ninety percent. The curve in FIG. 6 illustrates the variations in output pressure (dead-ended) as a function of the secondary supply pressure P_2 with the primary supply pressure at 20 p.s.i.g. Note that the variation in the output pressure is quite gradual.

The flow gains in the present device are on the order of approximately ten to one. Flow recovery can be increased, if desired, at the expense of pressure recovery by increasing the diameter of the duct 17 with respect to the other ducts. While the present device as above described has many basic performance characteristics superior to those in heretofore known proportional fluid amplifiers, the geometric configuration and location of the various ducts, jets and passages described have a further influence over these performance characteristics. The following dimensional analysis is an optimization of the fluid amplifier configuration for low noise level and high pressure recovery characteristics.

The configuration of the primary nozzle 11 has a significant affect in obtaining high pressure recovery. In order to have fully established pipe flow in the nozzle, the axial length of the reduced circular passage 26 should be at least ten times the diameter of that passage. Furthermore, the angle 50 of the conical portion 24 should be approximately thirty degrees for maximum pressure recovery.

As described above, the receiver orifice 40 is generally elliptical as it is formed by two circular ducts intersecting each other adjacent the tip of the receiver. The ratio of the major diameter Z to the minor diameter W (FIG. 2) and the depth 53 from the tip of the receiver to the splitter 41 are determined by the point of intersection of the two duct center lines with respect to tip 36 for any

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given ducts. The affect of the shape, of the orifice 40 on pressure gain and noise is significant. Increasing the major axis Z reduces the noise generated in the amplifier. Apparently, the chief source of noise is the interaction of the secondary and primary supply jets in the receiver. When the receiver orifice 40 is enlarged, i.e. by reducing the splitter depth 53 from tip 36, the influence of the receiver tip on the secondary supply jet is diminished because the distance from the tip to the free jet is increased. The equation for the size of the orifice 40 with respect to the depth of the splitter 41 and the included angle between the passages 16 and 17 is

$$Z = \frac{2W}{\cos \frac{\theta}{2}} - 2d \tan \frac{\theta}{2}$$

where d =splitter depth, Z =major orifice diameter, W =minor orifice diameter, θ =the included angle between the ducts 16, 17.

With the size of the ducting and passages as follows: nozzle 13, 0.040 inch; nozzle 11, 0.040 inch; passage 16, 0.031 inch; and passage 17, 0.031 inch; with the angle (θ) between the ducts being thirty degrees and bisected by the axis 30, a receiver having a ratio Z/W (major to minor axis ratio) of 1.39 has been found optimum from the standpoint of minimum noise.

The pressure recovery, pressure gain, flow recovery and the flow gain for four actual receivers 15 i.e. a , b , c and d , constructed in accordance with the present invention are given as a function of Z/W in FIGS. 7, 8, 9 and 10. During all the tests from which this data was obtained the primary supply pressure was at 20 p.s.i.g. The various Z/W ratios were obtained on the receivers by removing material from the receiver tip 40, thus increasing the Z/W ratio.

Referring to FIG. 7, it may be seen that the percent pressure recovery remains fairly constant for increasing values of Z/W up to about 1.28 and then begins to decrease. As indicated in FIG. 8, the overall pressure gain of these receivers generally increases with an increase of Z/W , reaches a maximum and then begins to decrease. For three of the receivers the overall gain reaches a maximum approximately at 1.28 Z/W , and as shown in FIG. 9 the flow recovery for three of the four receivers remains fairly constant over a wide range of Z/W .

The overall flow gain, illustrated in FIG. 10, does not vary appreciably for receivers a , b , and c for values of Z/W greater than 1.15.

It has been found apparent from the above data, presented only in summary form, and from other data, that the optimum ratio of Z/W for low noise the device is approximately 1.39. Further, Z/W ratio for high pressure recovery combined with high overall pressure gain is approximately 1.28. Further, as the percent flow recovery and the overall flow gain do not vary significantly about either of these values of Z/W they do not alter the optimum ratios determined for noise and pressure recovery and gain.

The axial distance L between the end of the nozzle 11 and the receiver tip 36 has an effect on pressure recovery and pressure gain. For lower values of primary supply pressure in the range of 2 to 20 p.s.i.g., the pressure recovery varies slowly with changes in L between 0.12 and 0.195 inch. However, for a primary supply pressure of 35 p.s.i.g., the variation in pressure recovery with changes in L is more pronounced and the optimum value for L is substantially 0.180 inch.

The configuration of the primary supply nozzle 11 has an affect on the optimum value L due to the fact that at high supply pressures diamond shaped shock patterns develop downstream from the primary supply nozzle. Furthermore, the overall pressure gain increases for both low and high primary supply pressures as the distance L increases. However, since the pressure recovery de-

creases above $L=0.180$, and since the noise increases as well above this value, it appears to be the optimum.

As shown in FIG. 11, the pressure gain varies as a function of the angle 60 (FIG. 1) between the control nozzle 13 and the axis 30 of the primary supply jet 11. As may be seen in FIG. 11 the lowest gain is with an angle of ninety degrees and the highest gain is with an angle of 75 degrees with the control flow slightly opposing the primary flow. However, the gain is almost as good at 82 degrees and the linearity is the best at this angle.

I claim:

1. A fluid amplifier, comprising: first means for establishing a supply stream, second means for establishing a second supply stream impinging on said first stream in a direction generally opposite said first stream, receiving means having an opening for receiving fluid from the interaction of said streams, said second means directing said second stream at an angle to said first stream to deflect the same toward said receiving means, means for disturbing one of said streams so that the interaction region of said streams moves relative to said receiving means, said second means for establishing said second supply stream being in said receiving means and communicating with said opening on the side thereof opposite said first means, and at least one discrete outlet passage in said receiver communicating directly with said opening on the side of said opening opposite said first means, said discrete outlet passage being not significantly greater in size than said first means for establishing a supply stream.

2. A fluid amplifier as defined in claim 1, wherein said first means, said second means and said receiving means lie in a common plane.

3. A fluid amplifier as defined in claim 1, including frame means having a low pressure central region, said first means including a primary supply nozzle mounted in said frame means and extending into said low pressure region, a receiver member in said frame means and having a receiver tip disposed generally in the path of flow from said primary supply nozzle, said receiver member having a first passage opening to said tip and defining said second means, said receiver member having said outlet passage intersecting said first passage substantially at said receiver tip and defining an orifice in said receiver member.

4. A fluid amplifier as defined in claim 3, wherein said modifying means includes a control nozzle mounted in said frame means and extending into said low pressure region for directing control fluid adjacent said first stream.

5. A fluid amplifier, comprising: first means for establishing a first supply stream, second means for establishing a second stream impinging on said first stream in a direction generally opposite said first stream, receiver means having an orifice for receiving fluid from the interaction of said streams, said second means being in said receiver means and directing said second stream at an angle to said first stream to deflect the same and being on the side of said orifice opposite said first means, discrete outlet passage means in said receiver means communicating directly with said orifice on the side thereof opposite said first means, and means for modifying one of said streams so that the angle of the flow vector of the fluid stream resulting from the interaction of said first and second streams changes with respect to said outlet passage means, said first and second supply stream establishing means being constructed so that the flow vector from the interaction of said streams is aligned with said outlet passage means in the absence of said modifying means.

6. A fluid amplifier as defined in claim 5, wherein said means for modifying one of said streams includes means for disturbing the first stream upstream of the interaction of said first and second streams to reduce the momentum flux of said first stream.

7. A fluid amplifier as defined in claim 6, including a receiver portion spaced axially from said first means, first passage means in said receiver having an axis intersecting the axis of said first means and defining said second means, said outlet passage means in said receiver portion having an axis intersecting the axis of said first passage, the receiver portion defining an interaction region for the first and second streams.

8. A fluid amplifier as defined in claim 7, wherein said first means and said first and outlet passage means are located so that with fluid flowing in said first means and in said first passage means under a predetermined relative pressure, the vector of the flow resulting from the interaction of said first and second streams is angularly aligned with said outlet passage means.

9. A fluid amplifier is defined in claim 8, wherein said means for modifying one of said streams includes means for reducing the momentum flux of said first stream whereby said resulting flow will move away from said second passage means so that the amplifier has a negative gain characteristic.

10. A fluid amplifier as defined in claim 9, wherein said means for reducing the momentum flux of said first stream includes a control nozzle for directing control fluid against said first stream.

11. A fluid amplifier as defined in claim 10, wherein the axis of said control nozzle defines an angle of between 70 and 85 degrees with the axis of said first means in a direction so that the control flow opposes the first stream.

12. A fluid amplifier as defined in claim 11, wherein said angle is 82 degrees for higher linearity.

13. A fluid amplifier as defined in claim 10, wherein the axial distances between the first means and the portion of the control nozzle further therefrom is in the range of 0.047 inch to 0.057 inch.

14. A fluid amplifier as defined in claim 13, wherein said distance is 0.047 inch for a high pressure gain characteristic.

15. A fluid amplifier as defined in claim 4, wherein the axis of said outlet passage means intersects the axis of said first means.

16. A fluid amplifier as defined in claim 7, and further including means defining a low pressure region between said first means and said receiver portion whereby modification of one of said streams causes proportional distribution of said resulting stream between said receiving means and said low pressure region.

17. A fluid amplifier as defined in claim 7, wherein the intersection of said first and outlet passage means defines a splitter and an orifice in said receiver portion, the axis of said first means being substantially aligned with said splitter.

18. A fluid amplifier as defined in claim 7, wherein the intersection of said first and second passage means defines a splitter in said receiver portion between said passages, said receiver portion having a tip in the path of said first stream through which the first and second passages open defining an orifice, the edge of the orifice and the axial location of the splitter being defined by the equation,

$$Z = \frac{2W}{\cos \frac{\theta}{2}} - 2d \tan \frac{\theta}{2}$$

when Z =major diameter of the orifice, W =minor diameter of the orifice, θ =angle between the passages, d =axial depth of the splitter from the receiver tip.

19. A fluid amplifier as defined in claim 18 wherein the ratio of Z/W is approximately 1.39 for high pressure recovery and low noise.

20. A fluid amplifier as defined in claim 18, wherein Z is approximately 0.050 inch and W is approximately 0.036 inch.

21. A fluid amplifier as defined in claim 7, wherein said first and second passage means have an included angle of approximately thirty degrees.

22. A fluid amplifier as defined in claim 21, wherein said included angle is substantially bisected by the axis of said first means.

23. A fluid amplifier as defined in claim 7, wherein said receiver portion has a tip in the path of flow of said first stream, said passages opening at said tip, said first means having an exit portion spaced from said tip approximately 0.180 inch for high pressure recovery when the supply flow from said first means is under a high pressure.

24. A fluid amplifier as defined in claim 5, wherein said first means includes a primary supply nozzle, said nozzle having a convergent conical upstream portion and a cylindrical downstream exit portion, said conical portion defining an angle of approximately fifteen degrees

with the axis of said passage, said passage having a length at least ten times the diameter thereof.

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