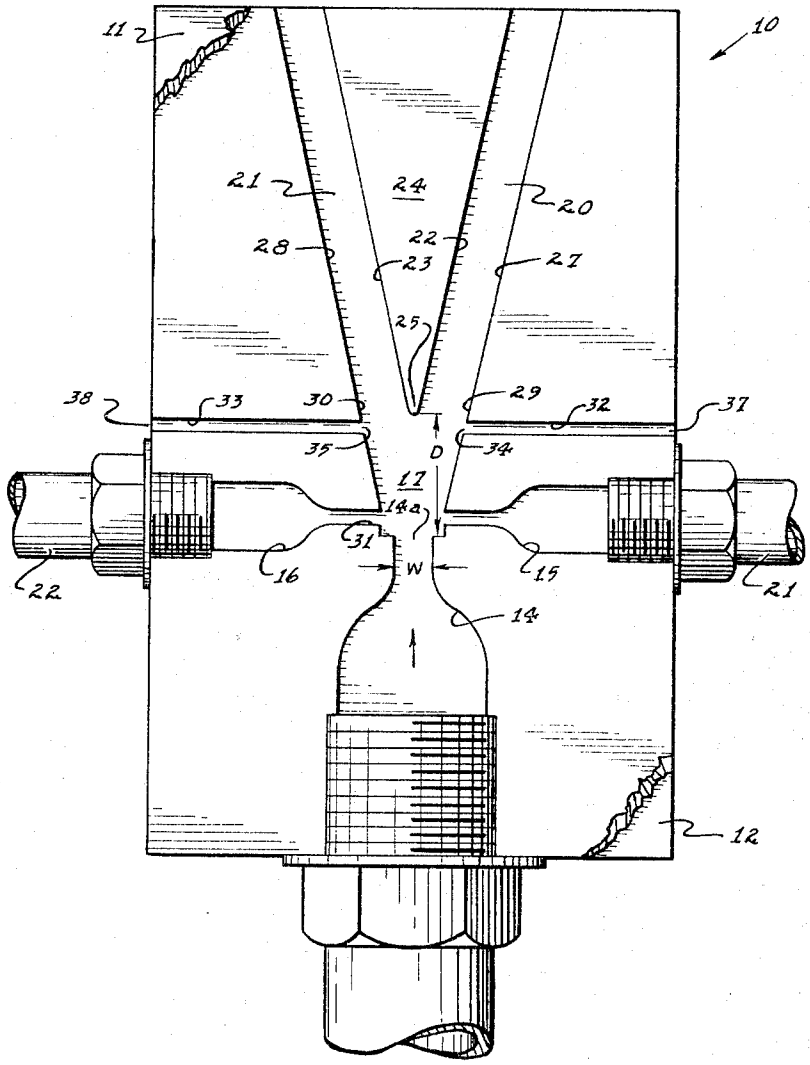
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VENTED PURE FLUID ANALOG AMPLIFIER

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# VENTED PURE FLUID ANALOG AMPLIFIER

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This invention relates generally to pure fluid amplifying systems and, more specifically, to a vented pure fluid amplifier of the analog type.

Pure fluid amplifiers utilizing power stream deflection to achieve amplification have been generally classified by those working in the art into two categories; momentum interchange or analog type pure fluid amplifiers, and boundary layer or digital type pure fluid amplifiers. Both types of pure fluid amplifiers are typically formed with an interaction chamber defined by an end wall and two outwardly diverging sidewalls extending from the end wall. A power nozzle having an orifice formed in the end wall is provided to issue a well-defined and relatively large energy stream, herein after referred to as the power stream, into the interaction chamber. A substantially V-shaped or other shaped flow divider is positioned with the converging apex thereof disposed a predetermined distance downstream of the end wall and the orifice of the power nozzle, the sides of the flow splitter being generally parallel to the diverging sidewalls of the interaction chamber. The diverging sides of the flow splitter and the extended sidewalls of the interaction chamber define sidewalls for left and right output passages into which the flow in the interaction chamber issues.

Fluid control signals in the form of control streams are supplied by a control nozzle to the interaction chamber, the control nozzle being positioned at an angle with respect to the power nozzle, generally 90°, and the fluid issuing from the control nozzle effecting amplified directional displacement of the power stream in the interaction chamber relative to the entrances of the output passages. Since all elements forming the amplifier remain stationary during the operation thereof, such amplifiers are commonly referred to by those working in the art as "pure fluid amplifiers."

In conventional momentum interchange or analog type of pure fluid amplifiers, the sidewalls of the inteaction chamber are set back remotely from the orifice of the power nozzle so that the power stream issuing from the power nozzle is displaced solely by control streams issuing from the control nozzles and the amount of displacement is proportional to the magnitude of the fluid control signals issuing from the control nozzles for certain ranges of control signal amplitudes. Thus, the output passages receive relative proportions of flow, pressure or energy of the power stream which are proportional to the corresponding parameters of the control streams required to effect displacement of the power stream in the interaction chamber. Since the output signals of this type of amplifier vary continuously as the control signals vary, this type of amplifier is commonly referred to by those skilled in the art as an "analog" pure fluid amplifier.

Contrasted with this type of pure fluid amplifier, a digital or boundary layer type of fluid amplifier is formed with the sidewalls of the interaction chamber positioned sufficiently close the the orifice of the power nozzle so that boundary layer effects including "boundary layer lock-on" can occur between the power stream and either sidewall toward which the power stream is displaced by fluid from an opposite control nozzle.

The boundary layer lock-on phenomena is due to boundary layer effects created between the power stream and a sidewall of the interaction chamber. For example, if



the power stream issuing from a power nozzle is directed toward the apex of the flow splitter, the fluid issuing from the power nozzle orifice in passing through the chamber, entrains fluid therein and removes the fluid to the output passages. If the power stream, however, is displaced slightly closer to, for example, the left sidewall than to the right sidewall of the interaction chamber by a fluid control pulse it is more effective in removing fluid in the region between the power stream and the left sidewall than it is in removing the fluid between the power stream and the right sidewall. Therefore, the pressure in the left region between the left sidewall and the power stream will become lower than the pressure in the right region between the power stream and the right sidewall, and this differential in pressure tends to effect displacement of the power stream towards and against the left sidewall. As the power stream is deflected further towards the left sidewall, it becomes more efficient in entraining and removing fluid from the left region, and the pressure in this region is therefore further reduced. The aforedescribed action is self-reinforcing and regenerative and eventually results in the power stream becoming completely deflected towards the left sidewall, attaching thereto, and entering the left output passage.

The attachment of the power stream to either sidewall occurs at points known as "points of attachment" which may be considered as being points of intersection between the power stream and the sidewall toward which the power stream is initially displaced. The sidewalls of this type of amplier may be regarded as producing gain in the amplifier because they effect switching of the power stream into an output passage toward which the power stream is initially directed even though the initially displacing control stream pulse is thereafter removed. Thus, the control stream pulse need only disturb the initial symmetry of the power stream flow until the aforedescribed regenerative lock-on cycle develops on the opposite side of the device, the sidewalls thereafter solely serving to effectuate complete displacement of the power stream into an output passage. The fluid output signal parameters from the output passage of the digital fluid amplifier is not proportional to the magnitude of the control stream signals since the displacement of the power stream is complete as soon as boundary layer lock-on effects are developed. Accordingly, this type of amplifier has been referred to by those skilled in the art as a digital type of pure fluid amplifier or flip-flop in contrast to the aforedescribed analog type.

As mentioned previously, the sidewalls of the digital type fluid amplifier effect complete switching of the power stream after the power stream is initially displaced by the control stream and hence the gain of this type of amplifier is theoretically infinite. As is now known to those working in the art, the degree of lock-on which is produced in any type of amplifier is determined by the relation between the width of the power nozzle orifice supplying the fluid stream to the width of interaction chamber, the distance between the opposite sidewalls of the interaction chamber adjacent the orifice of the power nozzle, the angle that the sidewalls make with respect to a centerline through the longitudinal axis of the power nozzle, the length of the sidewall, the spacing between the power nozzle and the apex of the flow divider, and the density, viscosity, compressibility and uniformity of the fluid employed as the working fluid in the amplifier as well as its velocity.

The apparatus of the present invention is described herein by reference to the particular situation which required a particular set of operating characteristics. As will be pointed out subsequently, the amplifying system resulting from the present invention has a considerably greater field of applicability than the particular application for which it was developed.

The present invention is intended to be employed to steer a ship by thrust vectoring of a fluid, for instance, water. The device has two final output channels directed in opposite directions so that the differential in flow from the two channels determines the total vectoring force available. In order to obtain a maximum vectoring force from the particular unit, it must be able to supply all the power fluid stream of the last stage to an output channel to the exclusion of the other so that a maximum differential in thrust may be provided when a fast turn is required. The total energy of fluid available to the entire unit is limited by practical considerations of space and power so that it is immediately apparent that a large proportion of the total energy must be supplied to the final stage of the unit to be available for the vectoring, as opposed to the control function. The limiting on total energy also makes it necessary to provide a final stage that is very efficient in conserving the momentum and pressure of the stream. Further considerations effecting the development of the unit were space which was very limited and constancy of gain of the unit.

Many of the above constraints imposed on the system normally require diametrically opposed solutions. For instance, the requirement that momentum and pressure of the power stream of the final stage be conserved to the fullest extent, requires the flow splitter to be located close to the power nozzle. If the flow splitter is located too far downstream the stream spreads resulting in pressure and momentum losses. However with the flow splitter located close to the power nozzle (say a distance equal to three widths of the power nozzle downstream from its outlet orifice) a large control stream is required in an analog unit to turn the stream through a large enough angle to fully deflect the power stream into one or the other outlet passages when a minimum radius turn is required. The unit must be analog in operation so that a full range of turning radii is available for maneuvering.

The above requirement of a large control flow is incompatible with the solution to the problem since such a large control flow can be obtained only after several stages of amplification which would reduce the flow energy in the final stage below that required. Thus the system as a practical matter requires a final stage amplification greater than available from any existing analog unit compatible with the requirements of space, momentum and pressure conservation, and the ability to completely deflect the stream to one output channel to the exclusion of the other ouput channel.

In accordance with the present invention a unit is provided which meets all of the above requirements relating to minimizing the number of amplifier stages so as to utilize a large proportion of the total energy available in the power stream of the final stage, and conservation of momentum and pressure of the fluid and small size by employing a unit with the flow splitter located close to the power nozzle orifice but having sufficient gain to provide the desired end result. Also the gain of the unit is relatively constant over the full operating range of the device. More specifically a final stage is provided having sufficient gain to utilize control signals from only a single prior amplifier stage to produce any range of deflections of its power stream up to full deflection.

The final stage of the amplifier is an analog unit which employs boundary layer effects to enhance its gain uniformly over the full range of deflections of the power stream. The amplifier has its sidewalls located relatively close (about two power nozzle orifice widths) to the power nozzle so that boundary layer effects are operative upon the power stream in all of its positions. Vents to a source of reference pressure, which may be ambient or atmospheric pressure, are let into the interaction region relatively close to the control nozzles so as to prevent positive feedback due to boundary layer entrainment from producing bistable action. Analyzing the characteristics necessary to achieve this result in terms of the standard



feedback equation for gain, $G/1-GB$, the feedback factor GB, must remain positive and less than one. Under these conditions, the gain, G, is increased but cannot become infinite and thus produce bistable action.

As previously indicated it is extremely difficult to produce full deflection of the power stream in a unit of the design under consideration. To assist and ultimately provide this capability in the present unit, the aforesaid vents are located such that the point of attachment of the power stream to the sidewall moves upstream of the vent as the stream approaches full deflection so that the flow from the vents cannot effect the boundary layer pressures under this extreme condition.

Broadly, therefore, it is an object of this invention to provide a fluid amplifier of the analog type wherein the apex of the flow splitter is located proximate the orifice of the power nozzle for providing maximum momentum and pressure conservation, and wherein the gain of the amplifier is sufficient to produce full deflection of the power stream and remains substantially constant over the operating range of the device.

Another object of this invention is to provide a fluid amplifier of the analog type wherein boundary layer effects are utilized concurrently with momentum interaction to effect complete displacement of the power stream into an output passage when the amplitude of the control stream reaches maximum value.

Yet another object of the present invention is to provide an analog amplifier employing boundary layer effects to provide gain enhancement and employing vents to feed fluid into the boundary layer region between the stream and sidewalls of the device so as to control the degree of gain enhancement and prevent bi-stable operation.

Still another object of the present invention is to provide an analog amplifier employing boundary layer effects to provide gain enhancement and employing vents to feed fluid into the boundary layer region between the stream and sidewalls of the device so as to control the degree of gain enhancement and prevent bi-stable operation and in which the vents are situated such that their effect on the boundary layer is terminated upon approximate full deflection of the power stream.

The above and still further objects, features and advantages of the present invention will become apparent upon consideration of the following detailed description of one specific embodiment thereof, especially when taken in conjunction with the accompanying drawing, wherein:

The drawing illustrates a plan view of the pure fluid amplifier constructed in accordance with the principles of this invention.

Referring now to the drawing for a more complete understanding of this invention, there is shown the pure fluid amplifier **10** constructed in accordance with this invention. The amplifier **10** is formed between two flat plates **11** and **12**, with upstanding members therebetween to form the various channels, orifices, passages, etc. required to define the amplifier elements. The plates **11** and **12** may be composed of any material compatible with the fluid employed in the system **10** and for purposes of illustration, the plates are shown to be composed of a clear plastic material so that the various elements of the amplifier may be seen. If the amplifier is a small unit, it may be composed of two plates sealed to one another with various channels etc. etched, molded, or otherwise formed in one of the plates, that plate being covered by the other plate so that the required passages, cavities and nozzles are enclosed and sealed in a fluid-tight relationship between the two plates.

The amplifier **10** is formed with a power nozzle **14** having an orifice **14***a*, a pair of opposed control nozzles **15** and **16**, an interaction chamber **17** positioned downstream of the orifice **14***a*. Output passages **20** and **21** are located downstream of the chamber **17** and are defined by converging sidewalls **22** and **23** respectively, of a flow splitter **24**, and opposite sidewalls **27** and **28** which are

extensions of the sidewalls 29 and 30, respectively, of the interaction chamber 17. The sidewalls 22 and 23 of divider 24 converge to an apex 25. The orifice 14*a* of the power nozzle 14 is formed in an end wall 31 defining the upstream end of the chamber 17.

A pair of venting passages 32 and 33 of relatively small cross-sectional area are formed in the plate 11 and terminate at ports 34 and 35, respectively, formed in the sidewalls 29 and 30, respectively. The pair of ports 34 and 35 communicate with the interaction chamber 17 upstream of the apex 25 and may be located within limits downstream of the orifice of the power nozzle 14 as set forth in greater detail subsequently. The ends 37 and 38 of the passages 32 and 33, respectively, remote from the interaction region 17 may communicate with an environment at ambient or other reference pressure.

In order to provide maximum pressure and momentum conservation as mentioned hereinabove, the apex 25 of the flow splitter 24 is positioned a distance D, that is approximately equal to or less than three times the width of the power nozzle orifice 14*a*, the width of the orifice 14*a* being referred to by the letter W. The sidewalls 29 and 30 of the interaction chamber 17 are positioned relative to the orifice 14*a*, a distance such that boundary layer effects are created between the power stream and the sidewalls 29 or the sidewall 30 towards which the power stream may be displaced by fluid jets issuing from the control nozzles 16 and 15, respectively, and concurrently by boundary layer effects.

The ports 34 and 35 may be positioned at different distances downstream of the orifice 14*a* if asymmetrical switching of the power stream is desired. However, for purposes of the specific use of the device under discussion the ports 34 and 35 are preferably located opposite each other and the critical adjustment that governs the operation of the amplifier 10 is the location of the ports relative to the orifice 14*a*.

As will be explained in greater detail during the subsequent discussion, the ports 34 and 35 should be positioned just downstream of the point of attachment created when the power nozzle is issuing a maximum energy power stream and the power stream is deflected to a maximum extent; that is, all of the power stream flow is directed to one output passage substantially to the exclusion of the other.

The operation of the amplifier 10 is explained by assuming that the power stream is issuing from the power nozzle 14, that the control nozzle 16 is receiving a successively increasing amplitude fluid signal, and initially that the passages or vents 32 and 33 are eliminated. Upon deflection of the power stream toward the sidewall 29, even though the deflection is quite small, the power stream becomes located closer to sidewall 29 than sidewall 30. The high velocity stream is therefore more effective in entraining fluid between the sidewall 29 and the stream than between the stream and the sidewall 30. The entrainment of fluid reduces the pressure between the stream and the sidewall 29 and tends to further deflect the stream towards that sidewall. As the stream approaches closer and closer to the sidewall 29, it becomes increasingly effective in entraining fluid along its right side until the feedback factor, in what is essentially a positive or regenerative feedback system, equals approximately one and the stream deects without a further increase in input signal to the maximum extent possible in the absence of increased signal. With the splitter 24 located so close to the power nozzle, the device is at a marginal or cross-over region between analog and bistable action. Specifically if the splitter is located less than three power nozzle orifice widths downstream, the transverse pressure that can be developed by boundary layer effects is not enough, in the absence of a large control stream, to completely deflect the power stream to one output passage before the stream strikes the apex of the flow splitter and therefore some of the fluid exits through the unselected output channel. If the apex of the divider is located more than three orifice widths downstream of the power nozzle orifice, the transverse pressure due to boundary layer effects is enough to completely deflect the stream. Since the present device is at about the cross-over point between the two types of operation described above, the stream may or may not deflect fully to an output channel once it has approached one sidewall as opposed to the other. In any event, a point is reached as the stream moves toward one sidewall, at which the boundary layer feedback factor equals approximately one and the stream will deflect to the maximum extent possible for that particular unit. Thus the gain of the amplifier is a discontinuous function, a highly undesirable result in the apparatus for which this amplifier is designed.

The objectionable operation described above is overcome in accordance with the present invention by employing the vents 32 and 33. When the power stream is deflected toward one sidewall, such as sidewall 29, due to fluid entrainment along the right side of the stream as viewed in the figure, the pressure in this region reduces further deflecting the stream. The feedback factor however is reduced, but not eliminated, by fluid flowing into this region of reduced pressure through vent 32. As the stream is further deflected due to increased control flow from nozzle 16, the stream becomes more effective in entraining fluid to its right but also the flow into this region through vent 32 increases and the same net gain results. As the stream is still further deflected the rate of fluid entrainment increases at a fast rate and also tends to accumulate directly some of the fluid flowing from vent 32. At this point the point of contact between the stream and sidewall 29 is approaching the region of the vent 32 and another effect begins to become significant. The angle between the stream and the sidewall is become large so that a large static pressure builds up at the point of attachment. (The point of attachment refers to the point of intersection of the power stream with the sidewall. Since the stream when deflected has a length along the sidewall, the point of attachment refers to the point of intersection closest to the power nozzle; that is, the upstream point of intersection.) The increasing static pressure also contributes to the pressure of the region between the stream and the sidewall 29 upstream of the point of attachment and counteracts some of the increasing effect of the stream in reducing pressure in this region. The net effect of these interacting flows and forces is that the amplifier has a relatively constant gain over its entire range of deflection, the gain of the amplifier however being greater than would be obtainable if the boundary layer positive feedback were not employed.

Continuing with the above description, upon the stream being fully deflected by the introduction of a large input signal and boundary layer effects, the point of attachment between the power stream and the sidewall 29 is located just upstream of the vent 32 so that the vent no longer effects the boundary layer pressure. This is essential since the static pressure developed by impact of the stream against the sidewall is now sufficient to maintain the proper balance between fluid withdrawal from and supply to the boundary layer region so that the overall gain is maintained at the proper value.

As indicated above, the boundary layer feedback enhances the gain of the unit by a fixed factor, for instance, 50% over that which would be available from a conventional analog unit. In consequence, the number of prior amplifier stages required to produce an input signal of sufficient magnitude to fully deflect the stream is reduced. Thus the objects of the invention are met in that the splitter is located such as to conserve momentum and pressure, space is conserved, and a large portion of the total available energy of the supply fluid is available to the last stage since the number of pre-amplifier stages are reduced.

Fluid signals supplied to the control nozzle **15** effect amplified displacement of the power stream in an opposite direction to that effected by the control nozzle **16**, the output fluid signals issuing from the output passage **20** being proportional to the amplitudes of the fluid control signals received by the control nozzles **15**. The operation in this case is as described above since the unit is symmetrical about its centerline.

In the event both control nozzles receive fluid signals, displacement of the power stream in the interaction chamber **17** will be proportional to the differential between the fluid streams issuing from both control nozzles, as will be apparent to those working in the art.

In general, the location of the ports **34** and **35** will be downstream of the orifice of the control nozzle and upstream a distance from the apex of the divider which is not greater than four times the orifice width, 4W, for the configuration shown in the drawings. Although fluid will issue from the passages **32** and **33** as the point of attachment crosses the ports **34** and **35**, respectively, the size of the passages and the location of the ports is such that the quantity of fluid received by the passages is negligible relative to the quantity of fluid issuing into the interaction chamber **17**. If desired, the ports **34** and **35** may be designed so that no fluid enters the venting passages as the point of attachment crosses the ports.

Although the invention has been described as applied to a device employed for steering a boat it is equally applicable to any situation where any of the factors discussed herein are important.

While I have described and illustrated one specific embodiment of my invention, it will be clear that variations of the details of construction which are specifically illustrated and described may be resorted to without departing from the true spirit and scope of the invention as defined in the appended claims.

What I claim is:

**1.** A fluid amplifier of the beam deflection type comprising a power nozzle having an orifice for issuing a constricted power stream, an interaction chamber positioned downstream of the orifice of said nozzle for receiving fluid therefrom, said interaction chamber including at least one sidewall extending from adjacent said power nozzle and diverging outwardly in the direction of power stream flow in said chamber, plural means for receiving flow from said chamber, means including a divider for dividing flow between said plural means, one of said plural means being defined at least partially by a wall of said divider located on the same side of the centerline of said power nozzle as said at least one sidewall, control means for issuing fluid into said chamber to effect displacement of the power stream relative to said divider, said sidewall and said divider being located relative to said power nozzle orifice to provide boundary layer positive feedback venting means including a port formed in said sidewall, said venting means communicating with a relatively constant pressure whereby power stream flow adjacent said port aspirates said venting means and reduces boundary layer effects between the power stream and said sidewall adjacent said port such that said amplifier has a boundary layer feedback factor which is positive and less than one, said port located downstream of and immediately adjacent the point of attachment between the power stream and said sidewall when said power stream is fully deflected into said one of said plural means.

**2.** The fluid amplifier as claimed in claim **1** wherein said control means comprises a control nozzle angularly positioned with respect to said power nozzle opposite said sidewall, fluid streams issuing therefrom effecting displacement of the power stream relative to said divider.

**3.** A fluid amplifier of the beam deflection type comprising a power nozzle having an orifice for issuing a constricted power stream, an interaction chamber positioned



downstream of said power nozzle for receiving fluid therefrom, said interaction chamber including a pair of sidewalls extending from adjacent said power nozzle and diverging outwardly in the direction of power stream flow in said chamber, plural output passages located downstream of said chamber for receiving fluid therefrom, flow splitting means including an apex located downstream of said chamber for dividing quantities of the fluid stream issuing from said chamber into each output passage, said apex being located a distance of approximately three power nozzle orifice widths downstream of said orifice of said power nozzle, said sidewall and said divider being located relative to said power nozzle orifice to provide boundary layer positive feedback, a pair of control nozzles angularly positioned with respect to said power nozzle, each control nozzle communicating with said chamber through a different sidewall for effecting directional displacement of said power stream in said interaction chamber by fluid control streams issuing therefrom, and at least one venting passage including a port formed in one of said sidewalls and communicating with a relatively constant pressure, said venting passage being aspirated by power stream flow across said port whereby boundary layer effects between said power stream and the sidewall downstream of said port are reduced by fluid entering said chamber from said venting passage such that said amplifier has a boundary layer feedback factor which is positive and less than one, said port being located downstream of the point of attachment of the power stream to the sidewall when the power stream is fully displaced into the outlet pasage located on the same side of the centerline of the power nozzle as said vent.

**4.** The fluid amplifier as claimed in claim **3** wherein a venting passage is provided in each sidewall and wherein the ports formed by each venting passage are positioned opposite each other.

**5.** A pure fluid amplifier of the combined stream interaction and boundary layer type comprising an interaction region, at least two output channels, a divider located between said output channels, a power nozzle for issuing a stream of fluid directed through said interaction region toward said output channels, a pair of sidewalls defining the lateral boundaries of said interaction region, said sidewalls diverging outwardly from adjacent said power nozzle and located sufficiently close to the centerline of said power nozzle to establish boundary layer effects between said power stream and said sidewalls, said sidewalls and said divider being located such as to produce a boundary layer feedback factor of less than unity and greater than zero, a pair of control nozzles for issuing fluid to deflect said stream of fluid so as to vary between two extremes the relative proportions of fluid directed to said outlet passages, said control nozzles communicating with said interaction region through different ones of said sidewalls adjacent said power nozzle, and a pair of vent passages providing communication through different ones of said sidewalls between said interaction region and a relatively constant pressure, said vent passages communicating with said interaction chamber at locations downstream of the points of attachment of the power stream to said sidewalls at the extremes of deflection of said stream and upstream of said points of attachment upon deflection of said stream of fluid to an extent less than said extremes of deflection.

**6.** A pure fluid amplifier of the combined stream interaction and boundary layer type comprising an interaction region, at least one output channel, a divider defining a wall of said output channel, a power nozzle for issuing a stream of fluid through said interaction region and toward said outlet passage such that at least a portion of said power stream when undeflected enters said outlet passage, a sidewall defining a lateral boundary of said interaction region and one wall of said output channel, said sidewall diverging outwardly from a point adjacent

said power nozzle being located sufficiently close to said power stream to have boundary layer effects established between said power stream and said sidewall, means for issuing a stream of fluid for deflecting said power stream towards said sidewall, a vent passage extending through said sidewall to provide communication between said interaction region and a generally predetermined pressure, said vent passage entering said region at a location downstream of and immediately adjacent to the extreme upstream location of the points of attachment of the power stream to said sidewall.

7. An analog pure fluid amplifier having stabilized boundary layer gain enhancement comprising a pair of output channels, an interaction region and power nozzle for issuing a stream of fluid through said interaction region towards said output channels, control means for developing a differential in pressure across said stream of fluid to deflect said stream between two positions as a continuous function of said differential in pressure and vary the relative proportions thereof directed to said outlet channels, a flow divider located between said output channels and defining one end of said interaction region, sidewalls defining opposite sides of said interaction region, said divider and said sidewalls being located such relative to said nozzle to establish boundary layer feedback, and means for maintaining the feedback factor of said boundary layer feedback at less than unity for deflections of said stream of fluid between said positions, said means comprising vents through said sidewalls located upstream



of the points of attachment of said stream of fluid to said sidewalls for deflections of said stream of fluid between said positions and located downstream of said points of attachment for deflections of said stream of fluid beyond said positions of deflection.

8. The combination according to claim 7 wherein said divider is located a distance from said power nozzle equal to approximately three times the width of said power nozzle.

9. The combination according to claim 7 wherein the distance between said sidewalls adjacent said power nozzle is not greater than approximately twice the width of said power nozzle.

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