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DESIGN OF A FLUID JET AMPLIFIER WITH REDUCED RECEIVER - INTERACTION-REGION COUPLING

by William S. Griffin
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SUMMARY

A bistable fluid jet amplifier has been developed to handle many of the undesirable effects of receiver loading, especially those in which reverse flow from the load to the amplifier occurs. This receiver reverse flow, which can be troublesome to fluid jet amplifiers of conventional design, has been dealt with by aiming the receivers of the Lewis Model B1 amplifier away from the interaction region and by including a small baffle wall to keep the receiver reverse flow and the interaction region entrainment flow from mixing. The diversion of receiver reverse flow was achieved without paying excessive penalties in receiver pressure and flow recoveries. The Lewis Model B1 maximum pressure and flow recoveries of 50 and 110 percent, respectively, were comparable to those of the conventional design amplifier which was used as a reference.

The Lewis Model B1 amplifier required control port pressures of only 12 percent of supply to switch the supply jet into a reverse flowing receiver pressurized at 100 percent of supply. The amplifier was still sensitive to negative receiver pressures, however, and would switch into a receiver pressurized at -15 percent of supply if no corrective control port pressures were applied. This effect could be important when driving a high inertial load such as a ram.

The amplifier exhibits a performance sensitivity of switching control pressures and flows to small manufacturing errors in the interaction region.

INTRODUCTION

In 1960, Diamond Ordnance Fuze Laboratories (now Harry Diamond Laboratories) introduced a series of fluid signal processing devices which were called fluid amplifiers. (Fluerics is the term adopted in July 1965 by the Government Fluid Amplifier Coordination Group to describe this general class of fluid devices. Within the general class of flueric devices are fluid jet amplifiers, vortex amplifiers, turbulence amplifiers, etc. Fluerics will be used throughout this report to denote such devices.)

Unlike the more conventional fluid signal processing devices available in 1960, flueric devices possessed no moving mechanical parts and relied instead on the interaction of streams of fluid for their operation. Their simplicity, ruggedness, and lack of moving parts made them appear quite reliable and suitable for use in extreme environments. Potential applications included the use of flueric devices as control components in the vicinity of a nuclear rocket engine, in jet engine inlet and fuel controls, and in hot gas servosystems. Considerable interest was aroused in their application, and a number of companies and Government agencies became active in the field (refs. 1 to 12).

Unfortunately, the development of practical flueric circuits proved more difficult than had originally been supposed. The fluid jet amplifiers of that time were often unstable or noisy when their receivers were blocked, and load-amplifier interactions occurred which degraded system performance. A load-amplifier interaction effect which proved troublesome was the coupling between a fluid jet amplifier and a blocked, highly capacitive load such as a piston or a bellows. In practical servosystems, however, bellows or piston loads are common, and their destabilizing effect on fluid jet amplifiers tended to hinder the development of flueric servosystems. This report presents a bistable fluid jet amplifier developed at the NASA Lewis Research Center; this Lewis Model B1 amplifier was specifically designed to handle such loads and the reverse flow which they can cause in the receivers of the amplifier. The amplifier is capable of driving reverse flowing loads with much smaller control signals than would be required of more conventional fluid jet amplifiers. This report presents a basis for design of such amplifiers, shows the detailed design of one selected model, and presents plots of the steady-state performance of the amplifier under a variety of receiver loading conditions.

SYMBOLS

D_j	width of main power nozzle, m (in.)
$\dot{m}$	mass rate of flow, kg/sec (lb mass/sec)
p	gage pressure, N/m^2 (lb force/in.^{2})

Subscripts:

a	atmospheric or atmospheric return
c	control
e	entrained
j	power nozzle or conditions at power nozzle
p	peeled off

r	receiver
s	supply conditions
1, 2	sides 1 and 2 of amplifier (fig. 1)

OPERATION OF INTERACTION REGION

A conventional bistable fluid jet amplifier is shown in figure 1. The control portion of the amplifier consists of a power nozzle, an interaction region, and a pair of control ports. The power nozzle forms a main power jet which is deflected in the interaction region by means of the wall attachment, or Coanda effect. The deflection of the jet is usually bistable, and the jet will attach to one of the two interaction region sidewalls as shown.

The jet may be switched from one sidewall to the other by application of pressure to either of the control ports, with deflection of the jet always being toward the control port having the lower pressure. After the jet has been deflected, it can flow into various types of receivers, one of which is shown in figure 2. Once the main power jet has been captured in a receiver, it can be diffused and used to actuate a load, such as a piston, or other fluid jet amplifiers.

Although a number of analyses have been developed to predict the attachment of a power jet to a single offset wall of infinite length (refs. 13 to 17), the analysis of a symmetrical, two-walled interaction region of finite length, such as shown in figure 1, has proved more difficult. However, the operation of the two-walled device does appear analogous to that of the single-walled model, and explanations of its operation have been

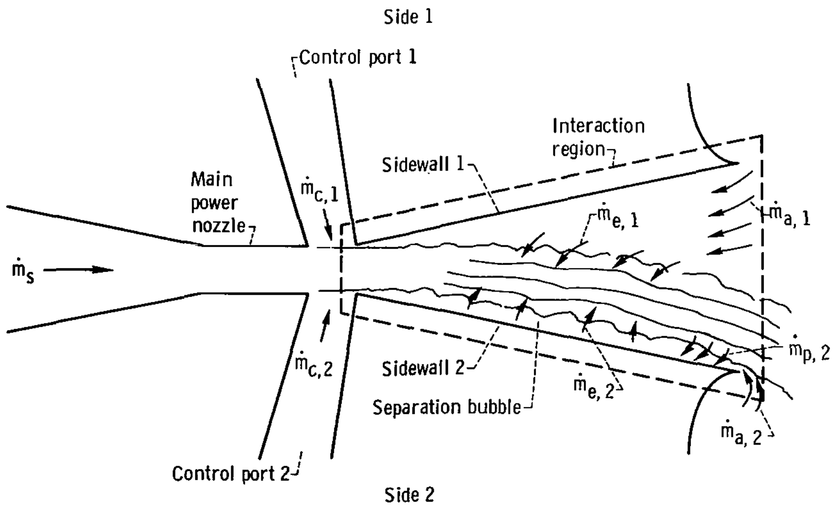
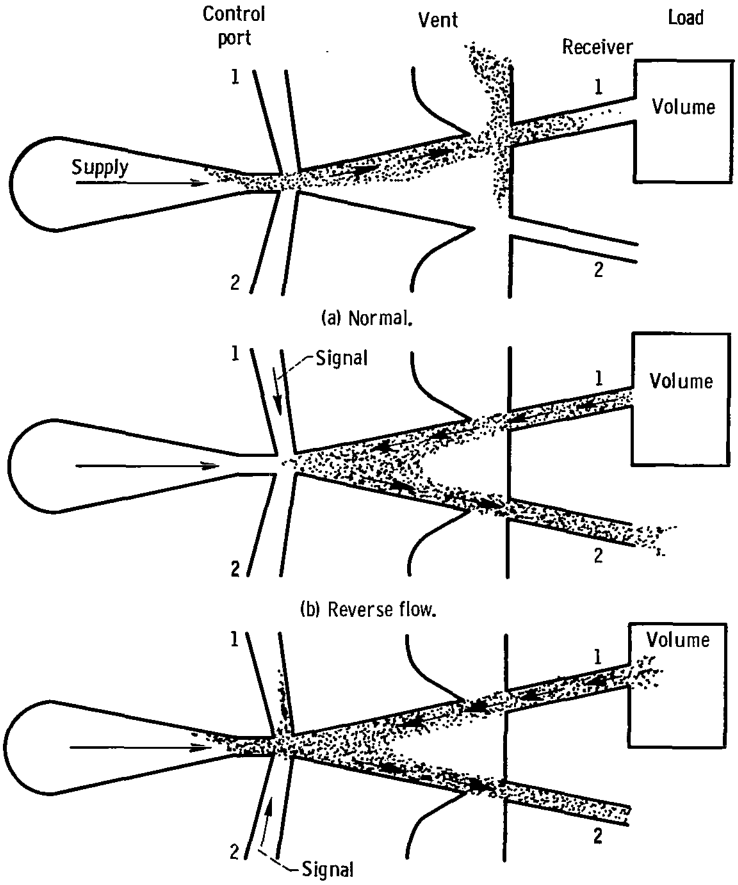


Figure 1. - Typical flow patterns in conventional, wall attachment bistable amplifier.



(a) Normal.

(b) Reverse flow.

(c) Attempt to switch.

Figure 2. - Performance of conventional design bistable element with various receiver loadings.

attempted by several authors (refs. 18 to 20). Basically, its operation is as follows.

The main power jet, after flowing past the control ports, enters the interaction region and begins to break up and diffuse into the surrounding stagnant fluid because of turbulent shearing stresses. The turbulent shearing stresses acting on the stagnant fluid effectively entrain that fluid (designated $\dot{m}_e$ in fig. 1) into the power jet. The power jet thus appears to widen and increase in mass flow. A control volume, bounded by the power jet, the sidewall, and the exit of the interaction region, may be drawn on either side of the power jet. In figure 1, the smaller of these two control volumes is denoted as the separation bubble. The flows into and out of these control volumes must balance during steady-state operation. Thus, from the notation of figure 1,

$$\dot{m}_{c,2} + \dot{m}_{p,2} + \dot{m}_{a,2} = \dot{m}_{e,2}$$

and

$$\dot{m}_{c,1} + \dot{m}_{p,1} + \dot{m}_{a,1} = \dot{m}_{e,1}$$

With the jet deflected to side 2, as shown, the entrainment flow $\dot{m}_{e,1}$ is easily furnished by an atmospheric return flow $\dot{m}_{a,1}$ which enters through a large effective orifice area between the power jet and sidewall 1. However, the effective orifice area for delivering the atmospheric return flow $\dot{m}_{a,2}$ to the separation bubble (side 2) has been decreased by deflection of the main power jet to that side. The pressure in the separation bubble must therefore decrease to provide the pressure drop necessary to cause $\dot{m}_{a,2}$ to flow into the separation bubble. The lower pressure in the separation bubble, however, will cause the jet to deflect still farther toward the sidewall and again reduce the effective orifice area for delivering $\dot{m}_{a,2}$. This process continues until the jet attaches to the sidewall. In a properly designed bistable fluid jet amplifier, the main power jet will be unstable in the centered position and will deflect toward one or the other of the two interaction region sidewalls until it is firmly attached.

The low pressure in the separation bubble will cause a certain amount of flow from the control port $\dot{m}_c$ to enter the separation bubble in the absence of a control pressure signal. The control flow $\dot{m}_{c,2}$, the atmospheric return flow $\dot{m}_{a,2}$, and the flow $\dot{m}_{p,2}$ that is peeled off the main jet when it impacts against the interaction region sidewall make up the flow $\dot{m}_{e,2}$ entrained by the main power jet as it passes over the separation bubble; therefore, $\dot{m}_c + \dot{m}_a$ must always be less than $\dot{m}_e$ for stable jet attachment. Thus, the jet will continue to deflect toward the sidewall until $\dot{m}_{p,2}$ is sufficient to satisfy the balance of flows into the separation bubble. If, however, the control flow $\dot{m}_c$ is increased to the point that $\dot{m}_c + \dot{m}_a$ is greater than $\dot{m}_e$, the main power jet will no longer need to attach to the sidewall to furnish flow $\dot{m}_{p,2}$ into the separation bubble. Thus, it will swing away and, being unstable in the centered position, attach to the other sidewall.

DESCRIPTION OF PROBLEM

If a fluid jet amplifier with low triggering pressure p_c and flow $\dot{m}_c$ is to be made, the jet entrainment flow $\dot{m}_e$ must be made very close to the atmospheric return flow $\dot{m}_a$. The jet attachment to the sidewall will not be highly stable, and small variations in the flows in the interaction region can cause the jet either to switch or to be much harder to switch. Since both $\dot{m}_e$ and $\dot{m}_a$ are large in comparison to $\dot{m}_c$, it becomes important to provide a quiet, ambient atmosphere downstream of the interaction region. Otherwise, fluctuations in downstream ambient pressure will cause fluctuations in $\dot{m}_a$ and variations in the switching characteristics of the amplifier.

One problem in providing a quiet, ambient atmosphere to the interaction region is illustrated in figure 2(a). In this view, the amplifier has been driving a blocked, capacitive load, such as a bellows or piston, and transient effects have died out. The main jet flow from the interaction region is impacting on the mouth of the receiver and flowing sideways out through the vents to the atmosphere. The presence of spillover flow from the receivers will cause some fluctuations in $\dot{m}_a$ as it flows to the interaction region. Thus, the receivers of an amplifier operating in the mode shown in figure 2(a) will often display high noise.

A more important situation is shown in figure 2(b). In this view, the amplifier has been switched away from the capacitive load. The capacitive load has begun to discharge and has created a reverse flowing jet which impinges on the interaction region. The reverse flowing jet will initially have a stagnation pressure equal to the maximum static pressure that the amplifier can develop when driving the blocked load. Typically, this would be 50 to 60 percent of supply pressure to the main power jet. As shown in figure 2(b), the momentum of this reverse flowing jet will keep the main power jet of the amplifier firmly attached to the lower wall. In addition, the introduction of the reverse flowing receiver jet into the interaction region probably upsets its flow patterns in much the same manner as introduction of flow by a control signal. Thus, to switch the main power jet back into the reverse flowing receiver, a control signal much larger than normal must be applied. This situation is shown in figure 2(c). Since receiver reverse flows will be generated whenever an amplifier is switched away from a capacitive load, large control signals may be required to drive capacitive loads at high switching speeds.

To obtain an indication of the severity of these effects, tests were made to determine the control pressures and flows required to switch a conventional fluid jet amplifier into a reverse flowing receiver. This would correspond to the situation in figure 2(c), in which a signal is being applied to control port 2 in an attempt to switch the main power jet into the reverse flowing receiver 1. The amplifier is shown schematically in figure 3. Figure 4 shows the required switching control pressures and flows plotted against the reverse flowing receiver pressure. The dashed curve is a plot of $p_{c,1}/p_s$ as a function of $p_{r,2}/p_s$, while the solid curve is a plot of $p_{c,2}/p_s$ as a function of $p_{r,1}/p_s$. For almost all the tests, the Mach number of the power nozzle was approximately 0.3, and the flows underwent little density change. Thus, gage pressures were measured instead of absolute pressures. Both pressures and flows were normalized with respect to supply pressures and flows furnished to the main power nozzle. As can be

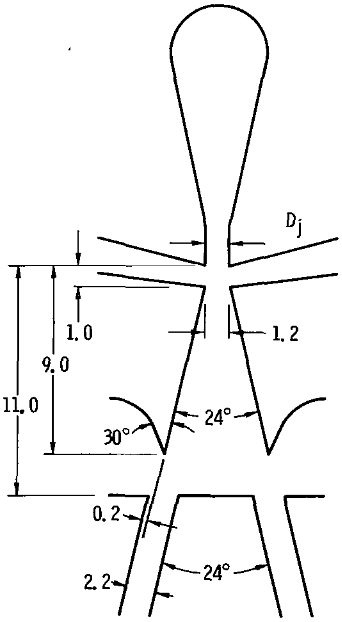
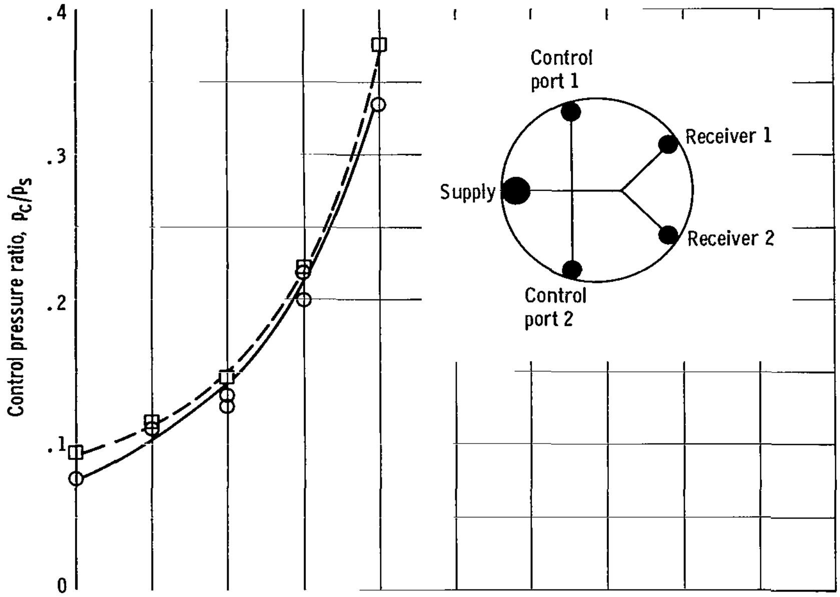
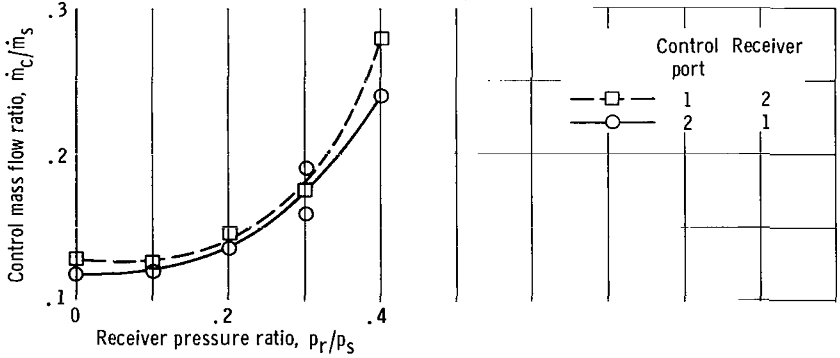


Figure 3. - Dimensions of standard bistable fluid jet amplifier selected for comparison with Lewis Model B1 amplifier. (All linear dimensions are to be multiplied by D_j.)



(a) Control pressures.



(b) Control flows.

Figure 4. - Control pressures and flows required to switch conventional fluid jet amplifier into reverse flowing receiver. Other receiver is vented to atmosphere. Supply pressure, 6.89×10^3 newtons per square meter gage (1.0 psig).

seen, the required control signals rise sharply as functions of the normalized pressure p_r/p_s of the reverse flowing receiver. If the receiver is loaded at a pressure greater than 40 percent of supply, the signal pressure gain p_r/p_c through the device becomes less than 1. Since this particular amplifier could develop a blocked receiver pressure of 55 percent of supply, time would have to be allowed for the volume load to discharge before the amplifier could be switched into it. Depending upon the size of the volume load and the control signals applied to the amplifier, both the signal pressure gain p_r/p_c and the signal flow gain $\dot{m}_r/\dot{m}_c$ through the amplifier and its speed of response could be severely penalized.

These comments will also tend to apply for the case in which the amplifier is driving a long line which is terminated by an impedance greater than the characteristic acoustical impedance of the line. In this case, the line can deliver reverse flow into the receiver of the amplifier when the amplifier is switched away from the line. This reverse flow will continue until pressure and rarefaction waves have traversed the line a sufficient number of times to discharge it. While this effect would not be as serious as the case of a dead-ended volume load, it could still be important in very high speed digital circuitry.

DESIGN APPROACHES

Two conflicting requirements had to be fulfilled in the design of the amplifier. First, the receiver reverse flow had to be diverted away from the interaction region, and it was desirable to supply a quiet, ambient atmosphere to the interaction region. Second, the receiver had to develop satisfactory pressure and flow recoveries during normal, forward flowing operation. Both changes in amplifier geometry and the interaction of flow fields could be used to accomplish these objectives. The former approach was chosen primarily because of the lack of flow visualization equipment at the time of development of the amplifier.

The resulting amplifier design is shown in figures 5 and 6. As can be seen, the receivers in the Lewis Model B1 amplifier are pointed away from the interaction region, and reverse flow exiting from them will flow out vents 3. The entrance to vent 3 is widened slightly so that the extra flow entrained by the receiver reverse flow jet will be captured and diverted away from instead of into the interaction region. A separate vent 2 is used to provide communication of the interaction region with the atmosphere. This communication with the atmosphere becomes important upon loading of the receiver toward which the jet is directed. If the receiver is loaded with an orifice load or is blocked, the flow pattern will appear somewhat like that shown in figure 7(a). As the main power jet flow enters the receiver inlet, a portion makes a sharp turn at the receiver mouth and exhausts out vent 3. Some of the flow (not shown) near the receiver mouth will reverse itself and travel backward along the wall in a boundary layer toward the interaction region. Without vent 2 this flow would enter the interaction region and could cause the jet to switch. However, vent 2 diverts this reverse boundary layer flow to the atmosphere. Vents 2 and 3 are exhausted separately to the atmosphere so that receiver spillover flow issuing from vent 3 remains isolated from the atmospheric return flow to the interaction region from vent 2.

A center dump vent 1 is used to divert a low-velocity portion of the main power jet away from the receiver inlet. Diversion of the low-kinetic-energy fluid enables higher pressures to be developed in the receivers.

The benefit of directing the receivers away from the interaction region is shown in figure 7(b). In this view, the amplifier has just been switched away from a volume load

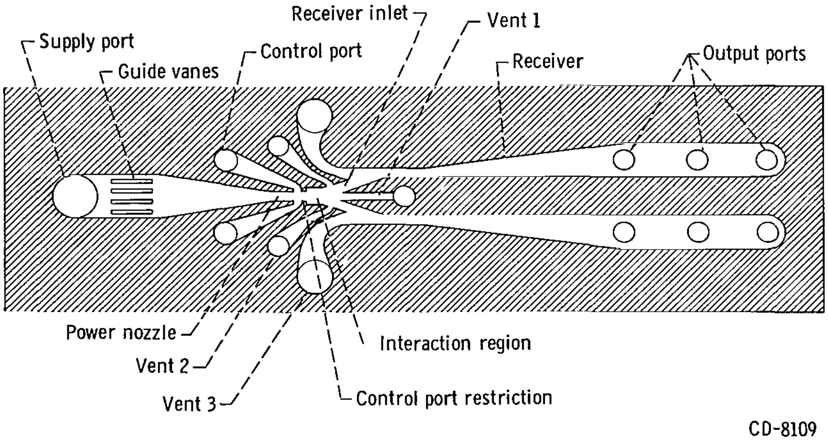


Figure 5. - Lewis Model B1 fluid jet amplifier.

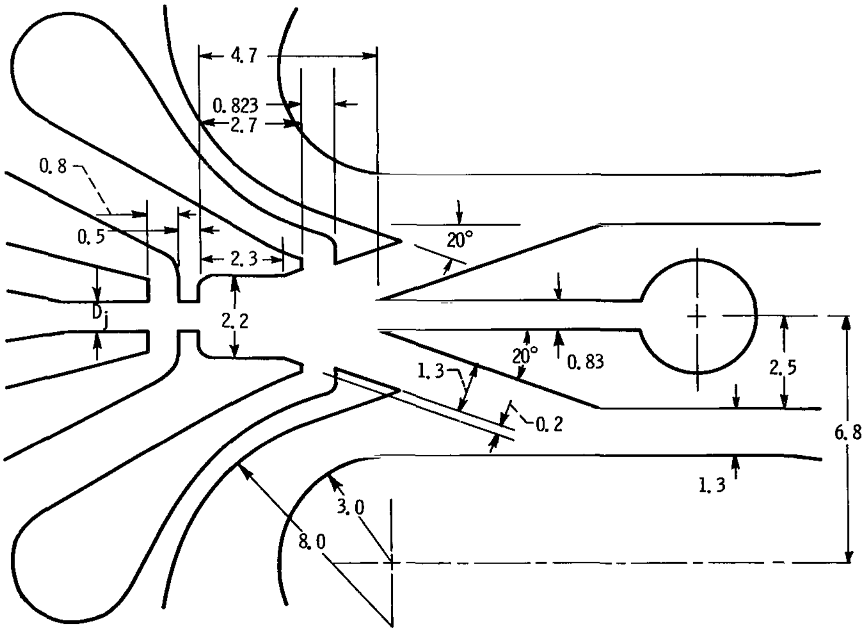
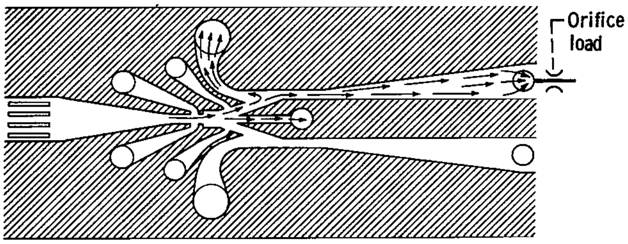
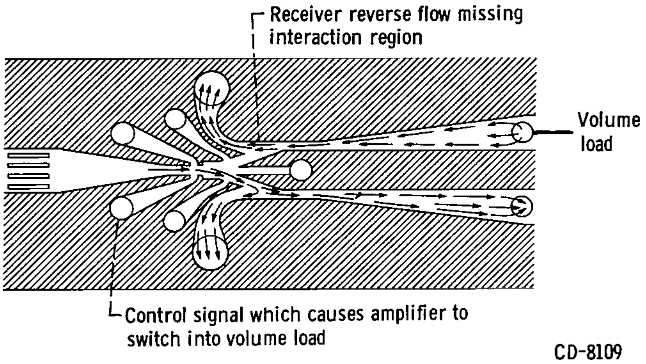


Figure 6. - Dimensions of Lewis Model B1 fluid jet amplifier. (All linear dimensions are to be multiplied by D_j.)



(a) Normal, forward flowing operation.



(b) Operation when receiver is reverse flowing.

Figure 7. - Performance of Lewis Model B1 fluid jet amplifier under various loading conditions.

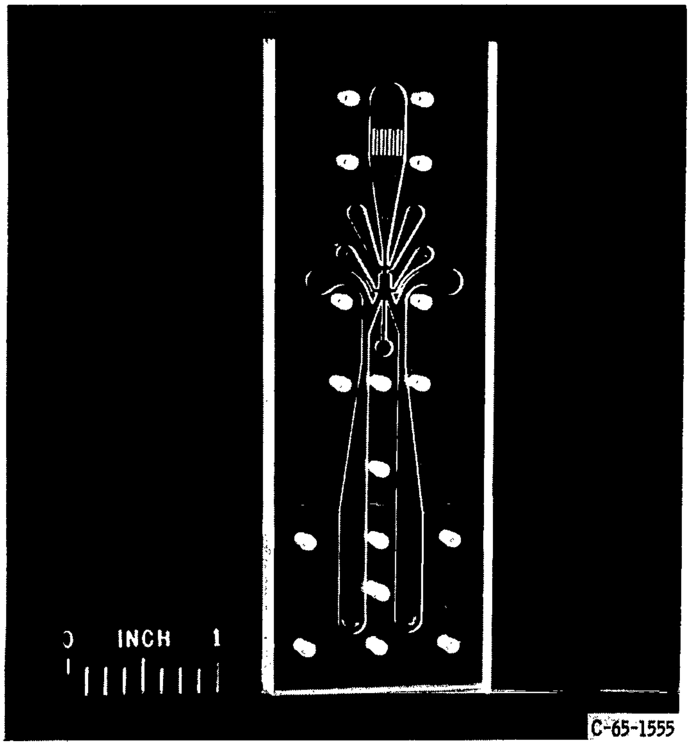


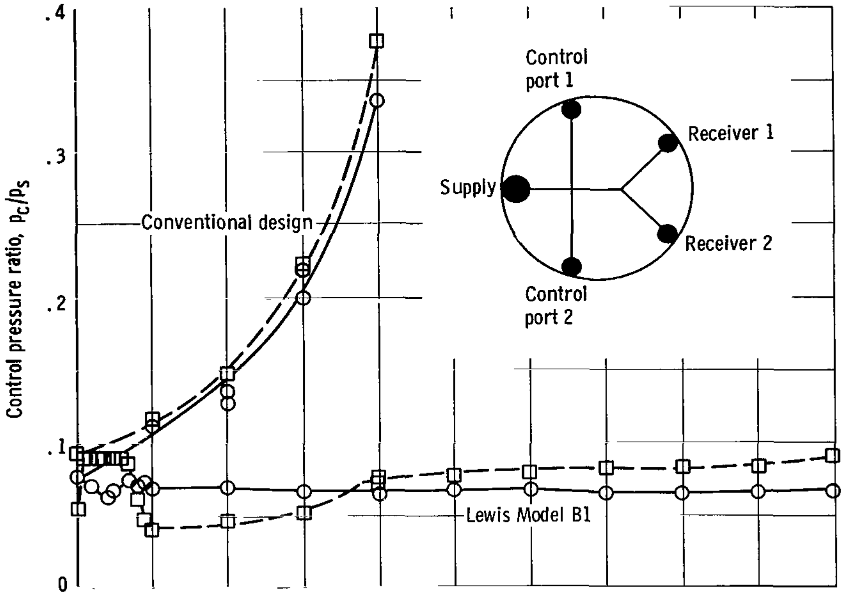
Figure 8. - Lewis Model B1 fluid jet amplifier.

and the load has begun to discharge through the left receiver. The receiver reverse flow jet thus created, however, is diverted into vent 3 instead of the interaction region. Vent 2 will still provide atmospheric return flow at close to atmospheric pressure to the interaction region. Thus, if a control signal is applied to the right amplifier control port before the volume load has finished discharging, the power jet can be switched back into the reverse flowing receiver.

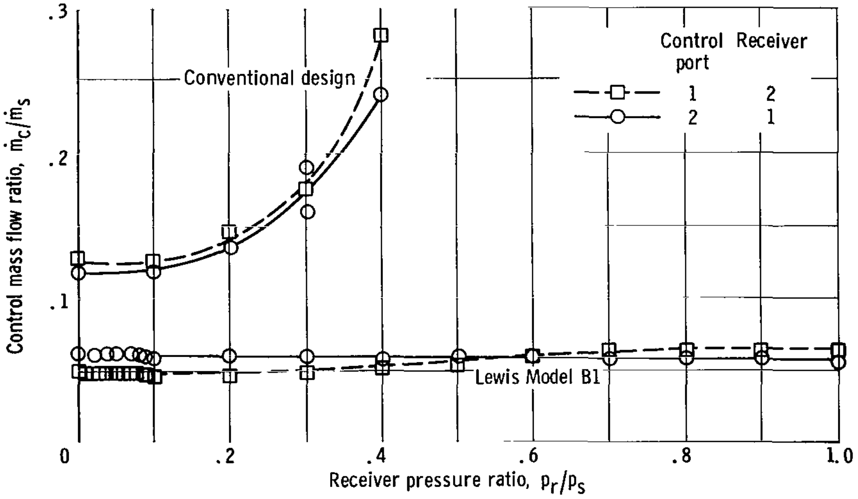
EXPERIMENTAL PERFORMANCE OF THE LEWIS MODEL B1 AMPLIFIER

Static tests were conducted on the Lewis Model B1 amplifier to determine its performance under various loading conditions. Dynamic performance was not evaluated since this report deals primarily with receiver design, while dynamic performance is primarily a function of interaction region design. Equipment and test procedures are described in appendix A.

The amplifier, shown in figure 8, was machined out of an acrylic block by a pantograph engraving machine. The power throat section was 0.101 centimeter (0.040 in.) wide by 0.152 centimeter (0.060 in.) deep. The root mean square wall surface roughness was optically measured and judged equal to or less than 0.000166 centimeter root mean square (64 μin.) in the



(a) Control pressures.

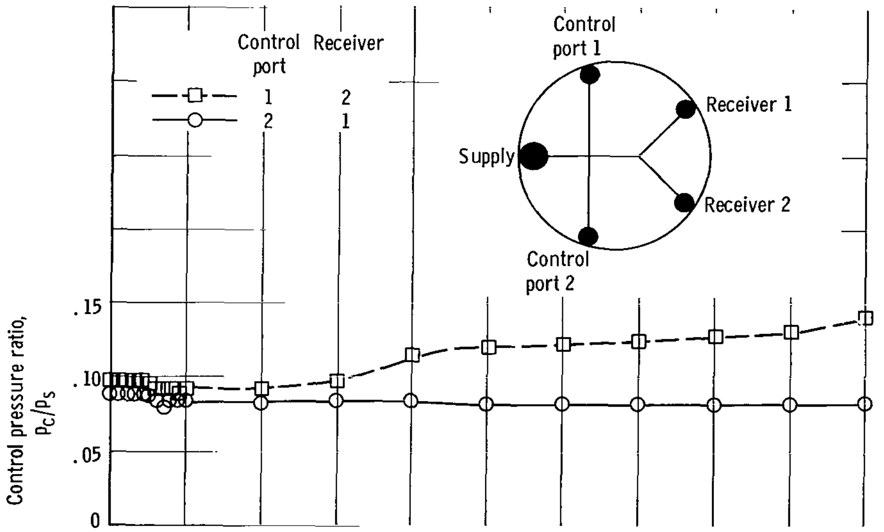


(b) Control flows.

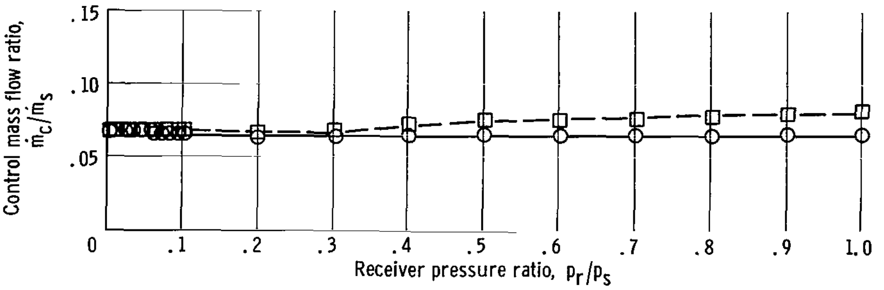
Figure 9. - Control pressures and flows required to switch conventional and Lewis Model B1 fluid jet amplifiers into reverse flowing receivers. Other receiver is vented to atmosphere. Supply pressure, 6.89x10^3 newtons per square meter gage (1.0 psig).

vicinity of the power nozzle and interaction region. No particular effort was made to trim the amplifier for symmetrical performance other than the exercising of suitable care in machining the entire unit. It should be pointed out, however, that the amplifier performance is very sensitive to small interaction region manufacturing errors.

Figure 9 shows the control pressures and flows required to switch a conventional amplifier and the Lewis Model B1 amplifier into a reverse flowing receiver with the other receiver being vented. The required static triggering pressures p_c/p_s of the Lewis Model B1 amplifier are much lower than those of the more conventional design. If the reverse flowing receiver is pressurized at 40 percent of supply, the conventional unit requires a switching control pressure in excess of 33 percent of supply, while the Model B1 amplifier can be switched into the reverse flowing receiver by means of a control signal of only 8 percent of supply. Furthermore, the Model B1 amplifier can be switched into a reverse flowing receiver when the receiver pressure is as high as 100 percent of the supply pressure to the main power nozzle. Figure 10 shows that this behavior also exists if the receiver from which the jet is being switched is blocked. However, as is



(a) Control pressures.



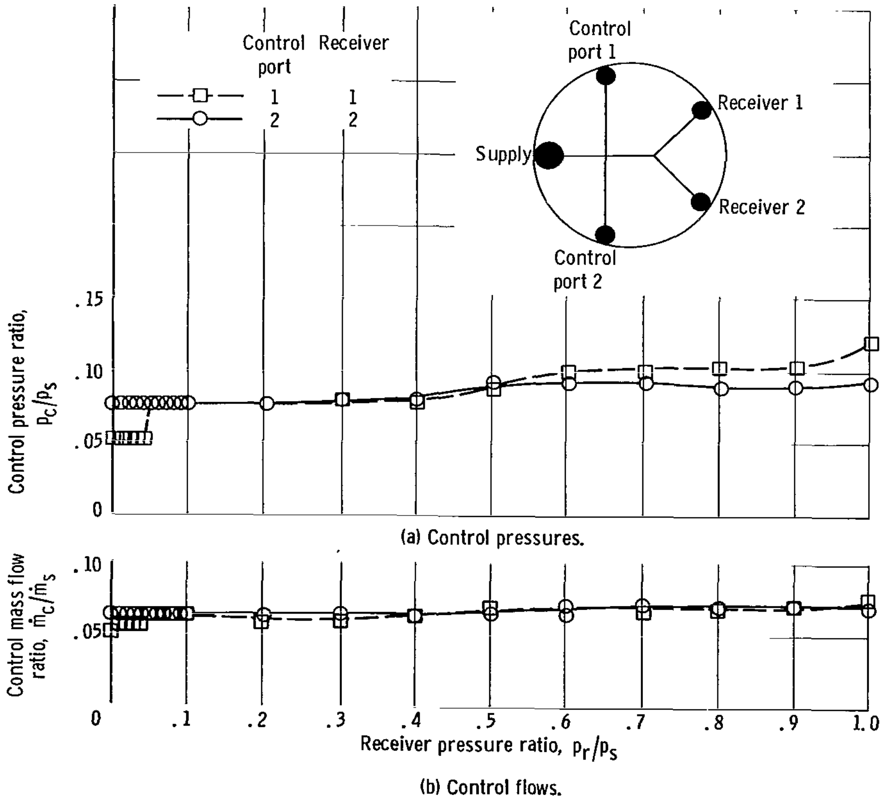
(b) Control flows.

Figure 10. - Control pressures and flows required to switch Lewis Model B1 fluid jet amplifier into reverse flowing receiver. Other receiver is blocked. Supply pressure, 6.89×10^3 newtons per square meter gage (1.0 psig).

shown in figure 10, some receiver-interaction region coupling exists which raises the triggering pressure of the amplifier slightly.

It is of interest to know the variation in switching control pressures of the Lewis Model B1 amplifier when switching away from a pressurized receiver. These control pressures are shown in figure 11 as functions of the pressure of the receiver into which the jet is flowing. The receiver into which the jet is being switched is vented to the atmosphere. It is noted that control pressures of 10 percent of supply are sufficient with receiver pressures up to 60 percent of supply. It should also be noted that the jet attachment becomes more stable with increasing receiver pressure. This behavior is opposite to that of a more conventional design which becomes less stable if a receiver is blocked.

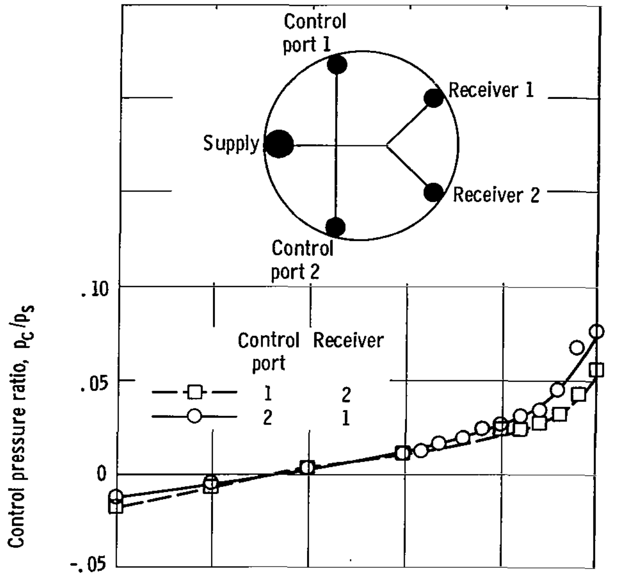
Although the triggering performance of the Lewis Model B1 amplifier has been made relatively insensitive to receiver reverse flow, a negative pressure in one of the receivers can cause the jet to switch into that receiver. This is shown in figure 12, in which the control pressures required to switch the amplifier into a negatively pressurized



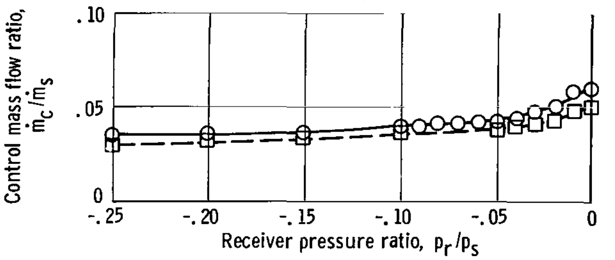
(a) Control pressures.

(b) Control flows.

Figure 11. - Control pressures and flows required to switch Lewis Model B1 fluid jet amplifier away from pressurized receiver. Other receiver is vented to atmosphere. Supply pressure, 6.89×10^3 newtons per square meter gage (1.0 psig).



(a) Control pressures.



(b) Control flows.

Figure 12. - Control pressures and flows required to switch Lewis Model B1 fluid jet amplifier into negatively pressurized receiver. Supply pressure, 6.89×10^3 newtons per square meter gage (1.0 psig).

receiver are plotted as functions of the receiver pressure. As can be seen, negative receiver pressures of 15 to 20 percent of supply are sufficient to switch the jet without the application of a control signal. It is to be noted that figure 12 is merely the left portion of figure 9 (p. 11). As will be shown presently, this triggering sensitivity to negative receiver pressure will become important if the amplifier is used to drive a piston.

Figure 13 shows x, y-recorder plots of the receiver pressure-flow characteristics when the jet was directed toward and also away from the receiver at which the measurements were being taken. It is noted that if the jet is switched away from the receiver and flow is drawn from the receiver (positive $\dot{m}_r/\dot{m}_s$), a negative receiver outlet pressure will result. If enough flow is drawn out of the receiver, the jet will finally switch into the negatively pressurized receiver. These switching points are noted in figure 13 and correspond to the negative receiver pressures in figure 12 which will cause the jet to switch without the application of a control signal. To complete the rest of the plot for negative p_r/p_s in figure 13, a continuous pressure was applied to the control port of the amplifier to keep the amplifier from switching.

The significance of the tendency of the amplifier to switch into a negatively pressurized receiver becomes apparent if the case of a frictionless inertial load, such as a well lubricated piston, is considered. With such a load, the steady-state pressure drop across the load will be zero, and the mass flow into the load will be approximately equal to the mass flow exiting from it. Hence, the two receiver pressures will be equal, and the flow out of one receiver will be equal to the negative of the flow out of the other (excluding the effects of compressibility). To aid in establishing this point, the lower half of figure 13 is reflected about the horizontal axis and is plotted in the upper half of the figure. The intersection of the two curves indicates that a normalized mass flow of ± 62 percent of supply and a normalized receiver pressure of 28 percent of supply are

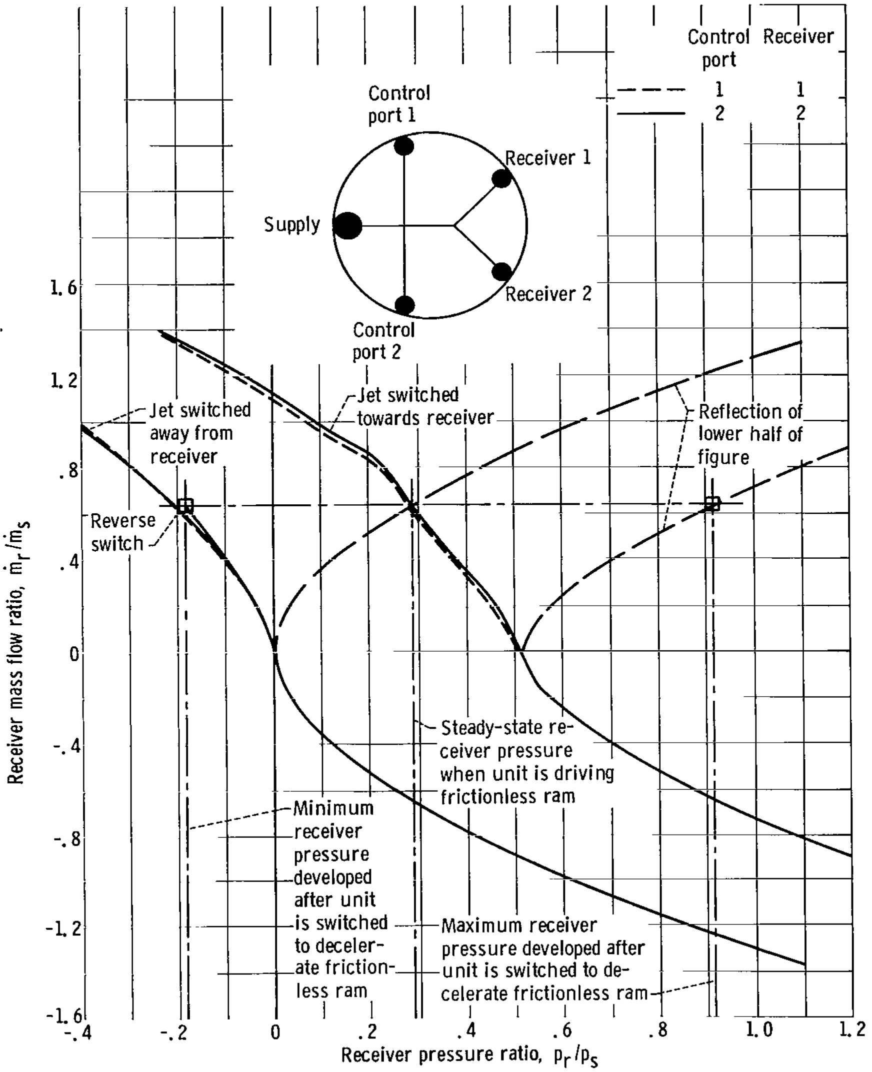
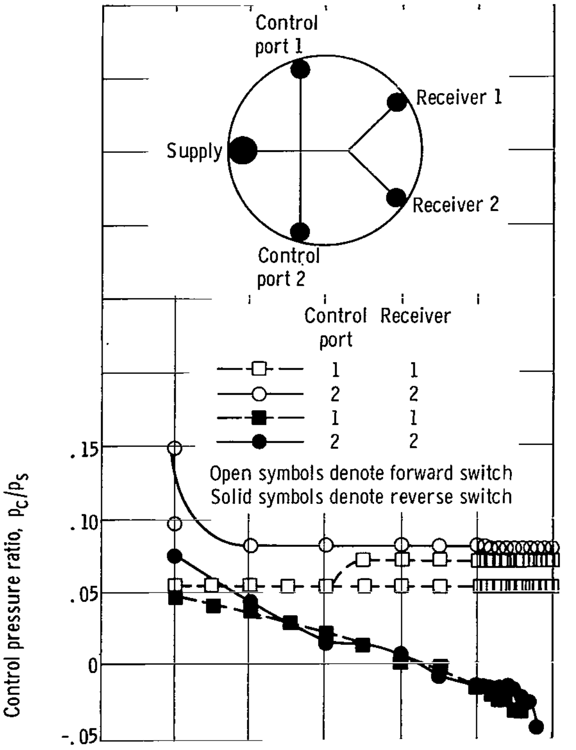


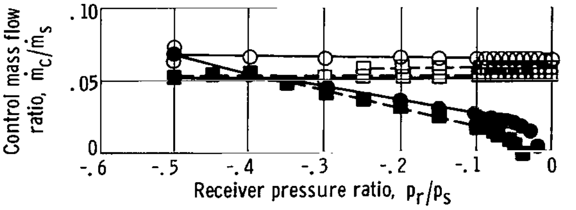
Figure 13. - Lewis Model B1 fluid jet amplifier receiver pressure-flow characteristics. Supply pressure, 6.89×10^3 newtons per square meter gage (1.0 psig).

created under such conditions. If a short-duration pulse is applied to the amplifier to cause it to switch and brake the piston, the receiver mass flows will initially remain the same because of the inertia of the piston. The new operating conditions for the receivers are indicated by the squares in figure 13. A maximum pressure of approximately 91 percent of supply exists in one receiver and a minimum pressure of -18 percent of supply is created in the other. This value of negative receiver pressure, as shown in figures 12 and 13, is close to the value which could cause the jet to switch back into the negatively pressurized receiver and again accelerate the piston up to maximum velocity.

Fortunately, this situation may be avoided if steady control pressures or long duration pulses, rather than short pulses, are used to control the Model B1 amplifier. All



(a) Control pressures.



(b) Control flows.

Figure 14. - Control pressures and flows required to switch Lewis Model B1 fluid jet amplifier away from negatively pressurized receiver. Supply pressure, 6.89×10^3 newtons per square meter gage (1.0 psig).

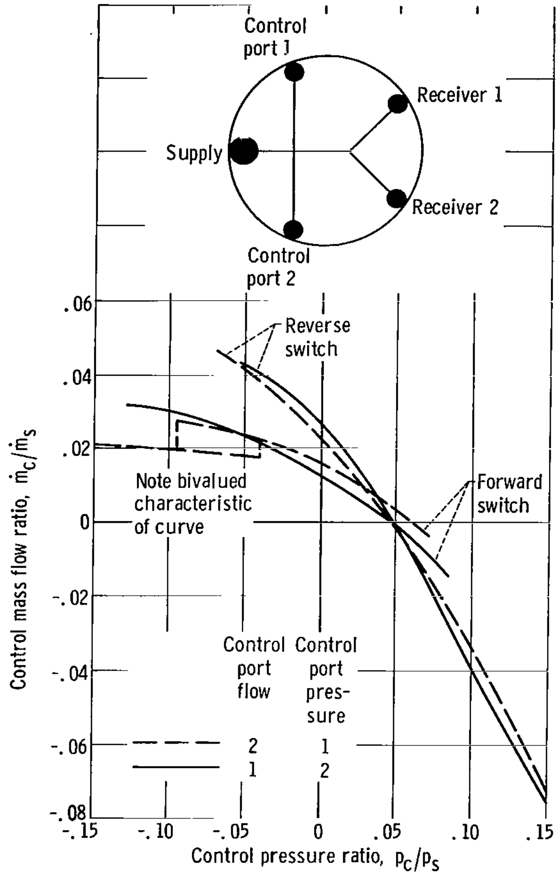


Figure 15. - Lewis Model B1 fluid jet amplifier control port crossflow characteristics. Supply pressure, 6.89×10^3 newtons per square meter gage (1.0 psig).

that is required is an appreciable hysteresis region between the control pressure required to switch the jet away from a negatively pressurized receiver and the control pressure which will permit the jet to switch back. This situation is illustrated in figure 14, which is merely the left portion of figure 11 (p. 13). Two sets of data are presented; the open symbols denote the control pressures which will cause the power jet to switch away from a negatively pressurized receiver (forward switch), and the solid symbols denote the control pressures which permit the jet to switch back (reverse switch). Circles and squares denote control ports 1 and 2, respectively. A hysteresis region exists between the curves defined by these two sets of symbols for negative receiver pressures less than 40 percent of supply. Thus, for p_r/p_s less than -40 percent, the jet, once switched, will stay switched. For p_r/p_s greater than -40 percent, the jet will tend to be rough in switching and will oscillate rapidly between the negatively and positively pressurized receivers. Control pressures much larger than those defined by the open symbols are required to keep the jet switched to the positively pressurized receiver under these conditions. Since there will always be some friction in the piston load, it is unlikely that such a negative receiver pressure will ever be exceeded.

The control port crossflow characteristics (flows in one control port due to pressurization in the other) are shown in figure 15. For positive control port pressures between 0 and 5 percent of supply, it is noted that control port crossflow is negligible. However, since control pressures of 10 and sometimes 15 percent of supply are required, control port crossflow might be a significant factor in some cases and should not be ignored. A small bivalued region in the curve exists (as noted in fig. 15) possibly as a result of some secondary wall attachment effects or flow pattern changes in the control port region.

Figures 16 and 17 show plots of the control pressures required to switch the Lewis Model B1 amplifier into an unloaded receiver as functions of amplifier supply pressure. As noted in the figures, the supply pressure that was used for taking all data in this report except for figures 16 and 17 was 6.89×10^3 newtons per square meter gage (1.0 psig). Thus, the data point $p_{c,2}/p_s = 0.08$ at $p_s = 6.89\times10^3$ newtons per square meter gage (1.0 psig) in figure 16 corresponds to the data point of $p_{c,2}/p_s = 0.08$ for $p_{r,1}/p_s = 0$ in figure 9(a) (p. 11). Depending upon the rapidity with which the control signal was increased to the switching point, one of two distinct triggering pressures was observed. These two triggering pressures were tabulated, when observed, and form the upper and

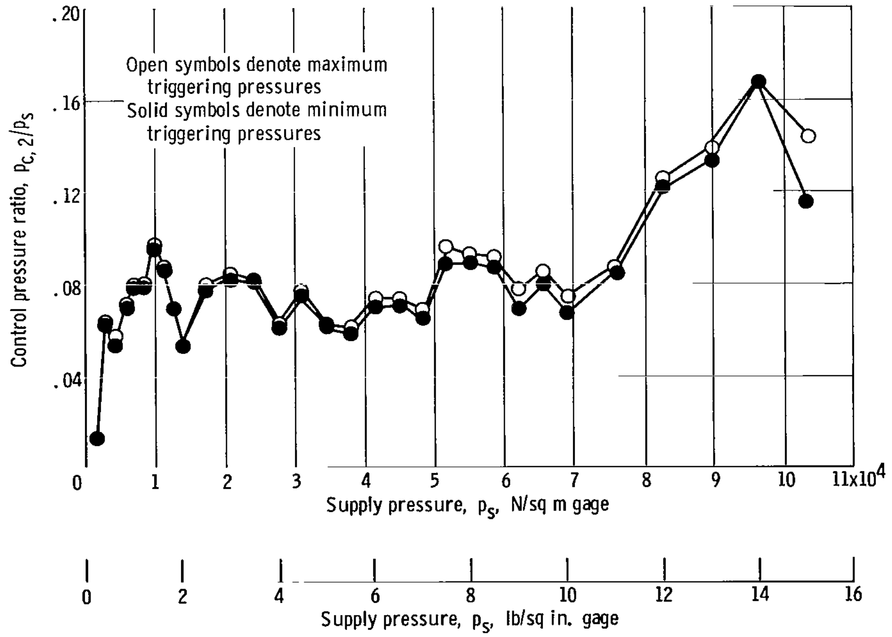


Figure 16. - Variation of control port 2 triggering pressures with supply pressure.

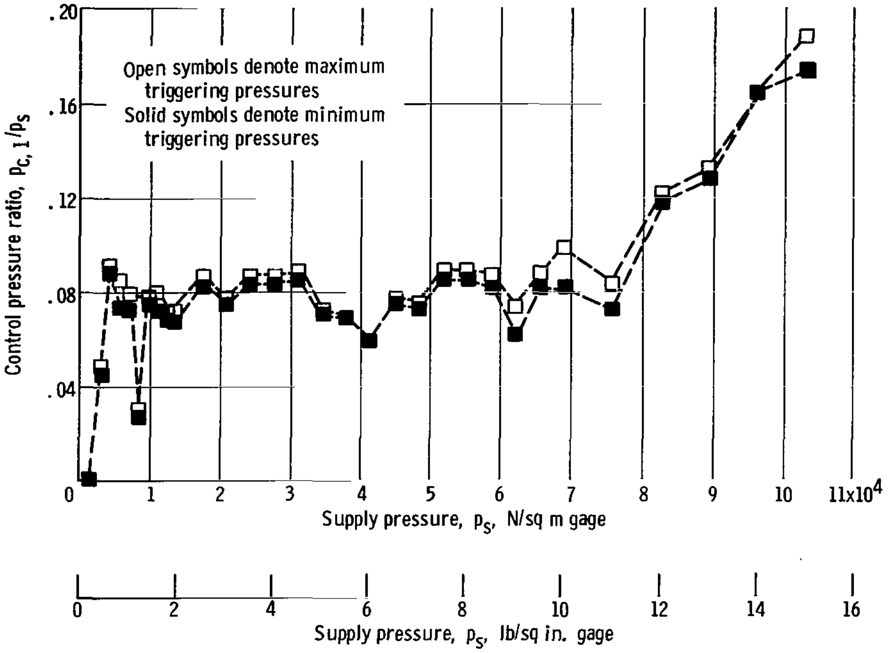


Figure 17. - Variation of control port 1 triggering pressures with supply pressure.

lower lines in the graphs. At times, this variation between maximum and minimum triggering pressures could be substantial, as, for example, the control port 1 switching pressures at an amplifier supply pressure of 6.89×10^4 newtons per square meter gage (10 psig).

In addition to the spurious changes in switching control pressures at a constant supply pressure, large variations in control switching pressure will occur as the supply pressure is changed. The triggering pressures vary erratically over the entire range of supply pressures. Occasionally, sharp dips in control pressure occur as in the case where control port 1 triggers pressure at a supply pressure of 8.27×10^3 newtons per square meter gage (1.2 psig). In this range, no apparent correlation exists to explain the erratic changes in triggering pressures. Although the amplifier design was symmetrical and the test unit was carefully machined, the control port switching pressures were usually asymmetrical. The degree of asymmetry tended to be of the same magnitude as the average variation of control switching pressure with supply pressure.

At the time of the writing of this report, the source of these performance irregularities had not been established. Duplicate amplifiers were made which exhibited variations in triggering pressures of ± 50 percent of the nominal values. Furthermore, unless the amplifiers were very carefully machined, their performance tended to be highly asymmetrical. As mentioned in appendix B, the amplifiers could be trimmed to give symmetrical performance, but the average triggering pressures might vary from +25 percent to -50 percent of the values reported herein.

Two limitations of minimum and maximum operating supply pressures are also shown by figures 16 and 17. The lower operating supply pressure is believed to represent a minimum throat Reynolds number (approximately 4770, based on throat width) at which the amplifier will function. The rise in triggering pressures after a supply pressure of 7.58×10^4 newtons per square meter gage (11.0 psig) is reached probably indicates the effects of compressibility.

CONCLUSIONS

It is concluded that a bistable fluid jet amplifier with reasonable receiver pressure and flow recoveries can be made which exhibits greatly reduced triggering sensitivity to receiver loading effects. The design is particularly good at handling receiver reverse flow such as might be delivered by a piston or bellows and should find application for such loads. At a supply pressure of 6.89×10^3 newtons per square meter gage (1.0 psig), the amplifier could be switched into a reverse flowing receiver pressurized at 100 percent of supply. Application of continuous control port pressures and flows of approximately 15 and 10 percent of supply, respectively, is sufficient to enable the amplifier tested to drive a piston under most conceivable modes of operation.

The interaction region exhibits a strong performance sensitivity to Reynolds number variations and to small manufacturing errors, especially wall roughness. Any particular amplifier may be trimmed to give symmetrical performance and will continue to give reasonably reproducible results.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 9, 1966,
122-29-03-09-22.

APPENDIX A

EQUIPMENT AND TEST PROCEDURES

Measurements of amplifier triggering pressure and flows as functions of receiver loading were conducted with the test setup shown schematically in figure 18. A servo pressure controller (fig. 19) was used to maintain either constant positive or constant negative pressures on one of the two receivers of the amplifier, regardless of the flow through the receiver. With this controller, receiver pressure was held to within 2 percent of the nominal value. The other receiver was optionally blocked with a needle valve

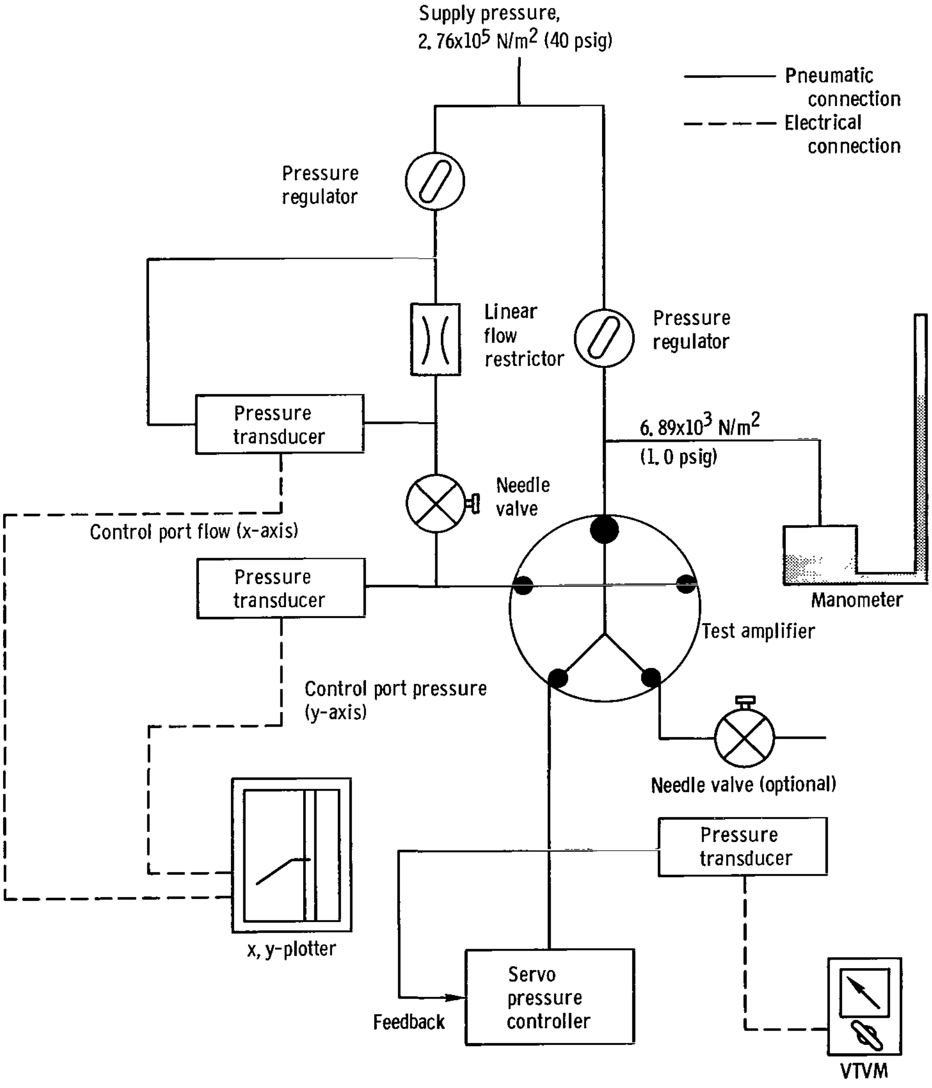


Figure 18. - Schematic diagram of test apparatus to measure control port switching pressures and flows.

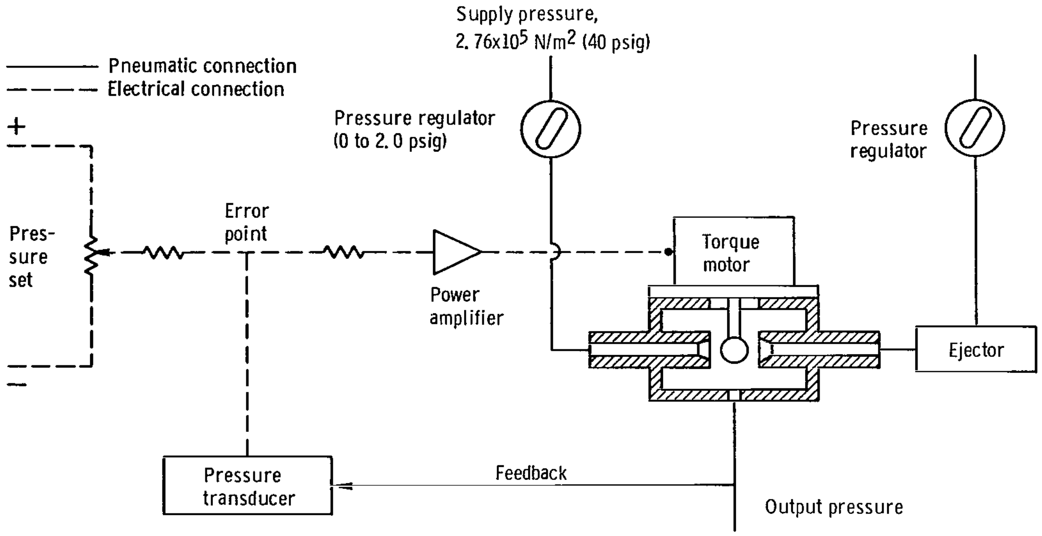


Figure 19. - Schematic diagram of servo pressure controller.

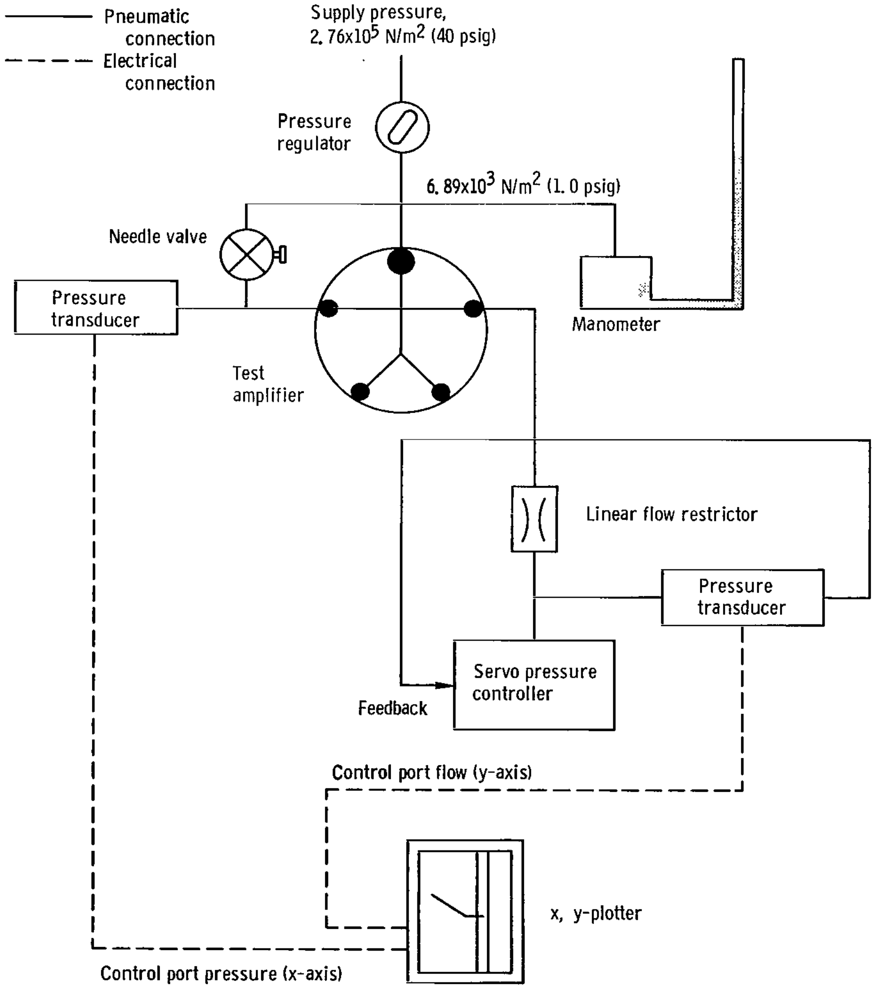


Figure 20. - Schematic diagram of test apparatus to measure control port crossflow characteristics.

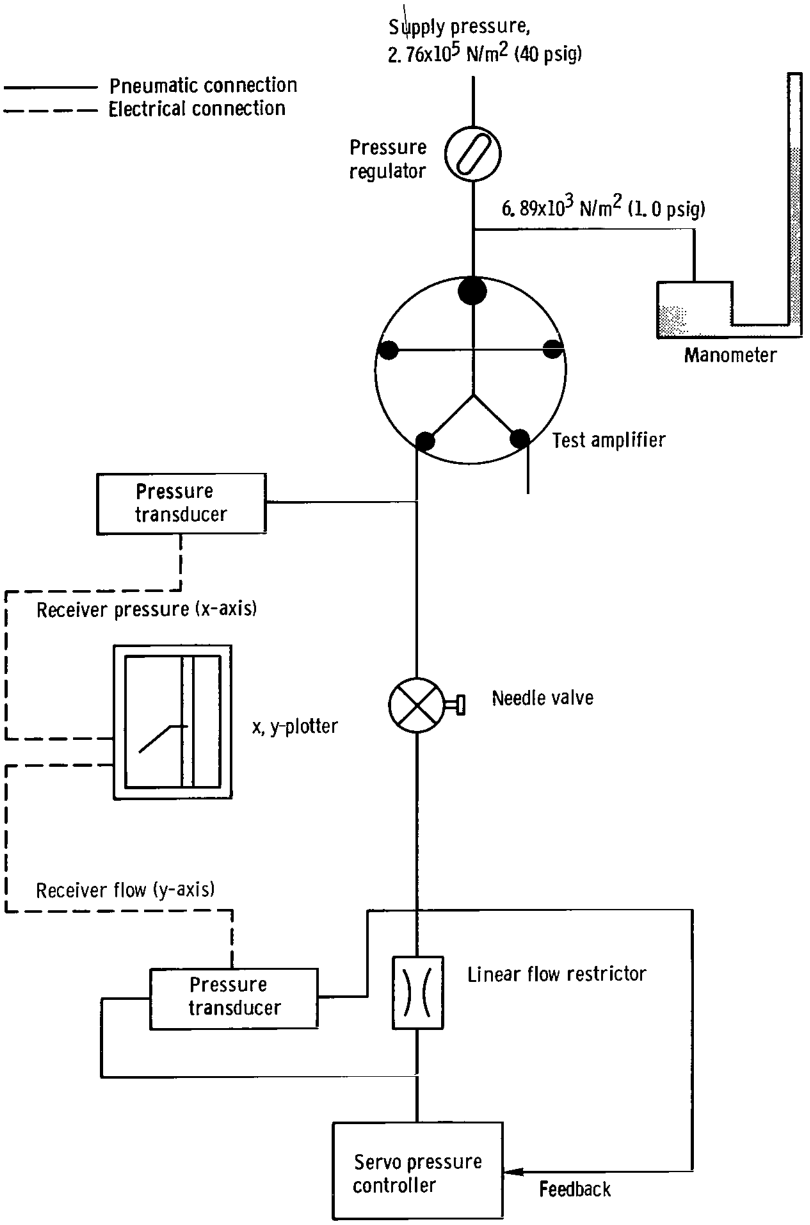


Figure 21. - Schematic diagram of test apparatus to measure receiver characteristics.

or left open to the atmosphere. The point of triggering was determined by observing the point at which the trace on the x, y-recorder plot made a sudden break from the previously smooth curve. Supply pressures for this and all other tests except those used for plotting figures 16 and 17 were a nominal 6.89×10^3 newtons per square meter gage (1.0 psig).

Control port crossflow characteristics (the flow in one amplifier control port as a function of pressure in the opposite control port) were measured with the test setup shown in figure 20. The servocontroller was again used to maintain atmospheric pressure at the amplifier control port at which the flow was being measured. Thus, a flow resistor with a linear pressure-drop - mass-flow characteristic could be used to measure control port crossflow without changing the ambient pressure supplied to the control port.

Receiver characteristics were measured with the setup shown schematically in figure 21. The servocontroller was again used to maintain the pressure upstream of the linear flow element constant but at a negative gage pressure equal to the supply pressure of the amplifier, 6.89×10^3 newtons per square meter gage (1.0 psig). Thus, measurements of receiver flow could be made at subambient pressures.

All tests of the amplifier except for the measurements of triggering pressures as functions of supply pressures (figs. 16 and 17, pp. 17 and 18) were conducted at a supply pressure of 6.89×10^3 newtons per square meter gage (1.0 psig) and a temperature of 297° K (75° F).

APPENDIX B

SOURCES AND MAGNITUDES OF ERROR

The estimated individual and total errors for pressure and flow measurements are listed in table I. The errors are normalized with respect to the nominal supply pressure and flow of the amplifier. Since percentage and absolute errors tended to be a function of the ranges of the pressure transducers and flow meters used, separate estimates are given for the control ports and receivers.

TABLE I. - ESTIMATED ERRORS

(a) Pressure errors

Type of error	Error, percent of nominal supply pressure
Control port	
Transducer hysteresis and nonlinearity	0.5
Transducer calibration	.1
Reading	.2
Total estimated control port pressure error	.8
Receiver	
Transducer hysteresis and nonlinearity	.5
Transducer calibration	.5
Total estimated receiver pressure error	1.0

(b) Flow errors

Type of error	Error, percent of nominal supply flow
Control port	
Transducer and flowmeter combined hysteresis and nonlinearity	0.3
Calibration	.3
Reading	.3
Total estimated control port flow error	.9
Receiver	
Transducer and flowmeter combined hysteresis and nonlinearity	1.0
Calibration	3.0
Total estimated receiver port flow error	4.0

The internal dimensions of the amplifier were verified with a toolmaker's microscope. Measurements of the amplifier discussed herein and of subsequent models indicated that tolerances in the nozzle and interaction region areas could be held to within approximately 0.0025 centimeter (0.001 in.), or roughly 2 percent of the power nozzle width (0.101 cm). The root mean square nozzle and interaction region wall roughness was approximately 166 microcentimeters (64 μin.). However, a strong variation in triggering pressures and flows resulted from one amplifier to the next and on the amplifier reported herein. At times, two distinct triggering pressures were noted (figs. 14, 16, and 17, pp. 16, 17, and 18). This variation in performance characteristics was apparently caused by variations in the flow patterns in the interaction region and is discussed in detail in the section EXPERIMENTAL PERFORMANCE OF AMPLIFIER. The amplifiers frequently had asymmetrical triggering pressures but could be trimmed to give symmetrical performance by shaving a small amount of material off the appropriate control port restriction.

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