NASA TECHNICAL MEMORANDUM

NASA TM X-1915

c. 1

NASA TM X-1915

A PROPORTIONAL FLUID JET AMPLIFIER WITH FLAT SATURATION AND ITS APPLICATION TO GAIN BLOCKS

by William S. Griffin and Vernon D. Gebben

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1969

1. Report No. NASA TM X-1915	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A PROPORTIONAL FLUID JET AMPLIFIER WITH FLAT SATURATION AND ITS APPLICATION TO GAIN BLOCKS		5. Report Date November 1969 6. Performing Organization Code
7. Author(s) William S. Griffin and Vernon D. Gebben		8. Performing Organization Report No. E-5157
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 126-31 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 25046		13. Type of Report and Period Covered Technical Memorandum 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A proportional fluid amplifier which exhibits flat saturation and a pressure gain greater than 6 has been developed. Three amplifiers were connected in series to form an open-loop gain block. The output of the gain block did not decrease below 95 percent of its maximum value for input signals ranging from those just sufficient to cause saturation to those 20 times that value. The performance was limited by zero changes and gain variations, both resulting from pressure level changes in the control ports.

17. Key Words (Suggested by Author(s)) Fluidics Fluid amplifiers Pneumatic control	18. Distribution Statement Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	31	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information Springfield, Virginia 22151

A PROPORTIONAL FLUID JET AMPLIFIER WITH FLAT SATURATION AND ITS APPLICATION TO GAIN BLOCKS

by William S. Griffin and Vernon D. Gebben

Lewis Research Center

SUMMARY

This report describes the design and performance of a proportional fluid jet amplifier developed at Lewis. This amplifier, designated as P1, has the flat saturation characteristics required by saturating proportional servocontrol systems.

Flat saturation was obtained by using a pressure-deflected jet amplifier with its control inlets directed towards the receivers. Two models were developed. The P1-a amplifier was designed for operation at supply pressures which maintain fully turbulent power jet flow. The P1-b amplifier was designed both for low supply pressure, where the power jet is laminar, and for high supply pressure with its turbulent power jet. The P1-b amplifier has a narrower center vent that accommodates the narrower power jet associated with laminar flow.

Both designs exhibited pressure gains of greater than 6. When the power jet is centered (zero differential output), the output low-frequency noise was less than 1 percent of the maximum output pressure. For control signals exceeding those that cause output saturation, the P1-a amplifier output does not decrease below 90 percent of its maximum output pressure. The P1-b amplifier output does not decrease below 70 percent of its maximum output pressure.

Three P1-a amplifiers were connected in series to form an open-loop gain block. This gain block exhibited an output pressure which did not decrease below 95 percent of its maximum value for input signals as high as 20 times those which cause saturation.

The P1 amplifiers experienced gain changes and zero changes as a result of varying the pressure level of the two control ports. The gain and zero changes limit the flexibility of application of gain blocks composed of P1 amplifiers.

INTRODUCTION

Since their introduction in 1960, fluid jet amplifiers have received considerable attention and research funding. This interest has been motivated by a number of desirable potential characteristics such as environmental insensitivity, low wear rates, convenience in packaging, use of a single working fluid for both information processing and load actuation, and low fabrication cost.

Both digital and proportional fluid jet amplifiers have been developed and have received limited use in (1) aerospace feasibility studies (refs. 1 to 8), (2) university developmental projects (e.g., refs. 9 and 10), and (3) industrial applications (e.g., refs. 11 and 12). Despite this interest and activity, fluid jet amplifiers have not yet found the widespread application originally anticipated (refs. 13 to 21). A primary reason for lack of wider use of proportional fluid jet amplifiers has been inferior performance in comparison to their electronic equivalents. In addition, proportional flueric systems have been more difficult to design and usually do not have performance equivalent to a counterpart electronic system.

Poor saturation can be an important performance limitation. Figure 1 shows the pressure gain characteristics of a typical, commercially available fluid jet amplifier operated with blocked output ports. Note the decrease in receiver pressure after maximum output pressure is reached. Eventually, as control port pressure is continuously increased, the differential output pressure of the amplifier decreases to near zero.

This saturation characteristic is especially undesirable if the amplifier of figure 1 is used in the closed-loop proportional gain block shown in figure 2. In figure 3, the differential output pressure drops off abruptly once a critical input is exceeded. The output remains at zero until the differential input signal is reduced to a value close to zero. The higher the forward loop gain, the closer to zero the input signal must be before the gain block can again operate normally.

If such a gain block is used in a saturating control system, the gain block must never be driven into saturation. This can be accomplished by increasing the supply pressures to increase the output ranges of the component amplifiers. The higher supply pressures increase the inherent noise of the fluid jet amplifiers. The outcome is a penalty in the servocontrol system signal-to-noise ratio.

To eliminate this noise problem, a program was undertaken at Lewis to develop a fluid jet amplifier with flat saturation. This report describes this amplifier, the design considerations, static characteristics, and theoretical performance in a closed-loop gain block.

DESIGN APPROACHES

Interaction Region

A conventional interaction region, shown in figure 4, has its two control nozzles directed at right angles to the centerline of the power nozzle. An increase in control pressure on one control port deflects the power jet from its centered position towards the opposite receiver. Maximum output is obtained when the power jet impacts squarely on the receiver (fig. 4(b)). As control pressure is increased past the maximum output value, the power jet is deflected past the receiver inlet (fig. 4(c)). Receiver pressure then begins to decrease and eventually falls to zero. The result is the undesirable saturation characteristic shown in figure 1.

Power jet deflections for very large differential control port pressures can be limited by control nozzles that are directed at a small angle to the power nozzle centerline. The angle should be such that the stream formed by the control nozzle is pointed at, and has an unobstructed route to, the receiver passageway. Such a geometry, under very high control port differential pressure, would simply use the control momentum to maintain amplifier output pressure. In effect, the control flow becomes the power jet.

Because of its angle, the control jet momentum in this type of design provides little help in deflecting the power jet during normal operation. Therefore, the pressure-deflection type of interaction region is required to produce high-gain characteristics. The pressure-deflection interaction region, however, can overdeflect the power jet before the control flow has sufficient momentum to maintain the amplifier output pressure. Two geometries that limit power jet deflections for intermediate control pressures are shown in figures 5(a) and (b).

Figure 5(a) shows the cusp type of interaction region. The bound vortex created in the cusp provides sharp limiting of the power jet deflection and does not cause the power jet to swing back towards the center as the control pressure exceeds the maximum deflection value. However, this design has several disadvantages. The vortex causes high noise and abrupt changes in control port impedance as the power jet is deflected, and delays deflection of the jet at its center position.

The inclined-wall interaction region shown in figure 5(b) provides higher centered gain and lower noise than does the cusp interaction region. However, it does not limit jet deflection as well. When the control pressure is increased beyond the maximum jet deflection value, the power jet swings back towards its centered position. The output rises to a maximum, decreases to a slightly lower value, and then rises continuously as the control pressure is increased. When the amplifier is used in a gain block, the effect of this characteristic can be decreased to a point where it is not a problem, as shown in figure 16.

Since the inclined-wall configuration of figure 5(b) gives the lower noise and higher gain of the two interaction regions, it was selected for the final design.

Receiver

Conventional receivers were employed in the P1 amplifier. Laboratory tests indicated negligible performance degradation as a result of receiver reverse flows delivered by the capacitive loads normally encountered in gain block circuits and other signal processing networks. For applications with large amounts of receiver reverse flow, a receiver design similar to that described in reference 22 can be used.

Three different receiver designs developed for the P1 amplifier are shown in figures 6(a) to (c). Common to all three is a baffle wall between the receiver inlet and the interaction region exit. This wall impedes secondary flows returning from the receiver, thereby reducing interference with the flow field at the interaction region exit. These secondary flows occur when the receiver is blocked and the power jet is deflected approximately 50 percent of its maximum deflection. Reduction of the interference greatly improves power jet stability, which, in turn, reduces output noise.

The receiver with the wide center vent (fig. 6(a)) exhibits high pressure recovery, high gain, and relatively low noise. The narrow flow dividers of the center vent, however, are fragile and do not reproduce well in an injection molding process. Another disadvantage occurs when the amplifier power nozzle operates at low supply pressure, where the power jet is laminar and smaller than the center vent. The mismatch between the jet and center vent produces a flat spot in the amplifier's gain characteristic curve. Thus, amplifiers using this type of receiver must be operated at high supply pressures.

The second design, shown in figure 6(b), has thick flow dividers with the tips of the flow dividers located in the same position as those in figure 6(a). At high Reynolds numbers, where the jet is turbulent, this design performs similarly to the design of figure 6(a). At low Reynolds numbers, its gain is erratic and nonlinear.

Figure 6(c) shows the third receiver design, which has a narrow center vent whose width is always less than the width of the power jet. It has the advantage of smooth, proportional characteristics at both high and low Reynolds numbers. Excellent performance was obtained at power nozzle Reynolds numbers down to 2360 based on power nozzle height h_j. This number appeared to be less than the transition value and was the lowest tested. It does not indicate the lower bound of operation. The narrow center vent improves the linearity but reduces the performance in the saturation region. The reason is that the overdriven power jet in this amplifier moves back toward the center and increases the pressure in the low-pressure receiver. The wider center vent reduces pressure buildup in the low-pressure receiver by exhausting more flow.

Final Amplifier Designs

Two configurations, designated as the P1-a and P1-b, were selected for evaluation.

Amplifier P1-a, shown in figure 7(a), uses the interaction region of figure 5(b) and the receiver configuration of figure 6(b). It is a general purpose amplifier suitable for signal processing circuits when its power nozzle Reynolds number based on h_j is greater than 3300. The P1-b amplifier, shown in figure 7(b), is a later design that combines the interaction region of figure 5(b) and the receiver of figure 6(c). It is a high-gain amplifier whose characteristics remain well behaved for both turbulent and laminar power jet flows. Since the P1-b amplifier has the wider operating range, it is fully dimensioned in this report.

Note, on both amplifiers, an axis of symmetry for the ports. This porting arrangement enables the amplifiers to be stacked on top of each other in a head-to-toe fashion for constructing multielement gain blocks and circuits.

Generally, both amplifiers had the same performance characteristics. The following experimental results present the complete static performance characteristics of the P1-a amplifier. Data on both amplifiers are presented when their characteristics are different.

EXPERIMENTAL RESULTS

Description of Test Procedures and Apparatus

The amplifiers were machined from acrylic blocks using a pantograph engraving machine. Power nozzle width was 0.040 inch (0.102 cm), and power nozzle height was 0.020 inch (0.051 cm). Figure 8 shows a typical amplifier.

Pressure-flow characteristics, pressure gain, noise, and effects of control port pressure level changes were measured on the P1-a and P1-b amplifiers. Pressure gain measurements were also made on an open-loop, three-stage gain block constructed of P1-a amplifiers.

Static measurements of pressure were made by strain gage pressure transducers whose outputs were recorded on an X-Y plotter. Total measurement error was estimated as less than 0.2 percent of amplifier supply pressure. Bandwidth of these measurements was limited by the response of the X-Y plotter. Manufacturer's specifications for the plotter listed a response of 20 hertz.

High-frequency noise was measured by piezoelectric pressure transducers whose outputs were read from an oscilloscope. The transducers were located at the end of a blocked line which had a 0.125-inch (0.317-cm) inside diameter and 3-inch (7.6-cm) length. Response of the line was not determined. Manufacturer's specifications for the transducers listed a resonant frequency of 60 000 hertz. Errors in the noise measurements were estimated as less than 50 percent of the measured value.

Flow measurements were made by measuring the pressure drop across a laminar flowmeter. The pressure drop was measured with a variable-reluctance-type pressure transducer whose output was recorded on an X-Y plotter. Total errors in flow measurement were estimated as less than 2 percent of the power nozzle flow.

The supply media was air whose temperature was between 76° and 80° F (298 and 300 K). Unless noted in the figures, all test data were obtained with a 5.0-psig (3.5-N/cm^2 gage) supply pressure P_s and with the vents exhausted to the atmosphere.

Amplifier Performance

Figures 9 to 11 show the control port, receiver, and pressure gain characteristics for steady pressure-flow operation. Figure 9 gives the control port characteristics of the P1-a amplifier. Control port characteristics of the P1-b amplifier were not measured since its interaction region is identical with that of the P1-a amplifier. Figures 10(a) and (b) show normalized receiver characteristics of both amplifiers. Pressure gain characteristics of both amplifiers are shown in figures 11(a) and (b). In figures 10 and 11, pressure was applied to the C_1 control port to obtain positive differential control port pressures and to the C_2 control port to obtain negative differential control port pressures. The other control port was left open to atmosphere. The maximum pressure gain, pressure recovery, and saturation characteristics are listed in table I.

Table I also gives the results of the high- and low-frequency noise measurements. The amplifier was operated with one control port open to the atmosphere. Highest noise

TABLE I. - P1 AMPLIFIER EXPERIMENTAL

PERFORMANCE CHARACTERISTICS

Performance characteristic	Amplifier	
	P1-a	P1-b
Blocked receiver pressure recovery, percent of supply pressure	53	52
Blocked receiver pressure gain	6.3	13
Minimum output pressure for input pressures in excess of those that cause saturation, percent of maximum output	90	70
Noise, percent of maximum output:		
0 to 20 Hz	1.0	1.0
0 to 30 kHz	----	12

in the P1-a amplifier occurred when the differential control port pressure was approximately 5 percent of supply pressure. Maximum peak-to-peak, low-frequency receiver noise for this condition was approximately 1 percent of maximum output pressure. The highest noise in the P1-b amplifier occurred when the differential control port pressure was zero.

Changes in the average value of the two control port pressures $\bar{P}_C$ affect the pressure gain and the null point of the P1 amplifiers. Gain change as a function of $\bar{P}_C$ of the P1-a amplifier is shown in figure 12. This data was obtained while elevating both control pressures to equal values and then varying one control port pressure. This gain change characteristic has been observed in other fluid jet amplifiers and has been used in an automatic flueric gain changer circuit for flight control systems (ref. 23). Zero shifts as a function of $\bar{P}_C$ are shown in figure 13(a) for the P1-a amplifier and in figure 13(b) for the P1-b amplifier. Control pressures in these tests were made equal by connecting the control ports to the same pressure source. The magnitudes of the zero shifts appear irregular and unpredictable.

In another test, the power nozzle of the P1-a amplifier was connected to a flow source formed by a choked orifice. The power nozzle supply pressure P_S was 0.50 psig (0.345 N/cm^2 gage) when both control ports were vented to atmosphere. As $\bar{P}_C$ increased above ambient, P_S also increased. The resultant variation in P_S as a function of $\bar{P}_C$ is shown in figure 14. In this test, the differential control port pressure was zero.

Since P_S varies as a function of $\bar{P}_C$, a test was made to determine the zero shift of the P1-a amplifier as a function of P_S. Results are shown in figure 15. Both control ports were vented to atmosphere.

Gain Block Performance

To evaluate the performance of a multistage, open-loop gain block, a three-stage gain block was constructed of P1-a amplifiers. Supply pressures to the amplifiers were set as follows:

Stage	Supply pressure, P_S	
	psig	N/cm^2
1	1.80	1.24
2	8.00	5.53
3	32.0	22.1

Pressure gain characteristics of the gain block are shown in figures 16 and 17. In figure 16, the C_2 control port of the first-stage amplifier was open to atmosphere. In figure 17, C_2 was maintained at a pressure equal to 5.4 percent of the third-stage supply pressure. Figure 17 includes the curve of figure 16 for comparison.

Figure 17 indicates that the output did not drop below 95 percent of its maximum value for input signals 20 times the value necessary to obtain maximum output from the gain block. In addition, the elevated control port pressure reduced the open-loop gain from 115 to 26 and caused the output zero shift to be approximately 50 percent of the third-stage maximum output pressure.

DISCUSSION OF RESULTS AND RECOMMENDATIONS

The original goal of developing a proportional fluid jet amplifier with reasonably flat saturation has been achieved. The dropoff in output pressure that occurs when the first-stage amplifier is overdriven can be dealt with by letting the first two or three stages in a proportional gain block overdrive the following stage by about 50 percent. Since the peak of the output pressure curve is relatively flat for control pressures up to double the value that saturates the output, the net result will be a highly flat saturation characteristic. This effect is demonstrated by the performance of the three-stage, open-loop gain block. Its saturation characteristics, shown in figures 16 and 17, are much better than those of its component amplifier (fig. 11(a)).

Both the P1-a and the P1-b amplifiers can be used in either open-loop or closed-loop gain blocks. Noise, gain, and linearity are satisfactory for this purpose.

Gain changes in the amplifiers of a closed-loop gain block can limit the circuit's performance. They cause a variation in the circuit's closed-loop gain which constitutes an effective nonlinearity in its output. The problem can be easily minimized or eliminated by adding stages of amplification. If enough stages are added, no matter how much the gain fluctuates within the circuit, the forward loop gain of the circuit remains high enough that it does not affect the closed-loop gain.

Adding stages of amplification, however, does not eliminate the nonlinear effects caused by output shifts in the amplifiers that result from changes in the average value of their control port pressure $\bar{P}_C$. When the output stage shown in figure 2 is a P1-a amplifier or another class B amplifier that has the lower of the two outputs equal to exhaust pressure, the first-stage $\bar{P}_C$ will be proportional to the higher of the two inputs, P_{i1} and P_{i2}. For example, let $P_{i1} > P_{i2}$; then $P_{o2} > P_{o1}$ and $P_{o1} = P_e$. Since P_{o1} is constant, P_{C1} is proportional to P_{i1}. For an infinite-gain block, $P_{C1} = P_{C2}$. Consequently, $\bar{P}_C = P_{C1}$. Therefore, $\bar{P}_C$ is proportional to P_{i1}, the higher of the two inputs. The first-stage $\bar{P}_C$ will approximately equal the higher input pressure if Z_1 is small in comparison to both Z_2 and the control port impedance. If class B amplifiers are also used for the other stages, the value of $\bar{P}_C$ for each stage will equal half the differential control pressure to the amplifier.

When the effects of $\bar{P}_C$ are considered, figures 13(a) and (b) indicate that noticeable zero shifts can be expected from the P1 amplifiers. In the circuit, these zero shifts are equivalent to adding external signals and, therefore, are essentially unaffected by changes in the forward loop gain. Hence, to minimize the zero shifts in the P1 amplifier outputs, the circuit should be designed to minimize the $\bar{P}_C$ variations that occur throughout the circuit.

A method of reducing the first-stage $\bar{P}_C$ relative to P_{S1} is to simply increase the first-stage supply pressure. Since the first-stage noise will be roughly a constant fraction of the amplifier's supply pressure, this procedure quickly results in unacceptable noise levels. However, it may be possible to reduce the aspect ratio of the first-stage amplifier by a factor of 2 and still have useful amplification characteristics. A smaller aspect ratio would cause laminar flow to exist at higher supply pressures. When laminar flow exists, the amplifier's noise is very low and probably will not cause objectional noise on the output of the gain block. Reduction of aspect ratio in the first-stage amplifier should be attempted in future investigations.

Constant first-stage $\bar{P}_C$ can be obtained in applications where ΔP_i is produced by a flapper valve, as shown in figure 18(a). If possible, the flapper valve should exhaust to a pressure which is lower than the amplifier exhaust pressure. The resulting push-pull ΔP_i signal could then be adjusted to create a minimum $\bar{P}_C$ that would remain constant. A minimum $\bar{P}_C$ has the advantage of providing the maximum first-stage gain. In applications where only one exhaust pressure is available, $\bar{P}_C$ can be maintained constant at an elevated pressure by using the P1-b amplifier in the last stage. When the differential control port pressure of P1-b increases, the pressure in one receiver increases while the pressure in the other receiver decreases.

The single-ended circuitry shown in figure 22(b) may be used to obtain a constant first-stage $\bar{P}_C$. The C_2 control port is connected to the line between two pressure-dividing orifices. If the resistances of these two orifices are kept small with respect to the amplifier's control port resistance, the P_{C2} biasing pressure will remain almost constant. If the open-loop gain of the gain block is large, the P_{C1} pressure will remain nearly constant and equal to the P_{C2} pressure. Disadvantages of the circuit include (1) higher nonlinearity since push-pull cancellation of signal distortion is not available, and (2) the fact that the bias pressure P_{C2} does not remain constant but changes slightly as a result of the changing input impedance of the amplifier. The changing bias pressure P_{C2} causes changes in the circuit's closed-loop gain.

The preceding circuitry reduces the nonlinearities that are caused by changes in the first-stage $\bar{P}_C$. However, they limit flexibility of application of the gain blocks. Design improvements in the basic P1 amplifier are required to minimize the zero shift and gain changes that are associated with changes in $\bar{P}_C$.

CONCLUSIONS

A proportional fluid jet amplifier with flat saturation has been developed and evaluated. This amplifier should find applications in proportional servocontrol systems.

Performance tests on the P1-a amplifier indicate that the gain changes and zero shifts in the first-stage amplifier constitute a fundamental limitation on the gain block's accuracy. Some circuitry techniques can be employed to reduce the nonlinear effects. These effects may be minimized by design improvements in the P1 amplifier.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 25, 1969,
126-31.

APPENDIX - SYMBOLS

C_1, C_2	amplifier control ports
D_j	width of power jet, in. (cm)
h_j	height of power jet, in. (cm)
$\dot{m}_{C1}, \dot{m}_{C2}$	amplifier control port mass flow rate, lbm/sec (kg/sec)
$\dot{m}_{R1}, \dot{m}_{R2}$	amplifier receiver mass flow rate, lbm/sec (kg/sec)
$\dot{m}_S$	amplifier supply port mass flow rate, lbm/sec (kg/sec)
P_{C1}, P_{C2}	control port pressures of a single amplifier or the first-stage amplifier, psia (N/cm^2 abs)
ΔP_C	differential control port pressure to a single amplifier or the first-stage amplifier, $\Delta P_C = P_{C1} - P_{C2}$, psi ($N/cm^2$)
$\bar{P}_C$	average of the control port pressures in a single amplifier or the first-stage amplifier, $\bar{P}_C = (P_{C1} + P_{C2})/2$, psia ($N/cm^2$ abs)
P_e	exhaust pressure, psia (N/cm^2 abs)
P_{i1}, P_{i2}	input pressures to gain block, psia (N/cm^2)
ΔP_i	differential input pressure to closed-loop gain block, $\Delta P_i = P_{i1} - P_{i2}$, psi ($N/cm^2$)
P_{o1}, P_{o2}	output pressures from gain block, psia (N/cm^2 abs)
ΔP_o	differential output pressure from gain block, $\Delta P_o = P_{o1} - P_{o2}$, psi ($N/cm^2$)
P_{R1}, P_{R2}	receiver pressures of amplifier, psia (N/cm^2 abs)
P_S	supply pressure to power nozzle of amplifier, psia (N/cm^2 abs)
P_{S1}, P_{S2}, P_{SN}	supply pressures to power nozzles of the first-, second-, and n^{th}-stage amplifiers, respectively, psia (N/cm^2 abs)
R_1, R_2	amplifier receivers
S	amplifier supply port (power nozzle)
Z_1, Z_2	input and feedback resistances in closed-loop gain block

REFERENCES

1. Cardon, M. H.: Replacement of Electronics With Fluid Interaction Devices. Rep. BRLD-2946, Bendix Corp. (NASA CR-54758), Aug. 31, 1965.

2. Kasselmann, J. T.; and Delozier, T. R.: All-Fluid Amplifier Development for Liquid Rocket Secondary Injection Thrust Vector Control. Rep. BRL-3875, Bendix Corp. (NASA CR-72145), Nov. 1967.

3. Rodgers, D. L.: Development and Flight Testing of a Fluidic Control System. NASA CR-913, 1967.

4. Howland, G. R.: Fluid State Amplifier and Compensation for the Model NV-B1 Gimbal Actuator. Rep. BPAD-864-15651R; Bendix Corp. (NASA CR-62522), Apr. 12, 1965.

5. Dexter, E. M.; et al.: Application of Fluidics to Automatic Flight Control. Bowles Engineering Corp. (USAAVLABS-TR-66-71, DDC No. AD-645759), Sept. 1966.

6. Ostlund, Orrin E.; and Beduhn, William G.: Fluidic Yaw Damper System. Rep. 20230-FRI, Honeywell, Inc., (AFFDL-TR-67-24, DDC No. AD-811542), Feb. 1967.

7. Atha, Larry C., et al.: Development of a Pure Fluid Missile Control System. Rep. RG-TR-65-22, U. S. Army Missile Command, Sept. 1965. (Available from DDC as AD-478880.)

8. Dunaway, J. C.: The Development of a Hot Gas Reaction Control Valve for an Antitank Missile. Rep. RG-TR-65-23, U.S. Army Missile Command, Sept. 15, 1965. (Available from DDC as AD-478067.)

9. Blaiklock, Paul: Development of a Pneumatic Stepping Motor. Sc.D. Thesis, Massachusetts Inst. Tech., 1967.

10. Orner, Peter A.: A Fluid Amplifier Controlled Pneumatic Turbine Servomechanism. PhD. Thesis, Case Inst. Tech., 1965.

11. Fluidonics Staff: Fluidics Systems Design Guide. Fluidonics Div., Imperial Eastman Corp., Chicago, Ill., 1966.

12. Glaskin, R. S.; and Meyer, C. H.: A Fluid Operated Diesel Locomotive Transition Control Unit. Presented at the Third Fluid Amplification Symposium, Harry Diamond Lab., Washington, D.C., 1965.

13. Yeaple, F.: No Moving Parts for Fluid Amplifier. Product Eng., vol. 31, no. 11, Mar. 14, 1960, p. 17.

14. Anon.: Future for Fluid Amplifiers? Electronics, vol. 33, no. 13, Mar. 25, 1960, p. 41.

15. Anon.: Fluid Computing Elements Open New Doors in Control. Control Eng., vol. 7, no. 5, May 1960, pp. 26-30.

16. Anon.: Fluid Systems Operate Without Moving Parts. Automatic Data Processing, vol. 12, no. 4, Apr. 1960, pp. 15-19.

17. Wood, O. Lew; and Fox, Harold L.: Fluid Computers. Int. Sci. Tech., no. 23, Nov. 1963, pp. 44-52.

18. Klass, Phillip J.: Fluid/Gas Systems Challenging Electronics. Aviation Week Space Tech., vol. 81, No. 22, Nov. 30, 1964, pp. 36-41.

19. Klass, Phillip J.: Fluid Sensors Open Way to Many Systems. Aviation Week Space Tech., vol. 81, no. 23, Dec. 7, 1964, pp. 52-59.

20. Gray, W. C.; and Stern, Hans: Fluid Amplifiers - Capabilities and Applications. Control Eng., vol. 11, no. 2, Feb. 1964, pp. 57-64.

21. Anon.: Fluid Flip Flops - When Should You Use Them? Electronic Des., June 7, 1961, pp. 56-59.

22. Griffin, William S.: Design of a Fluid Jet Amplifier with Reduced Receiver-Interaction-Region Coupling. NASA TN D-3651, 1966.

23. Beduhn, W. G.: An Automatic Flueric Gain Changer Circuit for Flight Control Systems. Advances in Fluidics. Forbes T. Brown, ed., ASME, 1967, pp. 415-425.

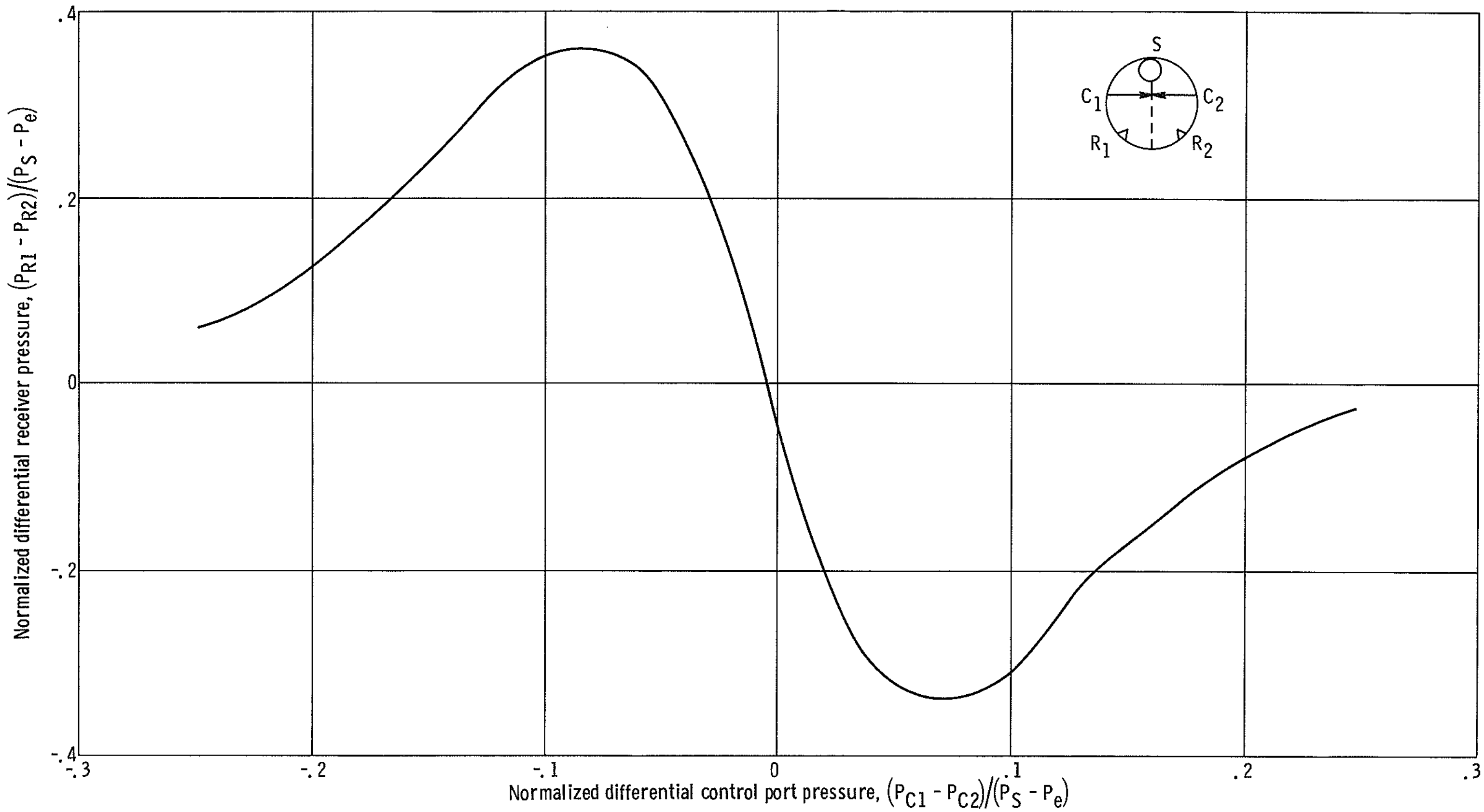


Figure 1. - Typical blocked receiver gain characteristic. Momentum-deflected fluid jet amplifier.

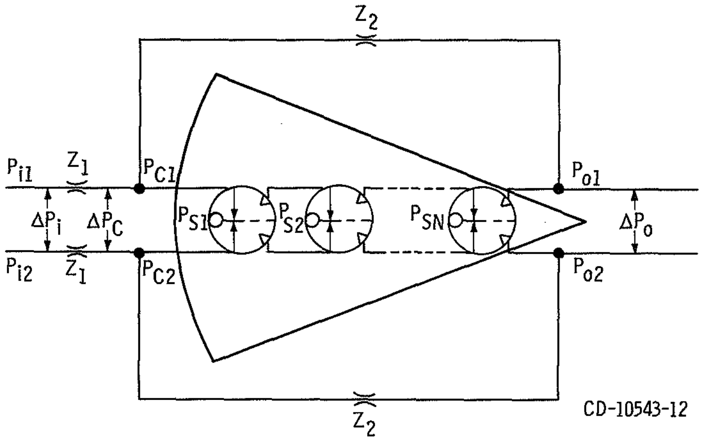


Figure 2. - Schematic of multistage, fluid jet amplifier, proportional closed-loop gain block.

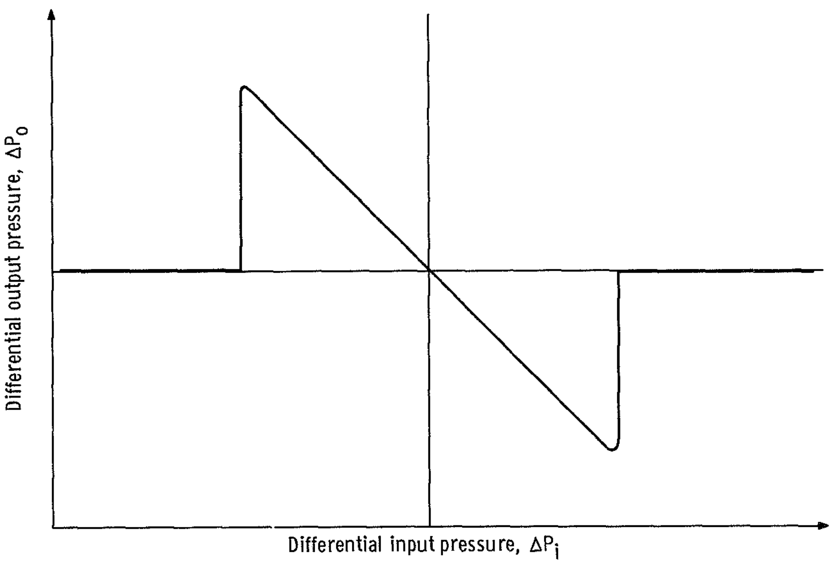
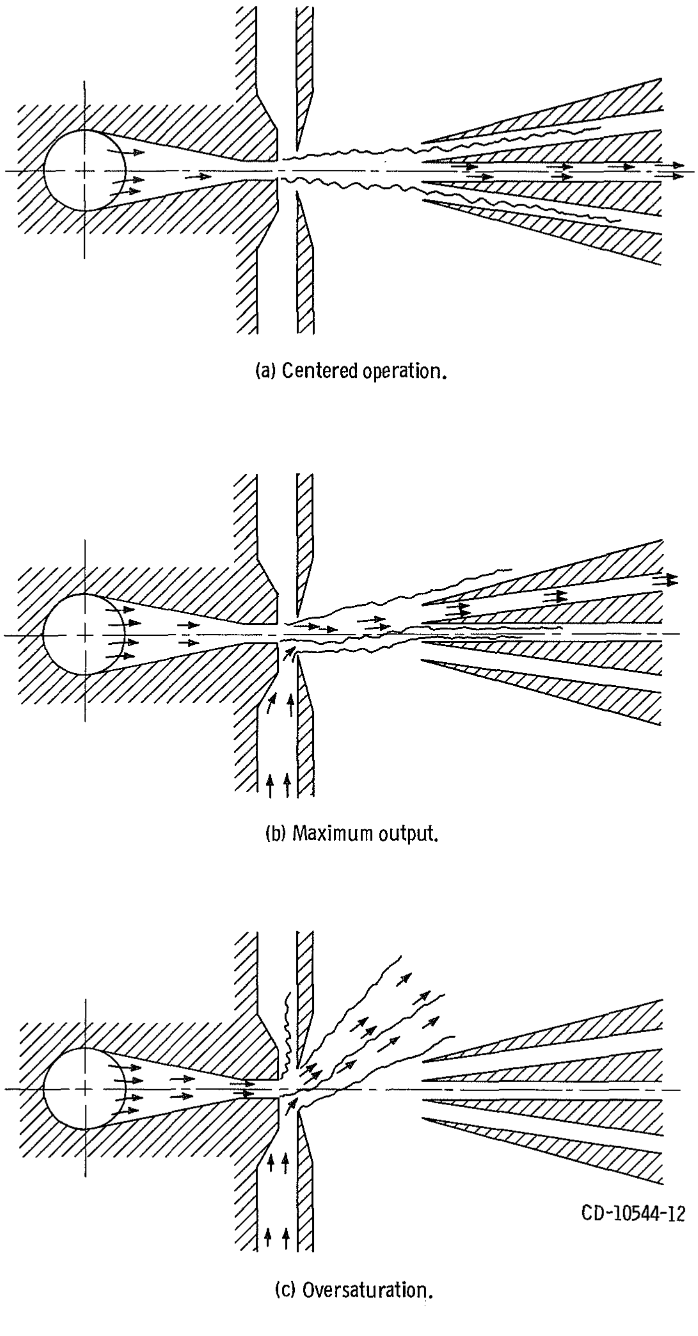


Figure 3. - Typical performance of high-gain proportional, closed-loop gain block using fluid jet amplifiers with amplifying characteristics similar to those of figure 1. Gain block has high forward loop gain.

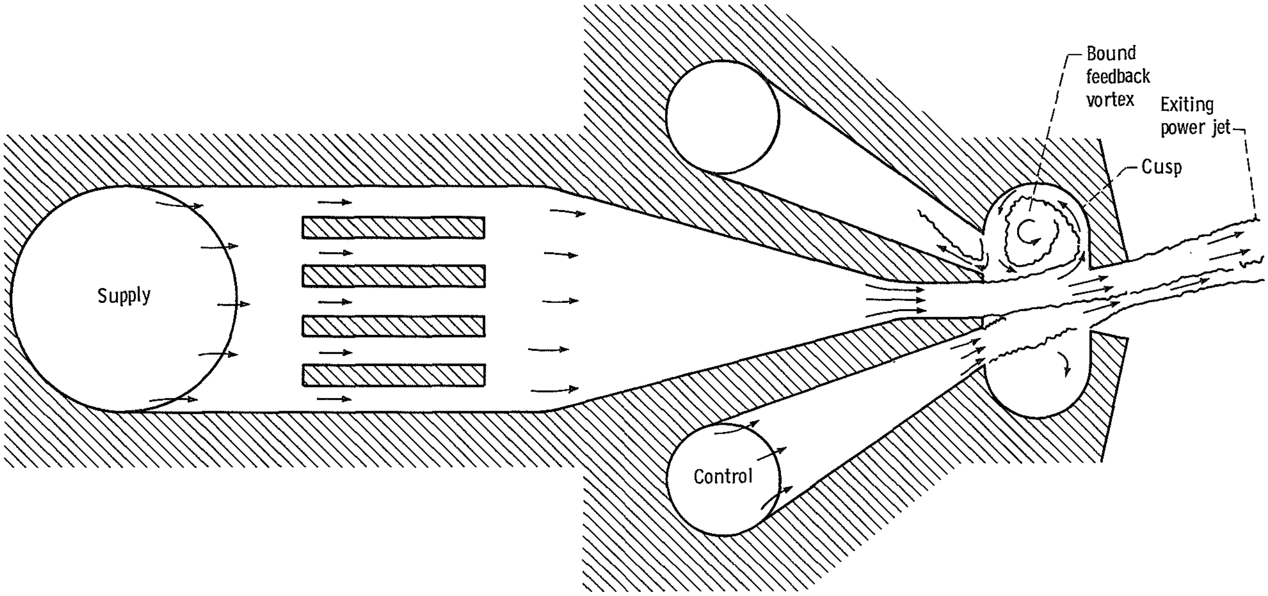


(a) Centered operation.

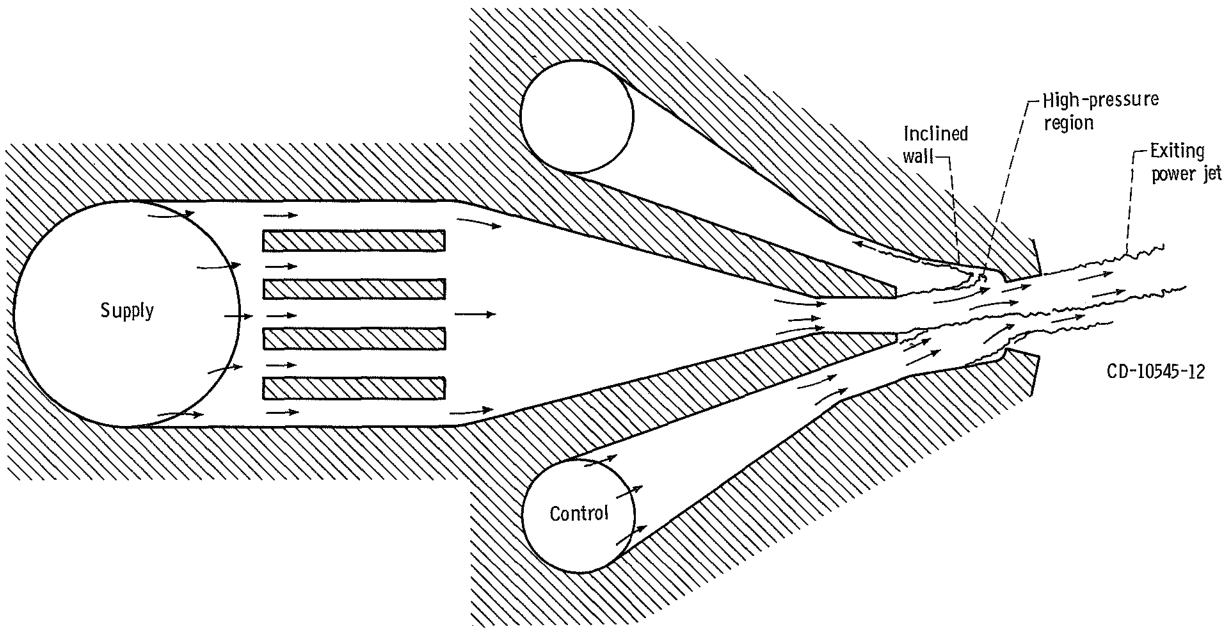
(b) Maximum output.

(c) Oversaturation.

Figure 4. - Flow patterns in momentum-deflected fluid jet amplifier during conditions of centered operation, maximum output, and oversaturation.

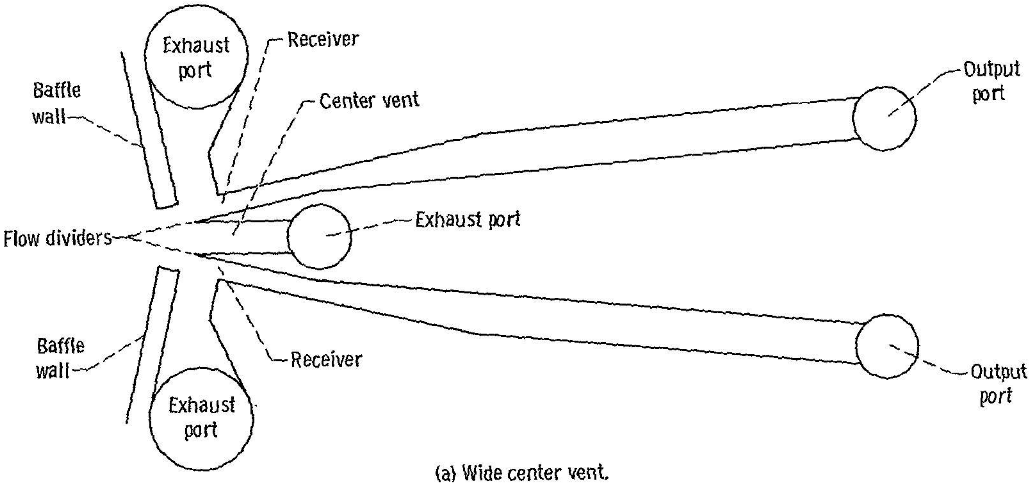


(a) Cusp design.

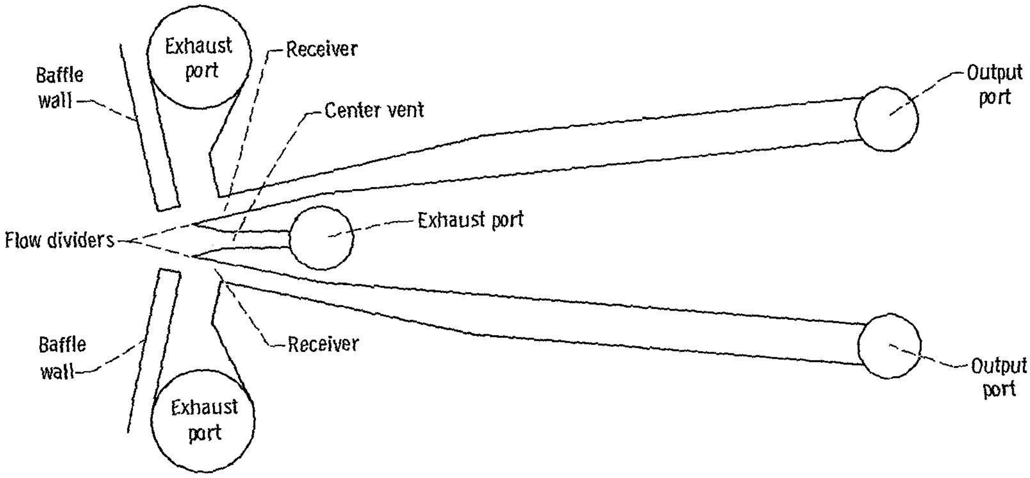


(b) Inclined-wall design.

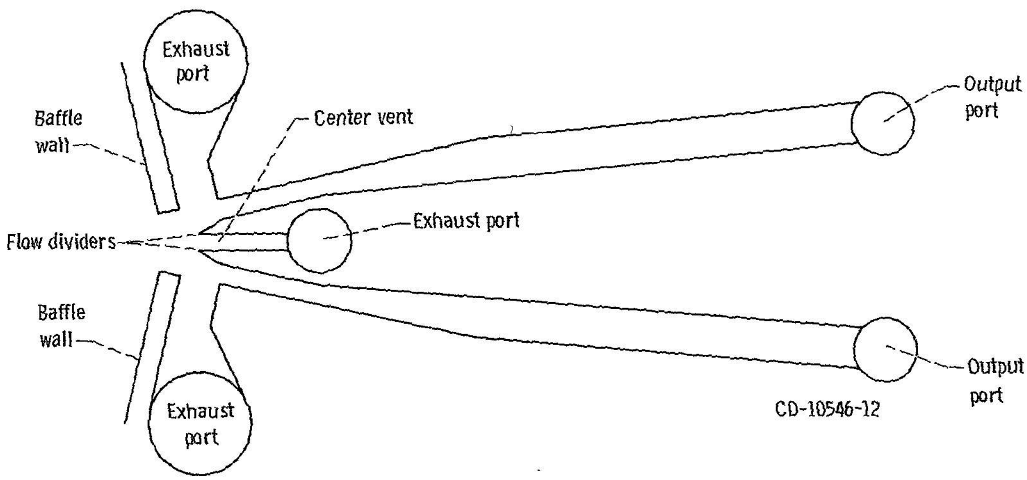
Figure 5. - Interaction regions designed to limit power jet deflection.



(a) Wide center vent.

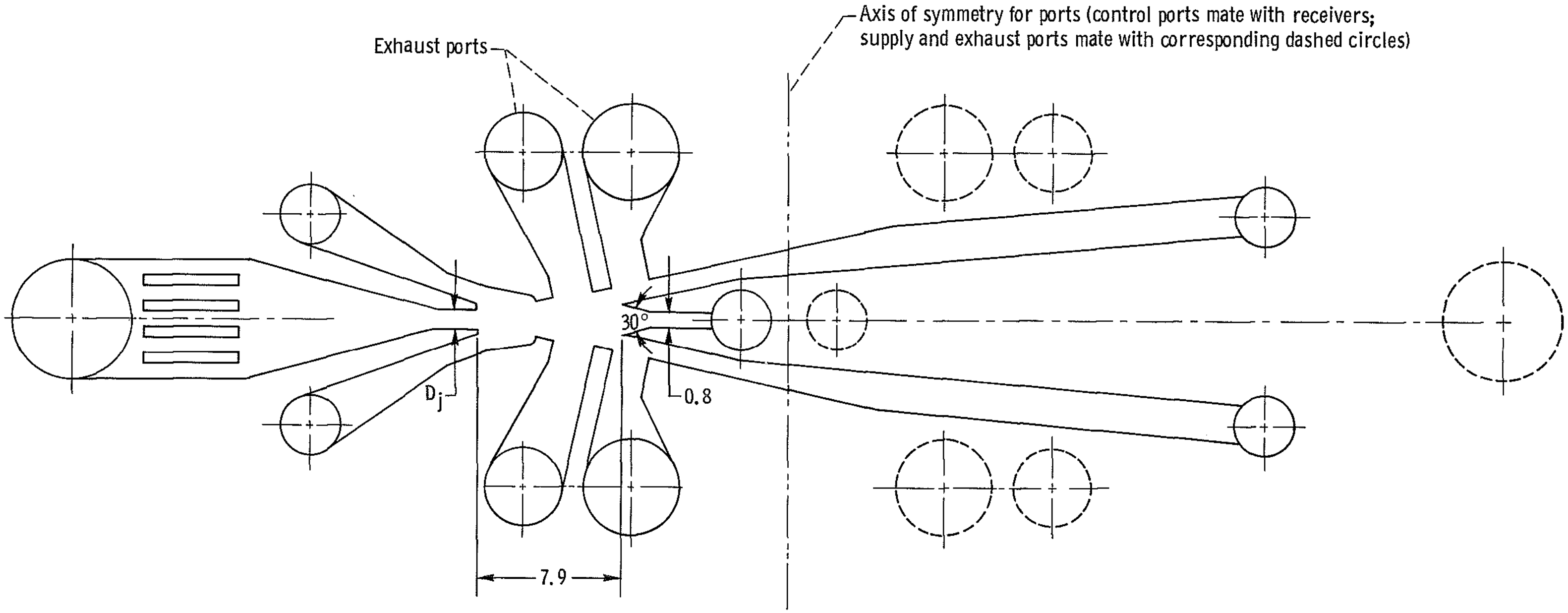


(b) Narrow center vent. Flow divider tips at same positions as those of figure 6(a).



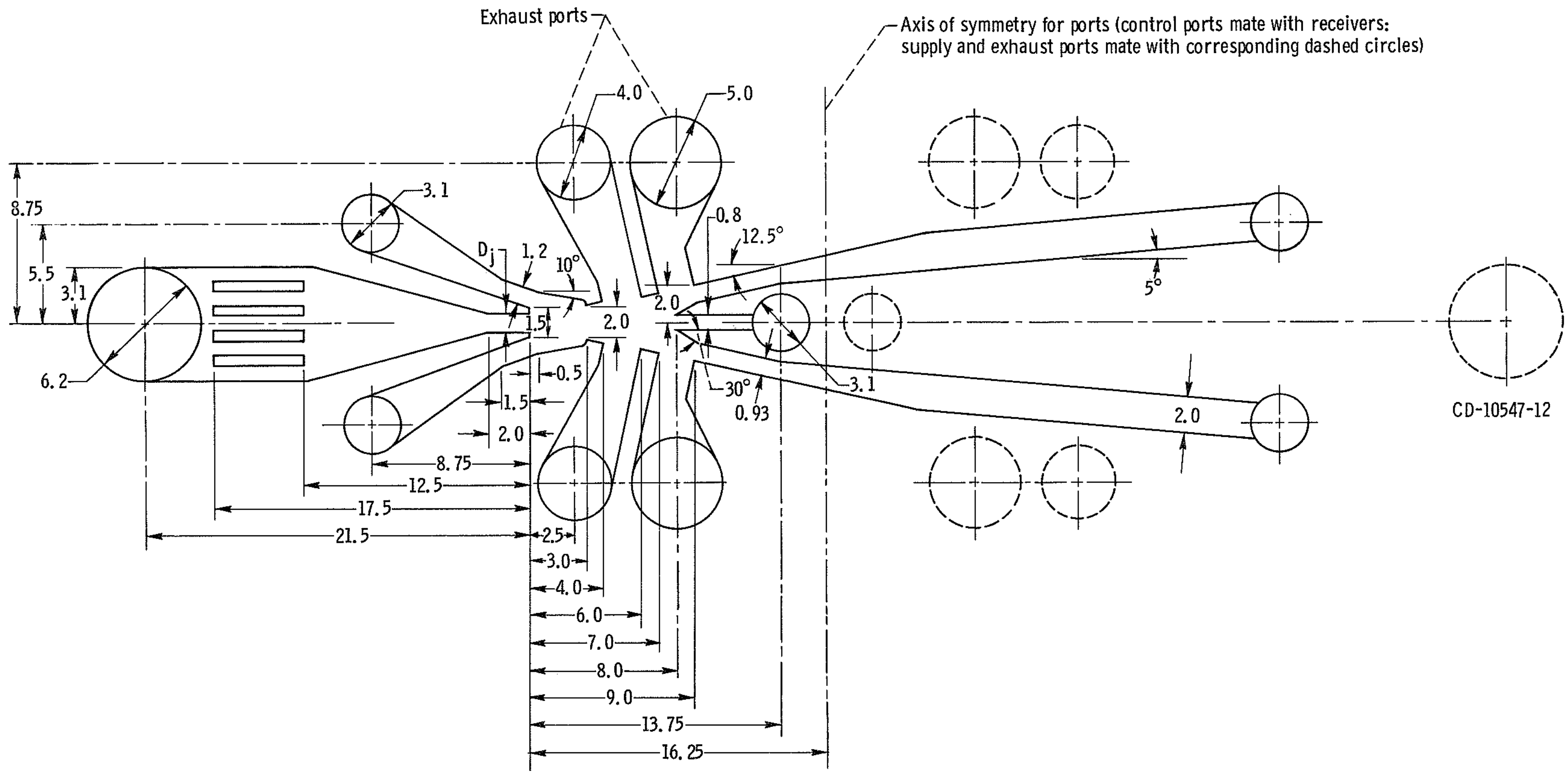
(c) Narrow center vent. Flow divider tips located at center vent walls.

Figure 6. - Receiver designs for PI amplifiers.



(a) P1-a amplifier. Dimensions not listed are same as similar dimensions on P1-b amplifier (fig. 7(b).

Figure 7. - Proportional fluid jet amplifiers. All linear dimensions to be multiplied by power nozzle width D_j.



(b) P1-b amplifier.

Figure 7. - Concluded.

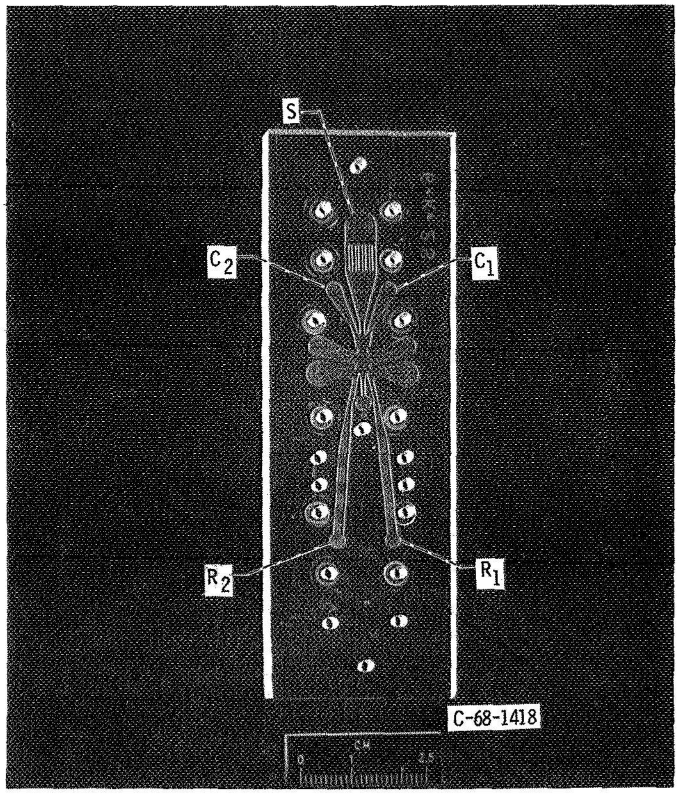


Figure 8. - P1-a proportional amplifier.

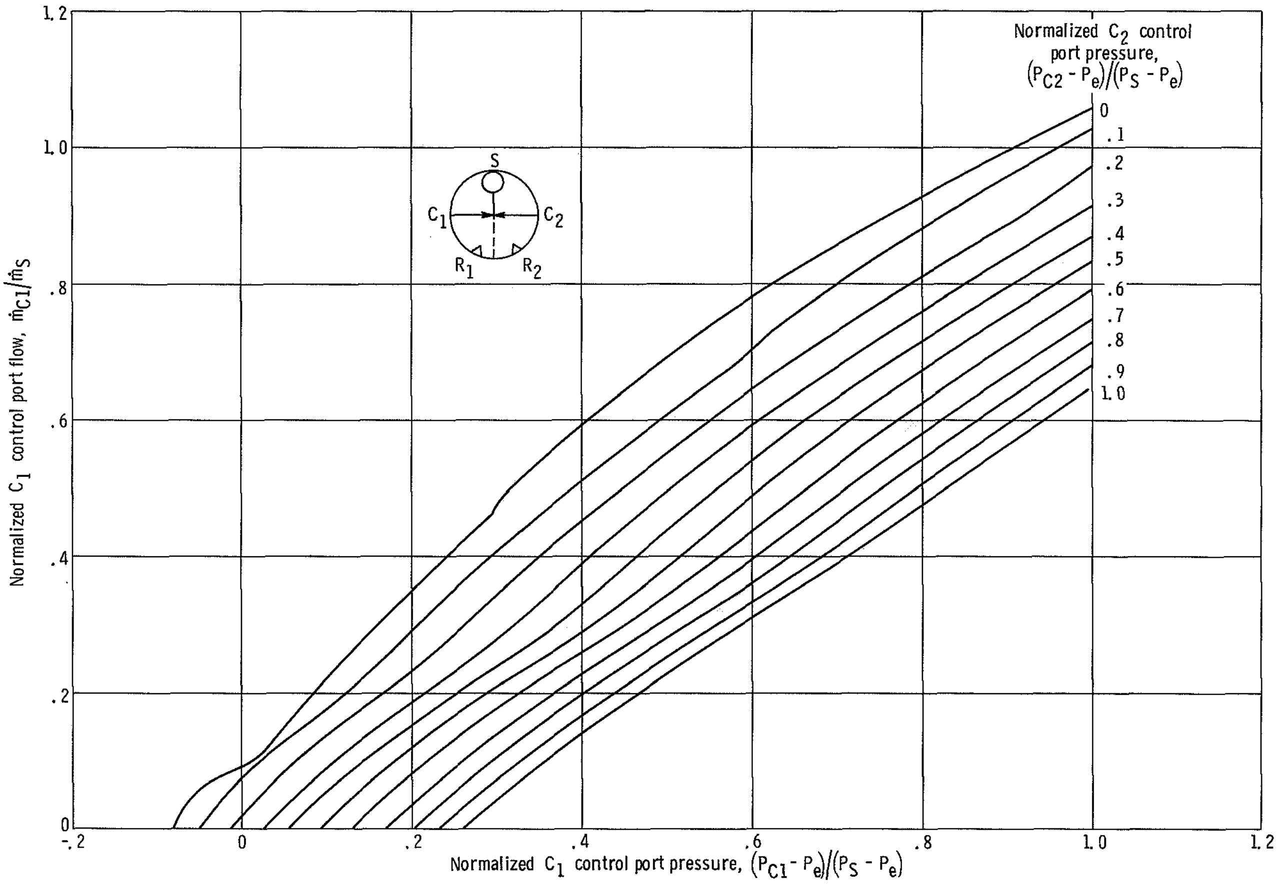
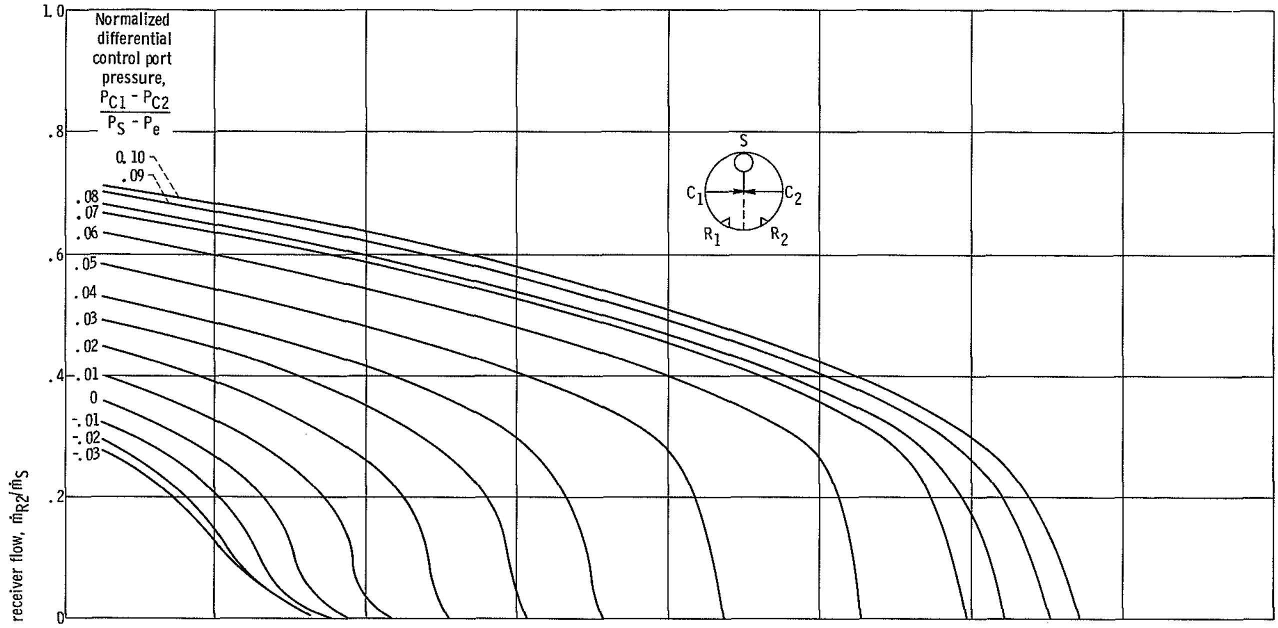
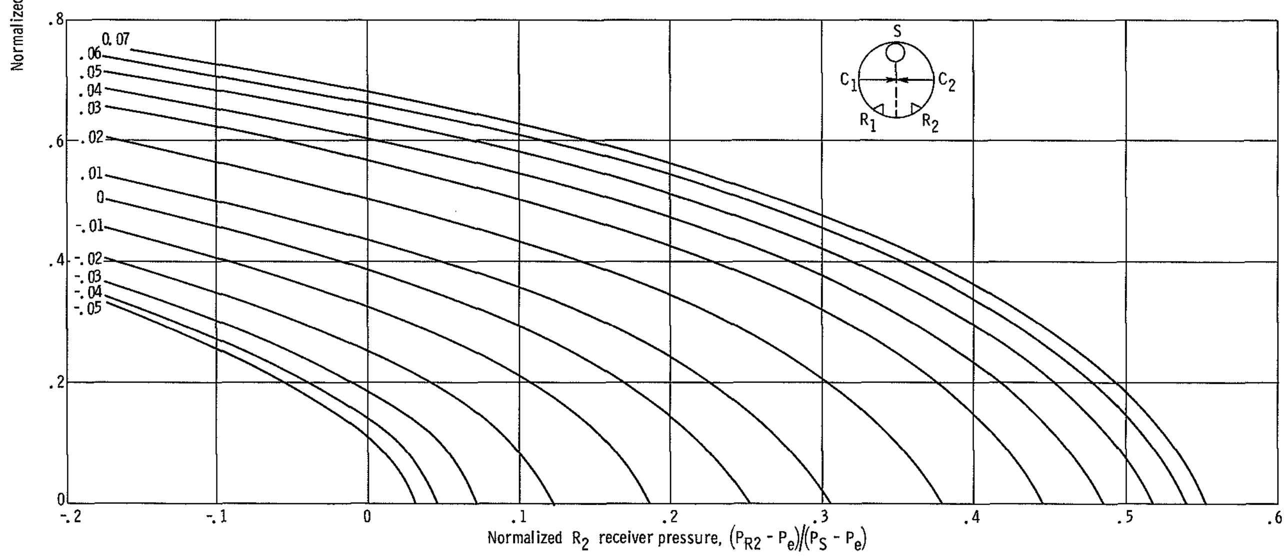


Figure 9. - Control port pressure-flow characteristics of P1-a amplifier.

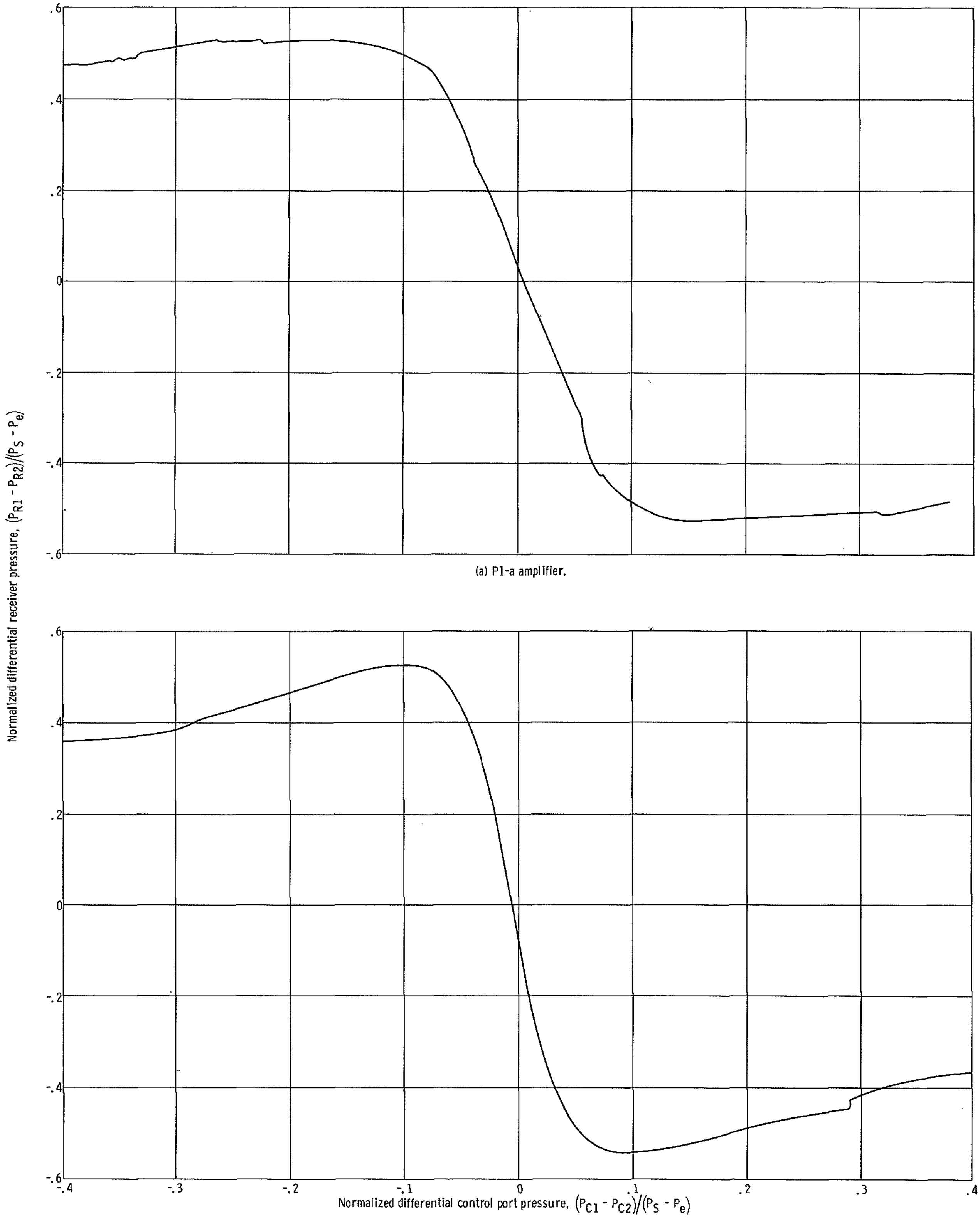


(a) P1-a amplifier.



(b) P1-b amplifier.

Figure 10. - Receiver pressure-flow characteristics.



(b) P1-b amplifier.

Figure 11. - Blocked receiver pressure gain characteristics.

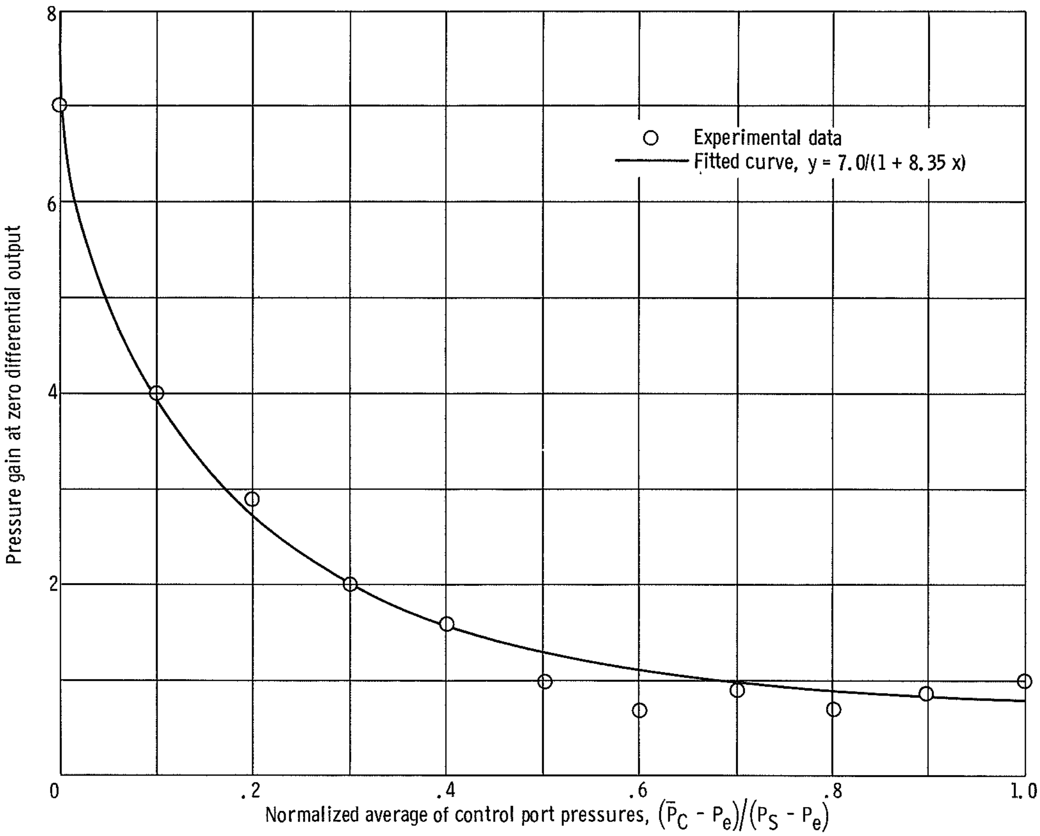
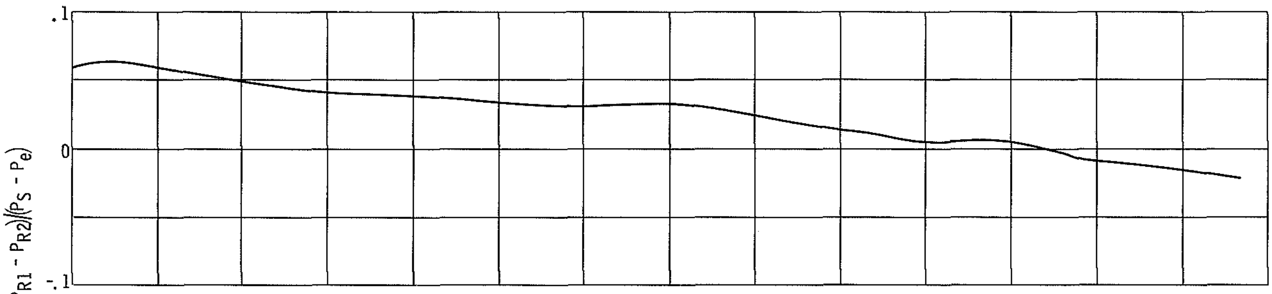
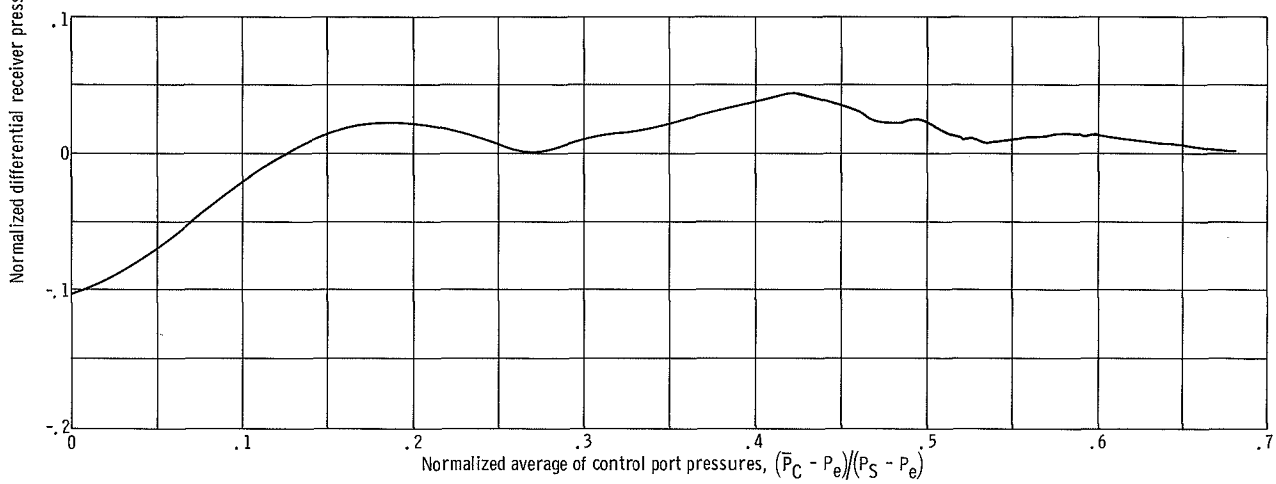


Figure 12. - Pressure gain changes of P1-a amplifier.



(a) P1-a amplifier.



(b) P1-b amplifier.

Figure 13. - Zero shifts of amplifiers operated with blocked receivers and equal control port pressures.

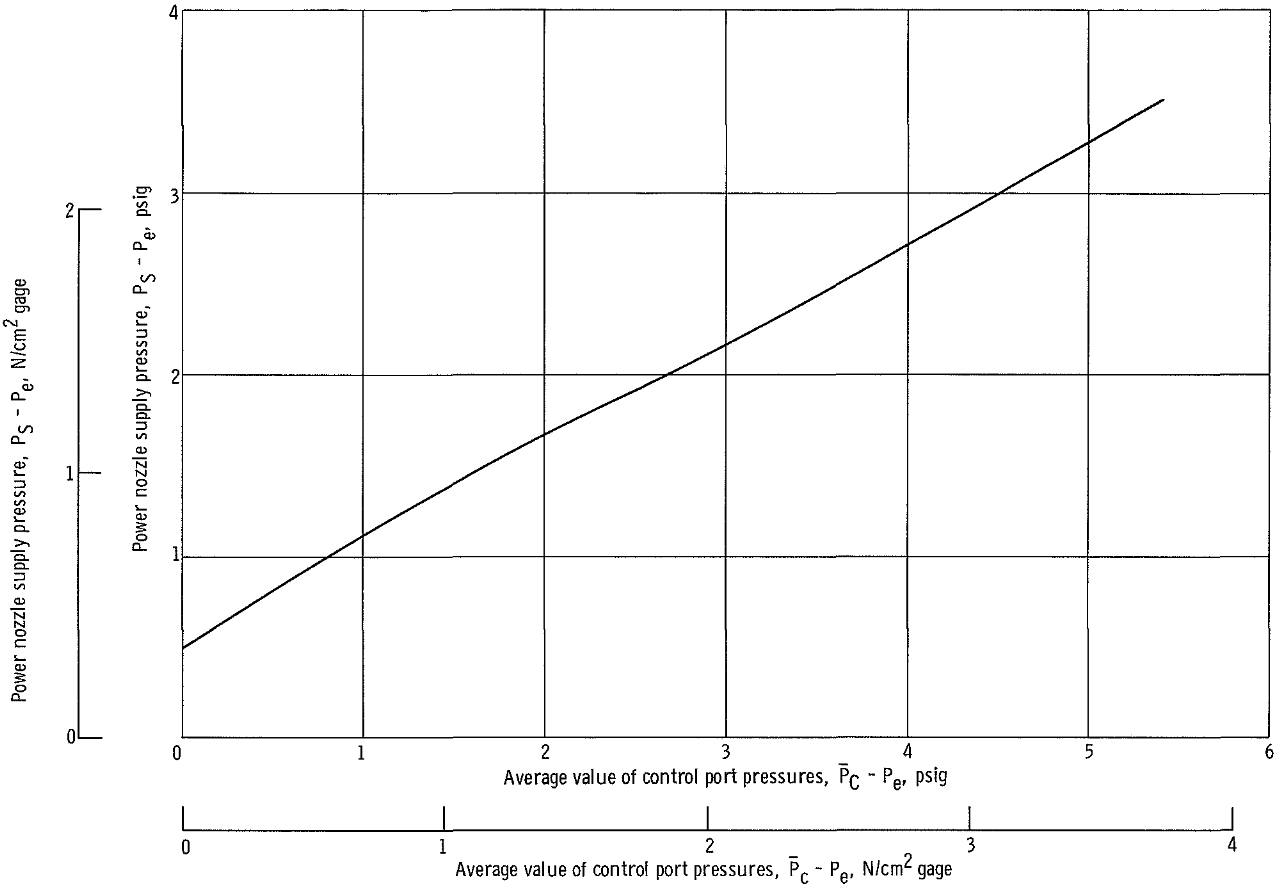


Figure 14. - Relation between average value of control port pressures and supply pressure of P1-a amplifier operated with choked orifice ahead of power nozzle and with equal control port pressures. Choked orifice in supply line was set at 0.5 psig (0.345 N/ cm^2 gage).

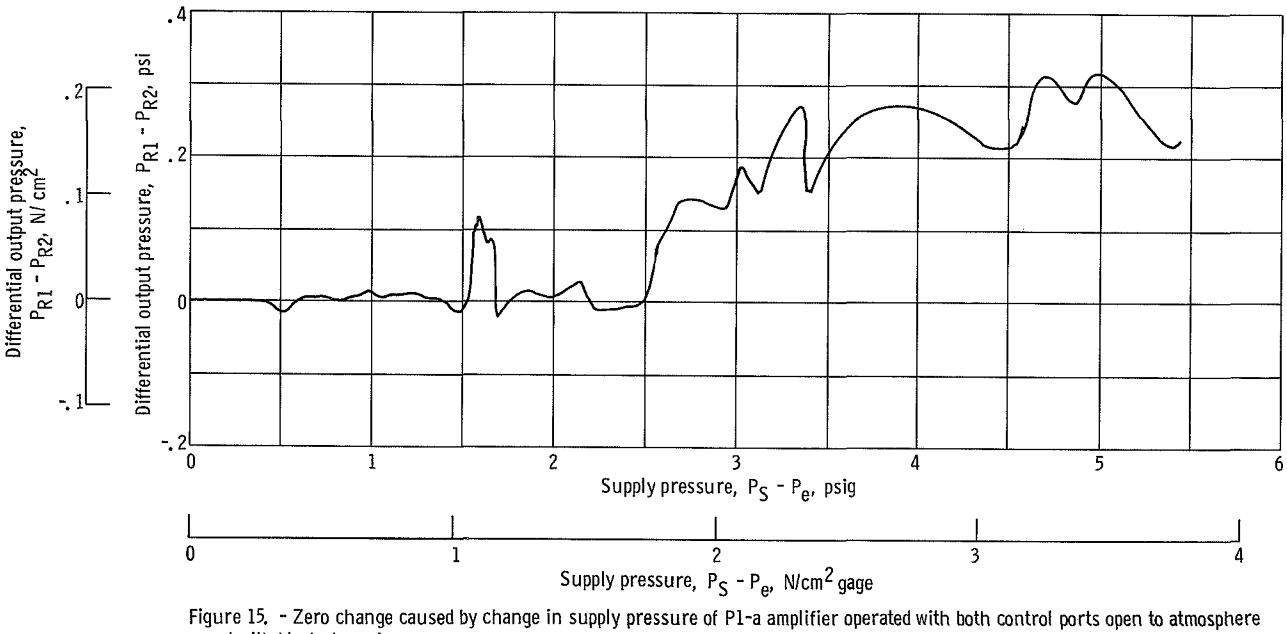


Figure 15. - Zero change caused by change in supply pressure of P1-a amplifier operated with both control ports open to atmosphere and with blocked receivers.

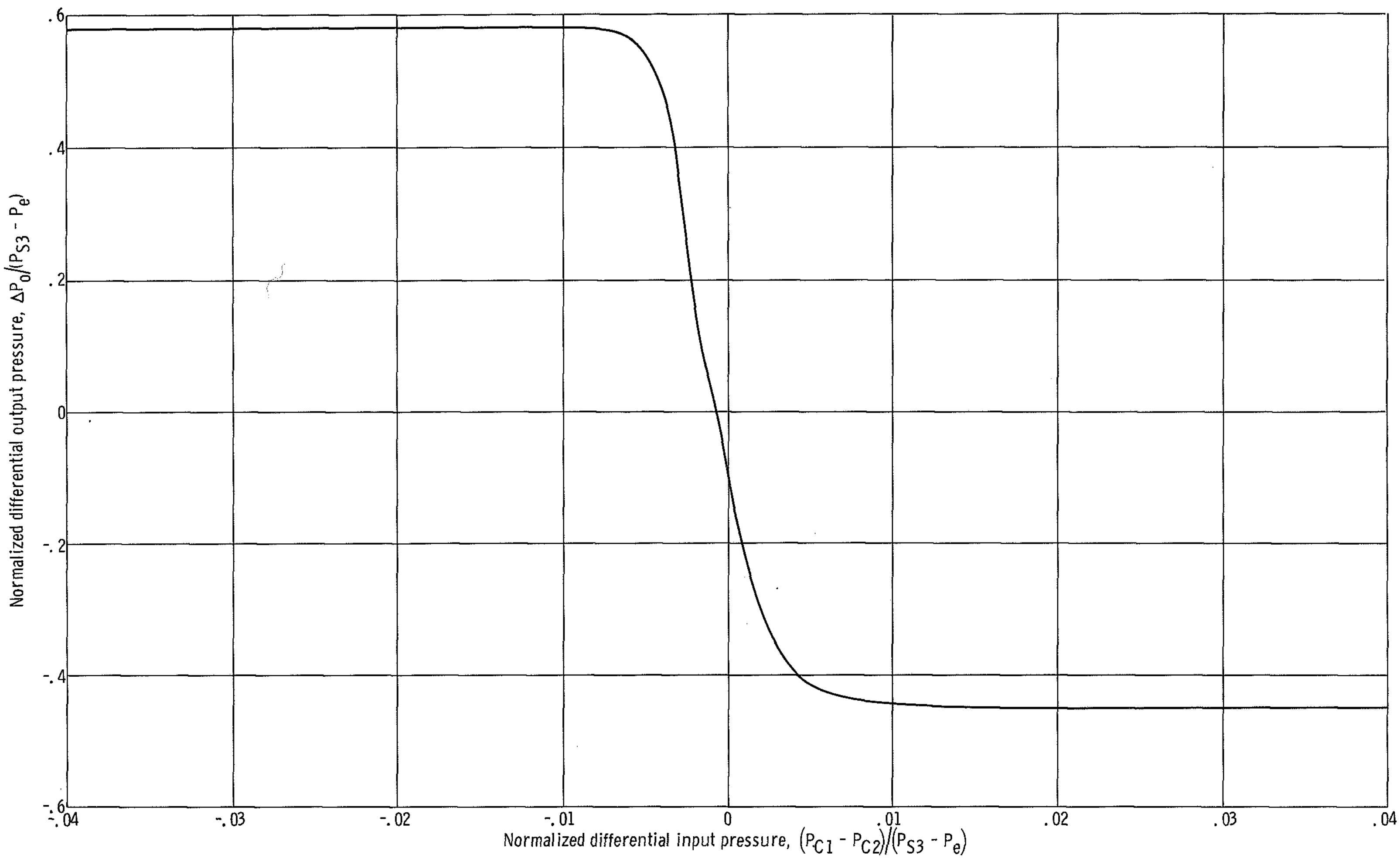


Figure 16. - Blocked receiver pressure gain characteristics. Three-stage open-loop amplifier using P1-a amplifiers with first-stage C_2 port open to atmosphere.

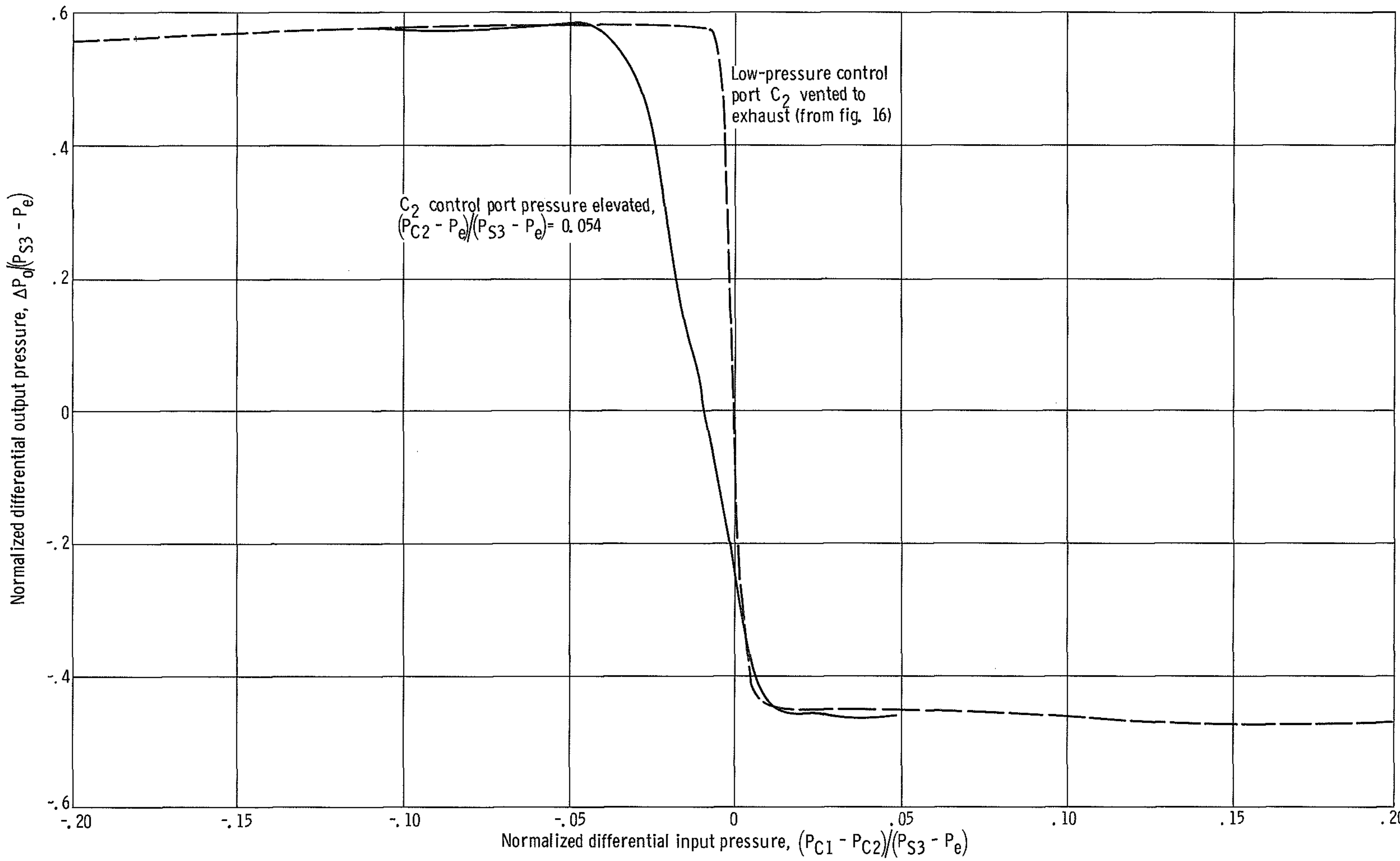
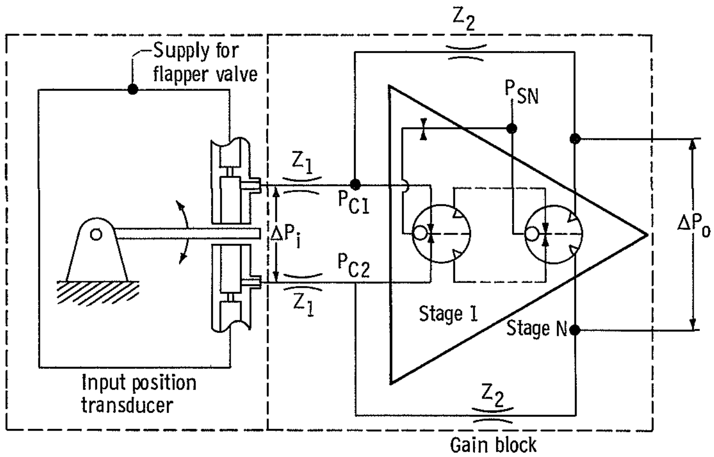
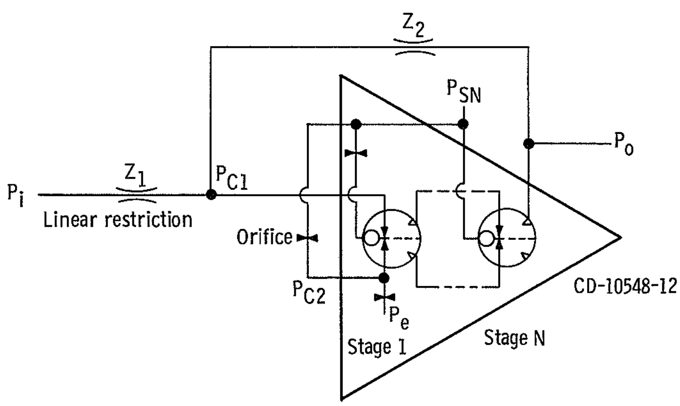


Figure 17. - Blocked receiver pressure gain of three-stage open-loop amplifier showing effect of elevated input pressure.



(a) Input stage in proportional servocontrol system.



(b) Circuit for amplification of single-ended signals.

Figure 18. - Gain block circuits which avoid changes in first-stage average control port pressure.

NASA-Langley, 1969 —— 3 E-5157

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

050 001 26 51 3DS 69304 00903
AIR FORCE WEAPONS LABORATORY/WLIL/
KIRTLAND AIR FORCE BASE, NEW MEXICO 8711

ATT E. LOU BOWMAN, CHIEF,TECH. LIBRARY

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546