NASA CR-72023
BRLD NO. 3395
COPY NO. 34

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

DESIGN, FABRICATION AND TEST OF A FLUERIC SERVOVALVE

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-7980

FACILITY FORM 602

N66 33498	
(ACCESSION NUMBER)	(THRU)
39	1
(PAGES)	(CODE)
CR-72023	15
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

By

THE BENDIX CORPORATION
RESEARCH LABORATORIES DIVISION
Southfield, Michigan

NASA CR-72023
BRLD NO. 3395

Quarterly Report

DESIGN, FABRICATION AND TEST OF A FLUERIC SERVOVALVE

Prepared by: C. E. Vos

C. E. Vos, Engineer
Machine and Propulsion Controls Department
Energy Conversion and Dynamic Controls Laboratory

Approved by: M. H. Cardon

M. H. Cardon, Project Engineer
Machine and Propulsion Controls Department
Energy Conversion and Dynamic Controls Laboratory

Approved by: L. B. Taplin

L. B. Taplin, Manager
Energy Conversion and Dynamic Controls Laboratory
Technical Director, Fluid State Programs

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

28 December 1965 - 28 March 1966

CONTRACT NAS 3-7980

Technical Management
NASA Lewis Research Center
Cleveland, Ohio 44135
Advanced Systems Division
Vernon D. Gebben

By

The Bendix Corporation
Research Laboratories Division
Southfield, Michigan 48076

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ABSTRACT N66-33498

A breadboard model of a pneumatic-input flueric servovalve, which operates with no moving parts, was designed and fabricated. Developmental tests of the power stage and an evaluation test of the breadboard servovalve were conducted, first using nitrogen as the working fluid, and then using hydrogen. The servovalve is designed to operating with H_2 at temperatures from 56°K (100°R) to 333°K (600°R), supply pressure of 148 N/cm^2 (215 psia), exhaust pressure of 34.5 N/cm^2 (50 psia), and maximum control pressure of 48.5 N/cm^2 (70.4 psia). This report presents the results of tests performed during the third three-month period of the program.

Author

SECTION 1

INTRODUCTION

The objective of this program is to develop a high-performance, pneumatic-input, four-way flueric servovalve with dynamic load pressure feedback. A flueric servovalve has no moving parts and therefore offers advantages in reliability and maintenance, particularly when it must operate in severe environments of nuclear radiation, temperature, shock or vibration.

Earlier flueric servovalve development efforts were presented in NASA report CR-54463, entitled "Design, Fabrication, and Test of a Fluid Interaction Servovalve." As an advancement stemming from that earlier development, the servovalve described in this report achieves higher performance by incorporating regenerative feedback for higher gain, along with dynamic load pressure feedback.

The design procedure and component development tests were presented in NASA reports CR-54783 and CR-54901, both entitled "Design, Fabrication, and Test of a Flueric Servovalve." A schematic, a photograph (exploded view), and an assembly drawing of the breadboard servovalve are shown in Figures 1-1, 1-2, and 1-3, respectively.

This development effort is divided into two phases. In Phase I, a breadboard model of the servovalve has been designed and fabricated, and is being tested at room temperature. In Phase II, a prototype servovalve will be designed to fit a flueric position servo for the control drum of a nuclear rocket and will be tested throughout the specified temperature range. This report covers the third calendar quarter of Phase I.

The results of this third-quarter effort are summarized in Section 2. Section 3 describes the results of development test of the power stage, and Section 4 describes an evaluation test of the breadboard servovalve. Goals for the next quarter are listed in Section 5, and the specifications of the breadboard servovalve are presented in Appendix A.

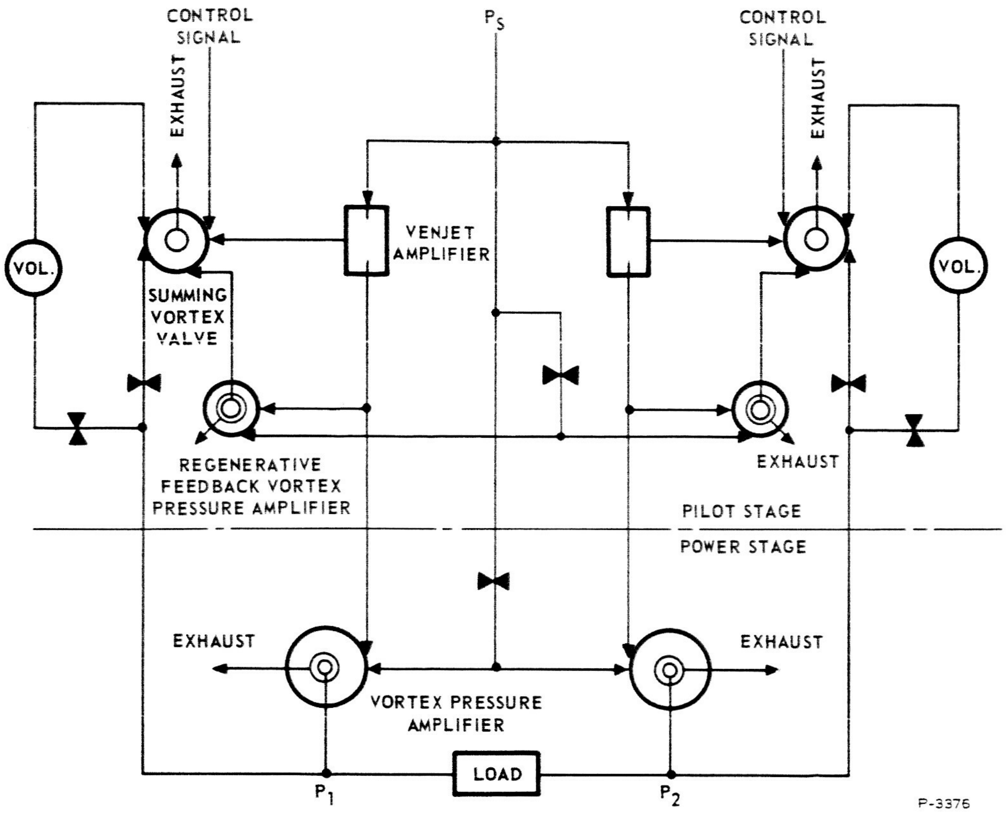

Figure 1-1 - Schematic of Flueric Servovalve

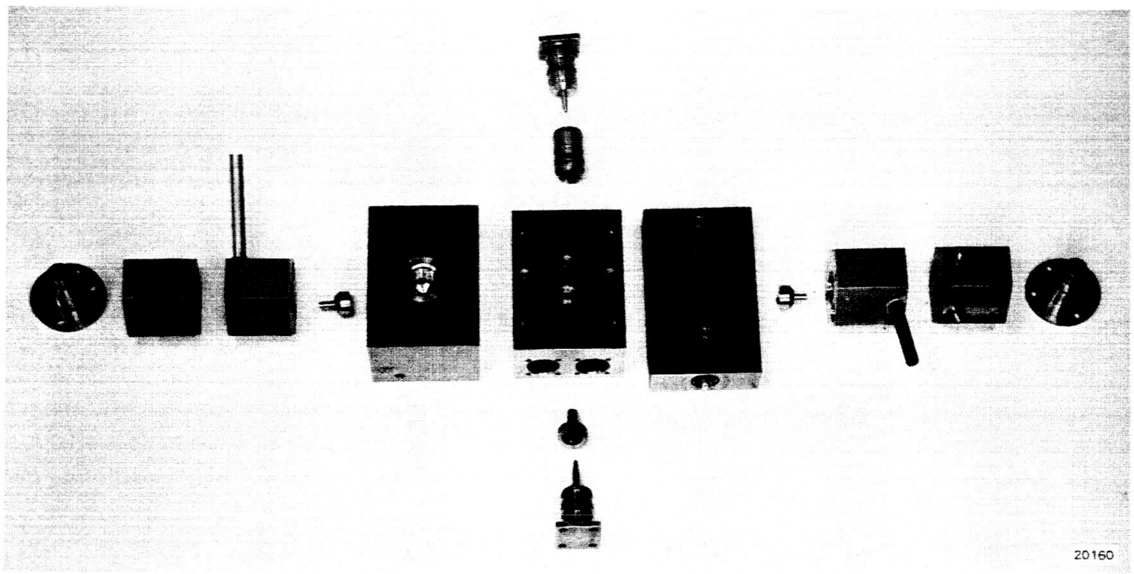

Figure 1-2 - Photograph of Breadboard Servovalve (Exploded View)

2	D	2158268	BODY, POWER STAGE	416 CRES	14
AR	B	2158269-1,2,3	SPACER, POWER STAGE	CRES SHIM STOCK	13
2	D	2158266-2	NOZZLE, POWER STAGE	416 CRES	12
1	D	2158841	MANIFOLD, LOWER	416 CRES	11
4			SOCKET HEAD CAP SCREW	#6-32UNC-3A x .38 LG.	10
4			SOCKET HEAD CAP SCREW	#6-32UNC-3A x 1.38 LG.	9
4			SOCKET HEAD CAP SCREW	#6-32UNC-3A x 1.62 LG.	8
38			"O" RING SEAL	SIZE AS REQ'D.	7
2	D	2158710	HOUSING, VENJET	416 CRES	6
AR	B	2158712-1,2,3	SHIM, VENJET	CRES SHIM STOCK	5
2	B	2158711-1,-2	NOZZLE, VENJET	416 CRES	4
4			SOCKET HEAD CAP SCREW	#4-40UNC-3A x .75 LG.	3
AR	B	2158712-1,2,3	SHIM, VENJET	CRES SHIM STOCK	2
16			SOCKET HEAD CAP SCREW	#4-40UNC-3A x .31 LG	1

4			SOCKET HEAD CAP SCREW	#4-40UNC-3A x 1.25 LG.	29
1	D	2158853	MANIFOLD, UPPER	416 CRES	28
2	C	2158272	NOZZLE, FEED BACK VALVE	416 CRES	27
2	D	2158273	LOWER HOUSING, FEED BACK VL.	416 CRES	26
2	D	2158274	UPPER HOUSING, FEED BACK VL.	416 CRES	25
8			SOCKET HEAD CAP SCREW	#4-40UNC-3A x .81 LG.	24
2	D	2158787	HOUSING, SUMMING AMPL.	416 CRES	23
2	C	2158786	BUTTON, SUMMING AMPL.	416 CRES	22
1	E	2158270	HOUSING, POWER STAGE	416 CRES	21
1			PLAIN NUT	1/4-28UNF-3A CRES	20
1	B	2158875	VALVE, NEEDLE	416 CRES	19
1			LOCK WASHER	1/4 DIA. CRES	18
2	D	2158266-1	NOZZLE, POWER STAGE	416 CRES	17
AR	B	2158269-1,2,3	SPACER, POWER STAGE	CRES SHIM STOCK	16
2	C	2158267	BUTTON, POWER STAGE	416 CRES	15

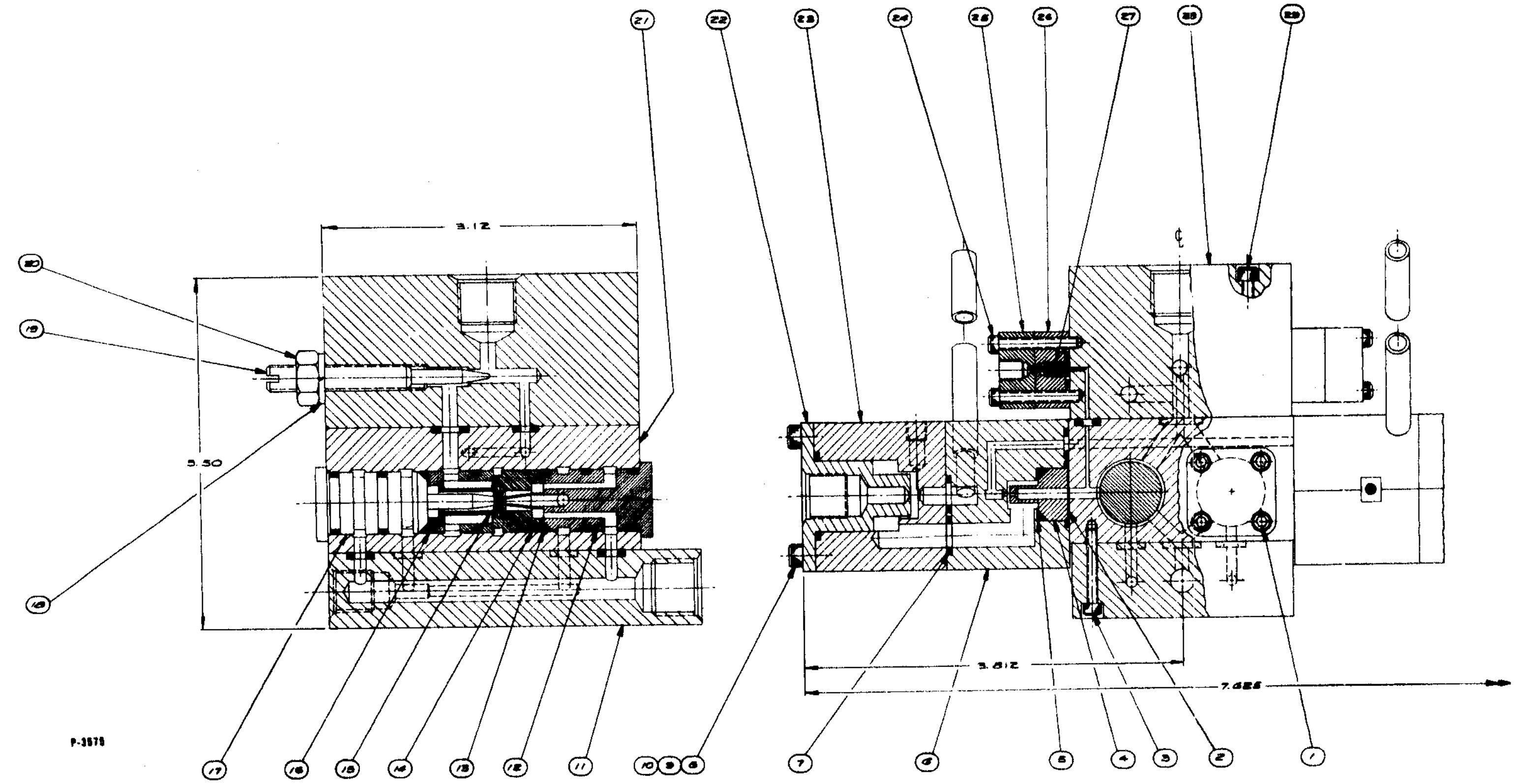

Figure 1-3 - Layout Assembly Drawing of Breadboard Model Flueric Servovalve

SECTION 2

SUMMARY

The servovalve consists of a pilot stage and a power stage. The power stage has two vortex pressure amplifiers* that are operated in push-pull. The pilot stage has two Venjet pressure amplifiers, two summing vortex valves, and two vortex pressure amplifiers which are used to provide regenerative feedback. In addition, dynamic pressure feedback is connected from the load to each summing valve. The output of each Venjet amplifier is the control signal to one of the power stage vortex amplifiers. Each Venjet is controlled by one of the summing valves, which in turn is controlled by an input signal and by the feedbacks.

2.1 STATUS AT START OF THIRD QUARTER

In the previous quarterly periods, the breadboard servovalve was designed, detail drawings were prepared, and all servovalve parts were manufactured, except for one of the two power stage vortex pressure amplifiers. Developmental tests of the pilot stage components were completed and tests of the power stage were begun. Component geometry and sizes that must be established through actual testing to achieve the desired performance were obtained from room temperature tests using nitrogen as the working fluid. A Venjet amplifier and a power stage vortex pressure amplifier also were tested with room temperature hydrogen. It was found that the performance characteristics of these components were almost the same with hydrogen as with nitrogen.

2.2 ACCOMPLISHMENTS DURING THIRD QUARTER

In this period, the second power stage vortex pressure amplifier was built and developmental tests were conducted to improve linearity

*THE OPERATING PRINCIPLES, TERMINOLOGY, AND SYMBOLOGY OF VORTEX PRESSURE AMPLIFIERS, VORTEX VALVES, AND VENJETS ARE GIVEN IN THE REPORT ENTITLED "DESIGN, FABRICATION, AND TEST OF A FLUID INTERACTION SERVOVALVE", (FINAL REPORT), NASA CR-54463 (N65-31178), MAY 17, 1965. REQUESTS FOR COPIES SHOULD BE REFERRED TO THE FEDERAL SCIENTIFIC AND TECHNICAL INFORMATION OFFICE, PORT ROYAL ROAD, SPRINGFIELD, VIRGINIA 22151. IDENTIFICATION NO. N65-31178, CATEGORY CSCL 13G. TWO DOLLARS FOR FULL-SIZE COPY; FIFTY CENTS FOR MICROFILM COPY.

and pressure recovery. One side of the servovalve (consisting of a vortex pressure amplifier, Venjet amplifier, summing vortex valve, and a regenerative feedback vortex pressure amplifier) was assembled and tested. No interface problems between the components were found. Then the two sides of the servovalve were assembled together and evaluation tests of the servovalve were conducted. For economy, all of the specified performance items were tested using nitrogen as the gaseous fluid, and these results were checked by repeating certain tests with hydrogen. The hydrogen tests were for linearity, flow recovery, pressure recovery, and input-signal power.

The developmental tests of the power stage vortex amplifier resulted in improved linearity. The second power stage vortex amplifier, which was tested with a longer exit orifice, proved to have superior pressure recovery and stability.

In the evaluation tests of the servovalve, the objectives were to determine if the components were matched properly in terms of gain characteristics and input-output pressure levels, to determine whether any areas would require further development by comparing the actual performance with the specified performance, and to compare hydrogen and nitrogen operation. The test results indicate that the servovalve frequency response and transient response will be more than adequate, and it was shown that the servovalve will operate on either hydrogen or nitrogen with minor differences in performance. The linearity of the servovalve is good through the middle 50 percent of the specified output differential pressure range and demonstrates a significant improvement over the previous laboratory type servovalve. However, the linear range must be extended and the maximum pressure differential must be increased, particularly for hydrogen operation. This will be accomplished by closer matching of individual component performance characteristics and by increasing the flow capacity of the pilot stage.

Stability tests of the power stage vortex amplifiers showed an oscillation in the output pressure over part of the output pressure range under closed load throttle conditions, and this characteristic caused the differential output pressure of the servovalve to be excessively oscillatory. Subsequent testing of the amplifiers established that this oscillation is caused by a negative resistance region in the pressure-flow characteristics of the probe-receiver of the vortex amplifier. It will be corrected through developmental testing to adjust size, shape and position of the probe-receivers.

2.3 FOURTH-QUARTER OBJECTIVES

Goals for the next period include conducting developmental tests to eliminate the vortex pressure amplifier oscillation and to improve the pressure recovery and linearity of the servovalve. The breadboard servovalve will then be acceptance tested, and the design of the prototype servovalve will be initiated.

SECTION 3

POWER STAGE VORTEX AMPLIFIER TESTS

Developmental tests were conducted during the third-quarter period to improve the linearity, pressure recovery and stability of the power stage vortex pressure amplifiers. Improved linearity was achieved by enlarging the vortex chamber diameter, which eliminated a negative resistance characteristic in the chamber flow. Pressure recovery was increased slightly and the stability was improved by lengthening the exit orifice. Tests were conducted to determine the source of a pressure oscillation that appeared in the vortex amplifier output, and it was found to be caused by a negative resistance region in the probe-receiver of each amplifier.

3.1 CHAMBER DIAMETER DEVELOPMENT

A schematic of the vortex pressure amplifier is shown in Figure 3-1. The significant dimensions of the amplifier, after enlarging the chamber, are as follows:

Vortex Chamber Diameter	1.112 cm (0.438 in)
Vortex Chamber Length	0.094 cm (0.037 in)
Button Diameter	1.062 cm (0.418 in)
Exit Orifice Diameter (two orifices)	0.094 cm (0.037 in)
Control Orifice Diameter (four orifices)	0.046 cm (0.018 in)

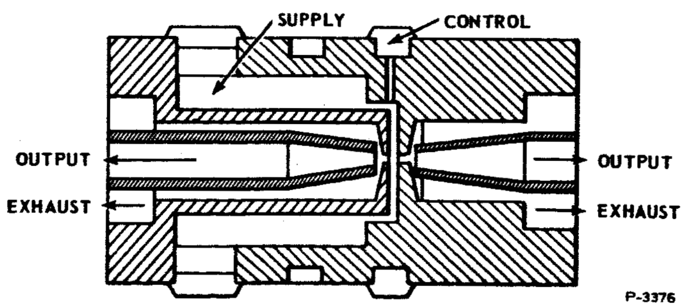

Figure 3-1 - Dual-Exit Vortex Pressure Amplifier

Receiver Diameter	0.104 cm (0.041 in)
Distance Between Exit Orifice and Receiver	0.028 cm (0.011 in)

In the initial tests of the vortex pressure amplifier that was built during the previous quarter, a negative resistance characteristic was found which resulted in a vertical portion of the supply flow versus control pressure curve as shown in Figure 3-2. Negative resistance in a vortex device ordinarily can be eliminated by increasing flow friction and viscous losses in one of two ways -- (a) shortening chamber length to increase viscous drag, or (b) enlarging chamber diameter to lengthen the swirling flow path. It was first attempted to eliminate the negative resistance by shortening the vortex chamber length, but this method was not effective. Then, returning to the original chamber length, the chamber and button diameters were increased, keeping the annular area around the button constant. The vortex chamber diameter, originally 0.660 cm (0.260 in), was first increased to 0.940 cm (0.370 in). This change eliminated some, but not all, of the negative resistance. The chamber diameter was next increased to 1.112 cm (0.438 in), and this change eliminated all of the negative resistance. The flow versus control pressure curve is shown in Figure 3-3.

The foregoing tests were conducted by modifying the chamber of the vortex amplifier that had been built during the previous quarter. After these tests, the second power stage vortex pressure amplifier was built with the new chamber diameter, and tests confirmed the improved linearity.

3.2 EXIT ORIFICE LENGTH

When the second power stage vortex pressure amplifier was built, it incorporated a longer exit orifice as a means of improving both output pressure stability and pressure recovery. The vortex chamber exit orifice length of the first amplifier was 30 percent of the orifice diameter. The blocked output pressure under the zero control flow condition would intermittently fluctuate between 91 percent and 75 percent of the vortex amplifier supply pressure. It was thought that a longer exit orifice would tend to straighten and focus the jet; so the orifice length of the second amplifier was increased to 4 times the orifice diameter. This change eliminated the intermittent output pressure fluctuation, and it increased the maximum blocked output pressure to 96 percent of the supply pressure. However, the minimum blocked

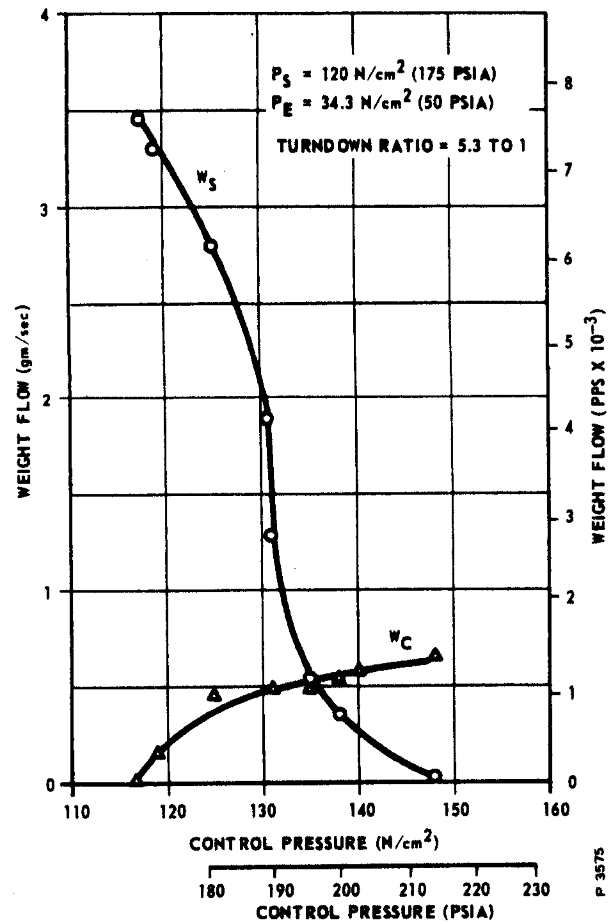

Figure 3-2 - Flow Versus Control Pressure Characteristics of Power Stage Vortex Pressure Amplifier with Small Chamber Diameter

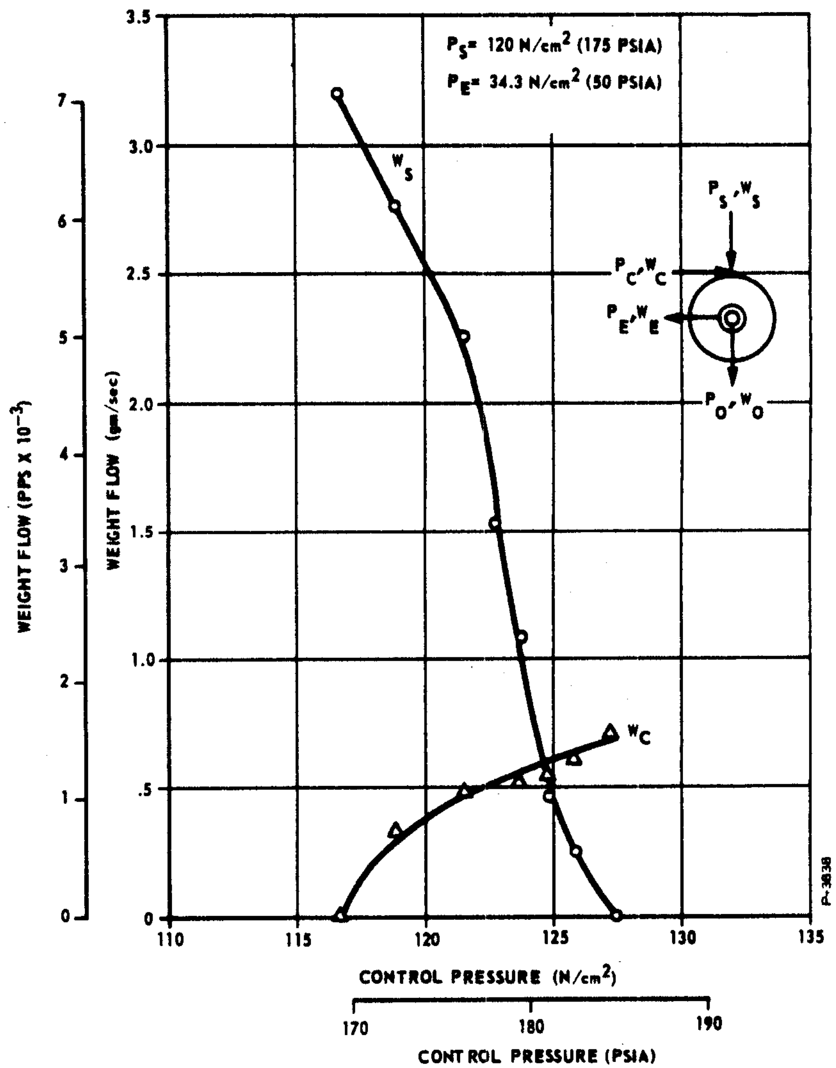

Figure 3-3 - Flow Versus Control Pressure Characteristics of Power Stage Vortex Pressure Amplifier with Large Chamber Diameter output pressure was higher also, so that the maximum pressure differential was only slightly higher, or 72 N/cm^2 (105 psi). A possible method of increasing this maximum output pressure differential will be to decrease the minimum blocked output pressure by increasing the distance between the vortex chamber exit and the receiver.

3.3 PROBE-RECEIVER FLOW TESTS

Prior to the evaluation test described in Section 4, in a test of a power stage vortex pressure amplifier, an oscillation was found in the output pressure with blocked output pressure ranging from 52 to 76 N/cm^2 (75 to 110 psia). In the servovalve evaluation test, it was found that this power stage oscillatory characteristic caused low frequency, high amplitude, unsteady variation of the differential output pressure under closed load throttle conditions. After the evaluation test was completed, further tests were performed on one of the power stage vortex pressure amplifiers in order to determine the source of the oscillation. It was suspected that the oscillation might be due to a negative resistance region in the pressure-flow characteristics of the receiver. The test results show that this is, indeed, the source of the oscillation.

A schematic of the test setup is shown in Figure 3-4. Flows were measured with float-type flowmeters and pressures were measured with standard bourdon tube pressure gauges. The supply pressure to the vortex pressure amplifier was set at 121 N/cm^2 (175 psia) and the exhaust pressure was set at 34.5 N/cm^2 (50 psia). Supply flow, receiver output pressure and receiver output flow data were taken with constant control pressure and with various values of output flow in both positive and negative flow directions. Data were taken at several control pressure levels in order to obtain a family of curves at constant control pressure levels.

The receiver output flow versus output pressure is shown in Figure 3-5. Positive flow is defined as flow in the direction from the vortex chamber toward the receiver. It is seen from the figure that a negative resistance region is present in all of the constant control pressure curves, except the P_c = 120 N/cm^2 (174 psia) curve, where the control flow is zero. The output pressure and flow were oscillatory everywhere in the negative resistance region and relatively quiet elsewhere. It was concluded that this negative resistance region was the source of the power stage vortex pressure amplifier oscillation.

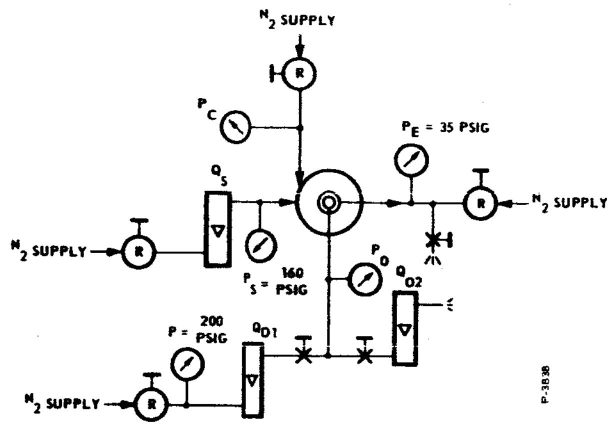

Figure 3-4 - Vortex Pressure Amplifier Test Schematic

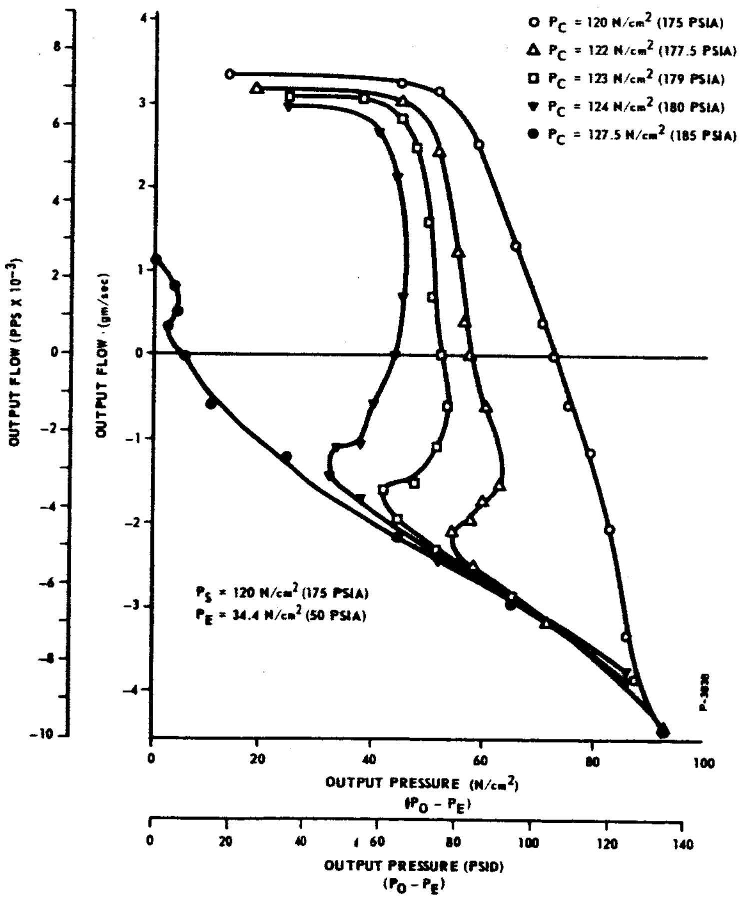

Figure 3-5 - Vortex Pressure Amplifier Receiver Output Flow Versus Output Pressure

In the next period, different receiver geometries will be tested in order to eliminate the negative resistance. These tests will include varying the nozzle-to-receiver distance, chamfering the receiver entrance, and trying various receiver entrance faces ranging from flat to sharp edged. .

SECTION 4

BREADBOARD SERVOVALVE EVALUATION TEST

The objectives of the evaluation test were to determine how well the complete servovalve would perform and what interface problems might exist between the components of the servovalve. The components previously had been separately tested and one side of the servovalve had been assembled and tested.

In the servovalve evaluation test, the linearity, flow recovery, pressure recovery and input-signal power were measured, first using nitrogen as the gaseous medium and then using hydrogen. The other performance items were measured using nitrogen only.

The test achieved its objectives by indicating which performance areas are adequate and which components need further rework or development.

4.1 TEST EQUIPMENT

Transient response, frequency response, output stability, threshold, hysteresis, and symmetry tests were conducted using the test setup shown schematically in Figure 4-1. An electropneumatic flapper-nozzle type valve was used to provide the input control pressures. The electro-pneumatic valve was controlled by a servoamplifier, and the input-signal was varied by a function generator. The differential output and input pressures to the servovalve were measured by means of differential pressure transducers. The pressures were recorded on an X-Y plotter or by photographing oscilloscope traces.

Tests of input admittance, control input power, and output flow versus differential output pressure were conducted using the test setup as shown in Figure 4-2. For these tests, float-type flowmeters were used to measure input, control and load flows, and standard bourdon tube pressure gauges were used to measure pressure.

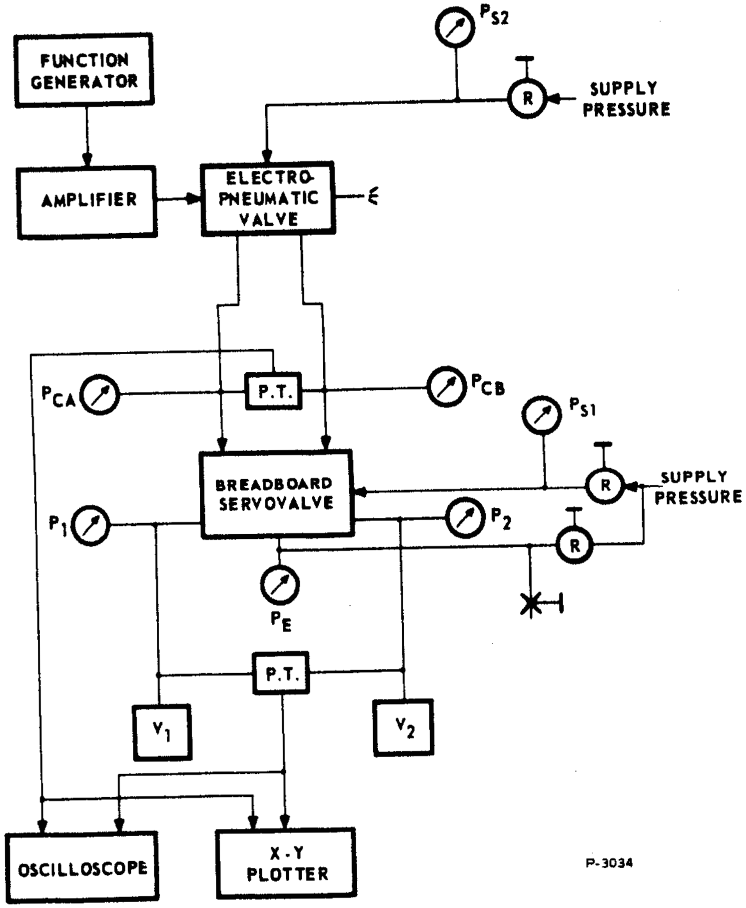

Figure 4-1 - Flueric Servovalve Test
Setup No. 1

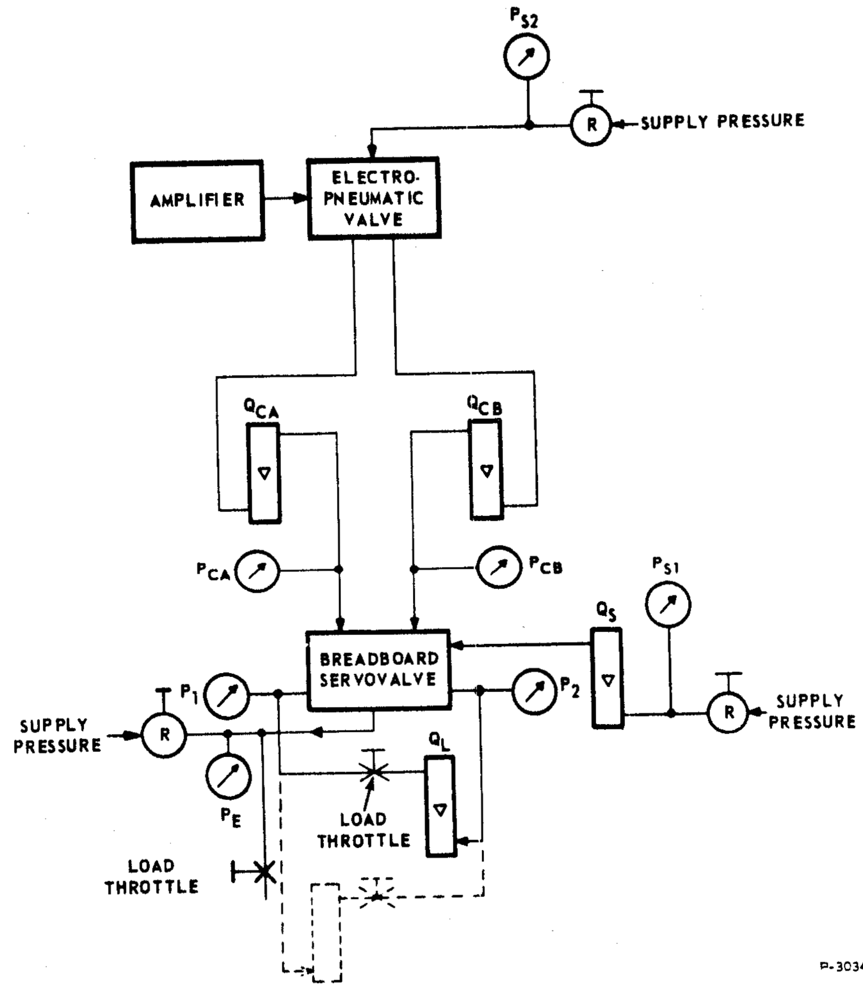

Figure 4-2 - Flueric Servovalve Test
Setup No. 2

4.2 TEST PROCEDURE

4.2.1 Transient Response

The transient response of the servovalve was measured by introducing a step input which resulted in a 20 N/cm^2 (29 psi) change in the differential output pressure, and by recording both the input and output pressures as a function of time. The load volumes were equal and the load throttle was closed.

4.2.2 Frequency Response

The frequency response was measured by introducing a constant-amplitude sine wave input-signal which resulted in a 41 N/cm^2 (16.1 psi) peak-to-peak amplitude in the output differential pressure at very low frequency. The output and input differential pressures were measured as a function of time at various frequencies. The load volumes were each about 4.9 cm^3 (0.3 in^3), and the load throttle was closed.

4.2.3 Output Stability

The output stability was measured by recording output differential pressure versus time with a constant input-signal. This test was performed with closed load throttle and with various load volume sizes and input-signal levels. The load volumes used were:

(1) $V_1 = 139\ cm^3\ (8.5\ in^3)$; $V_2 = 24.6\ cm^3\ (1.5\ in^3)$

(2) $V_1 = V_2 = 82\ cm^3\ (5\ in^3)$

(3) $V_1 = 24.6\ cm^3\ (1.5\ in^3)$; $V_2 = 139\ cm^3\ (8.5\ in^3)$

4.2.4 Threshold

The threshold was measured by recording the input and output differential pressures as a function of time with a sine wave input. The input-signal was gradually decreased until the output no longer followed the input.

4.2.5 Hysteresis and Linearity

The differential output pressure was recorded as a function of the differential input pressure on an X-Y plotter as the input-signal varied slowly from plus to minus and back to plus rated input-signal.

4.2.6 Input Admittance

The input admittance was established by recording the control input pressures and flows and the load flow for various throttle openings with a constant input-signal.

4.2.7 Control Input Power

The control input pressures and flows and output pressures were measured at various input-signal levels with closed load throttle.

4.2.8 Output Flow Versus Differential Output Pressure

The differential output pressure, load flow and supply flow were recorded at various settings of the load throttle with constant input-signal.

4.3 EVALUATION TEST RESULTS

4.3.1 Summary and Discussion of Results

The breadboard servovalve test performance is compared with the specified requirements in Table 4-1. The measured performance met, or came close to meeting, the specified requirements in supply flow, rated no-load flow, transient response, frequency response, threshold, and hysteresis. The test results also point out several areas which definitely require an improvement in performance. These are pressure recovery, linearity, and stability.

Preliminary checks of the servovalve performance prior to the evaluation test indicated that the servovalve would not operate properly with regenerative feedback in the pilot stage. There was a large area of hysteresis along with a bistable type of operation. One side of the servovalve had been previously tested satisfactorily with regenerative feedback in the pilot stage. But, when testing the complete servovalve, the difference in the gain characteristics of the two power stage vortex pressure amplifiers caused the regenerative feedback vortex pressure amplifiers to operate improperly. Therefore, as a temporary expedient to permit the evaluation test to proceed without delay, the regenerative feedback amplifiers were disconnected from the servovalve circuit and the test was performed without them. The effect of this was to increase the maximum input-signal pressure slightly and to increase the total maximum input-signal power by a factor of about two.

Table 4-1 - Breadboard Flueric Servovalve Performance

Item	Specified*	Measured (N_2)	Measured (H_2)
3.1.5 Supply Flow	1.82 rated no-load output flow max.	2.0	1.93
5.2 Rated Input Signal	7 N/cm^2 (10 psi) max.	10 N/cm^2 (14.5 psi)	9.3 N/cm^2 (13.5 psi)
5.3 Input Signal Pressure Bias	45 N/cm^2 (65.3 psia)	53.7 N/cm^2 (76.7 psia)	51.2 N/cm^2 (74.2 psia)
5.5 Total Input Power	2.1 watts max. N_2 @ 530°R 7.7 watts max. H_2 @ 530°R	10.5 watts	31.0 watts
6.2 Rated No-Load Flow	2.76 gm/sec (0.0063 pps) N_2 @ 530°R 0.782 gm/sec (0.00173 pps) H_2 @ 530°R	3.0 gm/sec (0.0067 pps)	0.816 gm/sec (0.0018 pps)
6.4 Pressure Recovery	82 N/cm^2 (119 psi)	67 N/cm^2 (98 psi)	57 N/cm^2 (83 psi)
6.5 Linearity-Deviation Gain Variation	10% max. 2 times avg. max.	19% 2 times	25% 3.6 times
6.7 Stability	0.4 N/cm^2 (0.58 psi) p-p	9 N/cm^2 (13.1 psi)	Not Measured
6.8 Transient Response	62.5% F.V. in 0.055 sec 90.0% F.V. in 0.210 sec	0.110 sec 0.190 sec	Not Measured
6.9 Frequency Response Phase Shift and Amplitude Ratio	20° max. @ 6 hertz 90° max. @ 60 hertz ±2 db max. @ 0-60 hertz	20° @ 5 hertz 90° @ 45 hertz ±1.7 db	Not Measured
6.11 Threshold	0.5% max.	1%	Not Measured
6.11 Hysteresis	3% max.	3%	Not Measured

*See Appendix A

P-3838

Because of the oscillation of the power stage differential output pressure, the load pressure dynamic feedback circuit could not be evaluated, and therefore it, too, was disconnected from the servovalve for this test.

The results of the frequency response and transient response tests show that the response of the servovalve will be more than adequate. The breadboard servovalve components were packaged separately in order to achieve flexibility rather than compactness. Repackaging to decrease connecting line volumes and using hydrogen rather than nitrogen would bring the performance well within the specified limits.

The supply flow was 2.0 and 1.93 times the rated no-load flow on nitrogen and hydrogen, respectively, as compared with the specified value of 1.82 times rated no-load output flow.

The threshold was measured by applying a sine wave input and gradually decreasing the amplitude while recording the output of the servovalve. The threshold is defined as the increment of input-signal required to produce a change in the output signal. Thus, if the input sine wave is reduced until the output amplitude becomes zero, the input amplitude at that point is a measure of the threshold. Actually, the threshold of the servovalve should be zero, because of the nature of its flueric components, which have no inherent hysteresis. Thus, the output amplitude should go to zero only when the input amplitude is reduced to zero. However, the oscillation in the output obscured measurements at low input amplitude so that the test data only show that the threshold is not more than one percent.

Input-signal power is defined as the product of the input-signal volumetric flow and the pressure difference between the input-signal pressure and the servovalve exhaust pressure. The maximum total input-signal power was excessively high for two reasons. The regenerative feedback was not used and thus more control flow was required. Also, the input-signal pressure is high because of the pressure level characteristics of the Venjet amplifier. The Venjet amplifier output pressure versus chamber pressure curve is at a higher chamber pressure than was desired.

The linearity will be improved by increasing the flow capacity of the pilot stage and also by better matching of the gain characteristics of the power stage and the pilot stage individual components. This will be done by testing of gain characteristics and making fine adjustment of such dimensions as orifice diameters, chamber lengths, and distances between nozzles and receivers.

The oscillation of the output differential pressure was found to be caused by a negative resistance region in the pressure-flow characteristics of the vortex pressure amplifier receiver as described in Section 3. Elimination of the negative resistance will be attempted by varying the geometry of the receiver entrance.

The maximum pressure recovery or output differential pressure was 68 N/cm^2 (98 psi) versus the required 82 N/cm^2 (119 psi). The two power stage vortex pressure amplifiers had different chamber exit orifice lengths, and the amplifier with the shorter orifice length had lower pressure recovery. Use of the longer exit orifice length type of vortex amplifier on both sides of the power stage will improve the pressure recovery.

4.3.2 Evaluation Test Performance Data

A typical trace of the transient response is shown in Figure 4-3. The response time values listed in Table 4-1 are the average of several traces. The differential output reached 62.9 percent of the step in 0.110 second and settled within 90 percent of the final value in 0.190 second.

The frequency response data is shown in Figure 4-4. The input-signal was 6.2 percent of the rated input-signal rather than 2 percent as called out in the specifications, so that the differential output pressure sine wave data would not be obscured by the output pressure oscillation. The phase shift was 90 degrees at 45 hertz. The differential output pressure amplitude variation was less than ± 1.7 db from 0 to 80 hertz. This phase shift without amplitude variation indicates that a signal delay of approximately 8 milliseconds occurs in the breadboard servovalve.

Representative differential output pressure stability data is shown in Figure 4-5. The data was taken after filtering the electrical signal of the differential output pressure transducer with a $1/(0.05S+1)^2$ filter. The upper photograph shown was taken on an average differential output pressure of 0. The maximum amplitude of oscillation in this case was 9 N/cm^2 (13.1 psi) peak-to-peak to a frequency of about 6.3 hertz. The differential output pressure was oscillatory over most of the differential input pressure range, except at near ± 100 percent rated input-signal, where the output differential pressure is relatively quiet as shown in the lower photograph in Figure 4-5.

The differential output pressure versus differential control input pressure with closed load throttle is shown in Figure 4-6. The linearity and hysteresis performance was determined from this curve. The deviation from a straight line of the trace is 19 percent of the rated value, which exceeds the specified maximum of 10 percent. The maximum pressure gain is 2 times the average pressure gain, which is just equal to the specified limit. The curve does not pass through the origin because of the difference in gain characteristics of the two power stage vortex pressure amplifiers. These data were taken with nitrogen as the gaseous medium.

Figure 4-7 shows the servovalve pressure gain with hydrogen as the gaseous medium instead of nitrogen. The deviation from a straight line of the gain curve is 25 percent of the rated value, and the maximum pressure gain is 3.6 times the average gain. It is seen from

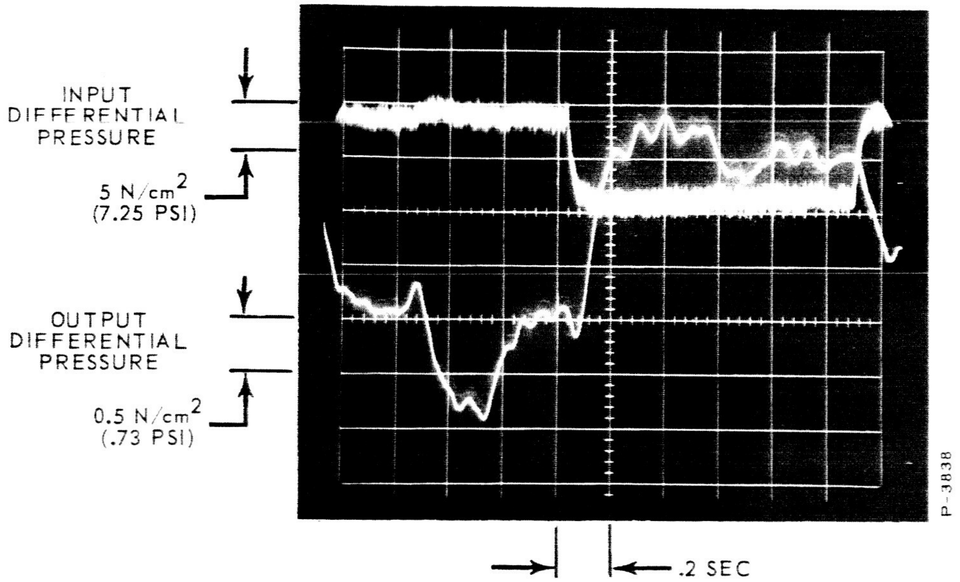

Figure 4-3 - Transient Response of Breadboard Flueric Servovalve

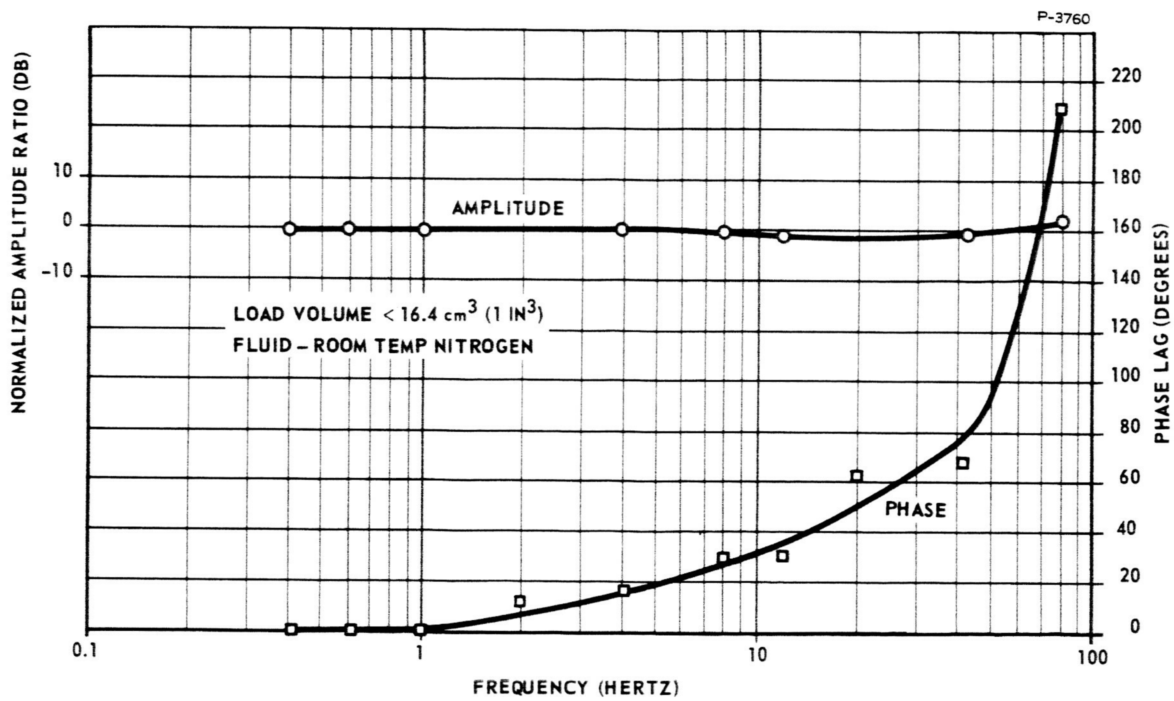

Figure 4-4 - Frequency Response of Breadboard Flueric Servovalve

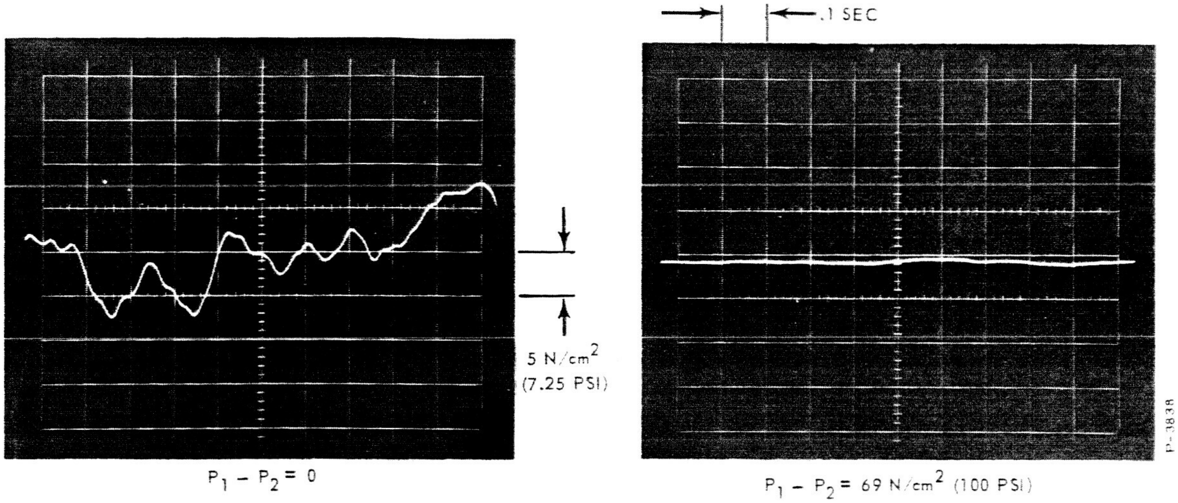

Figure 4-5 - Differential Breadboard Flueric Servovalve Output Pressure Stability

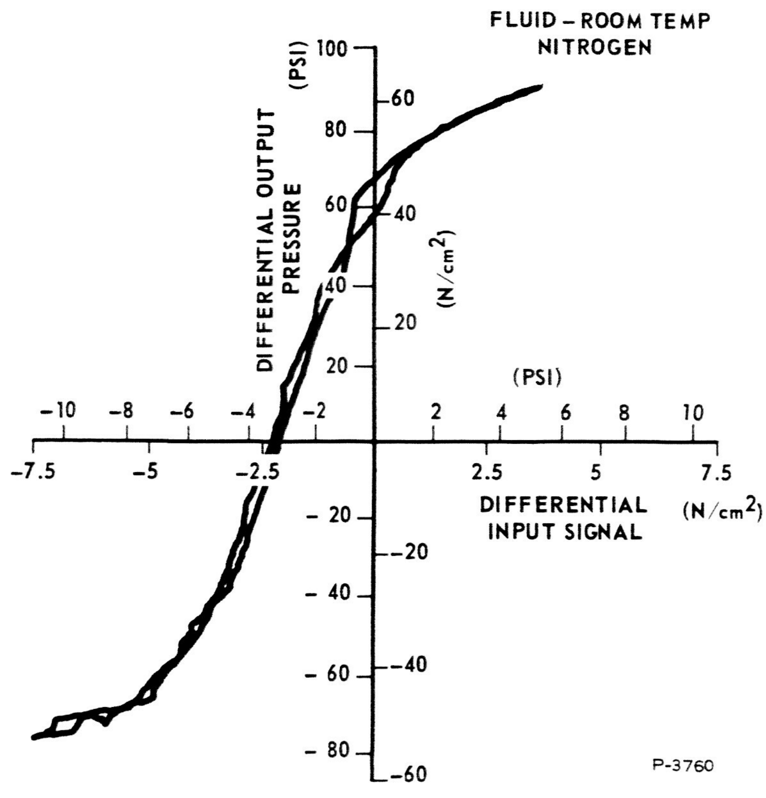

Figure 4-6 - Differential Output Pressure Versus Differential Input Signal of Breadboard Flueric Servovalve with Nitrogen

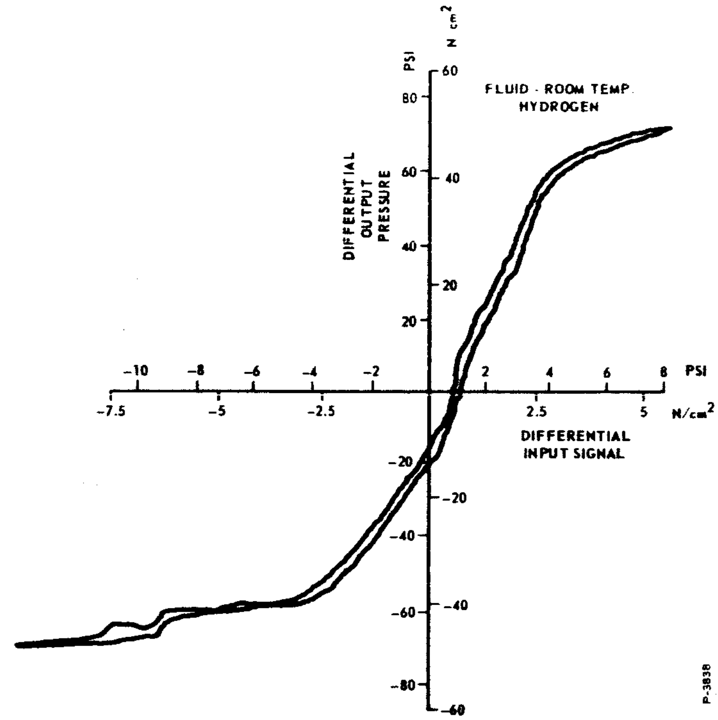

Figure 4-7 - Differential Output Pressure Versus Differential Input Signal of Breadboard Servovalve with Hydrogen

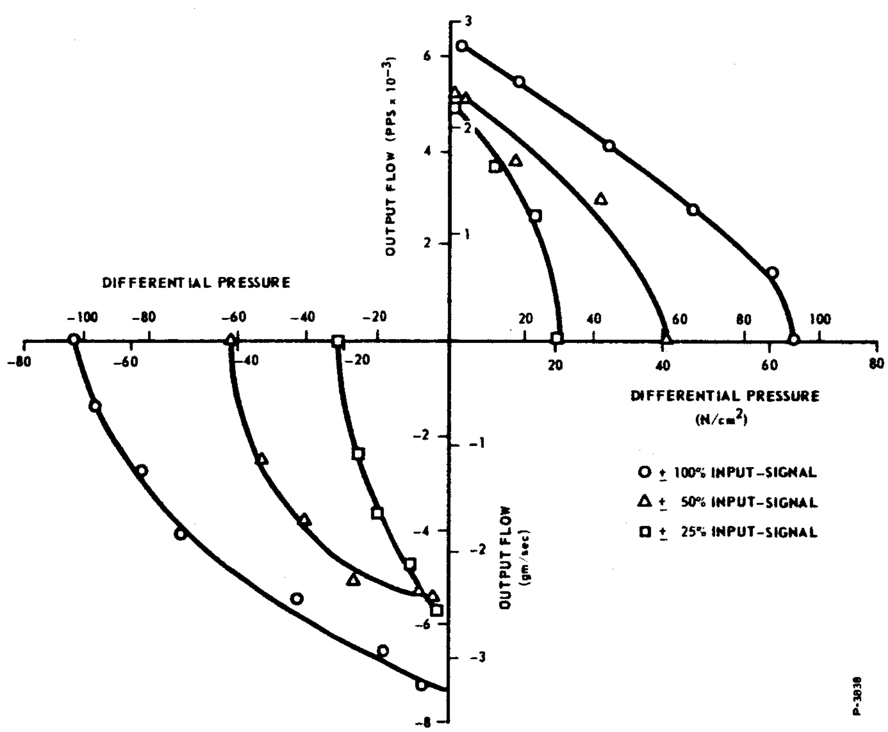

Figure 4-8 - Breadboard Flueric Servovalve Output Flow Versus Differential Pressure comparison with the curve in Figure 4-6 that there is a large zero shift and a decrease in the maximum differential output pressure. In previous tests of individual components, it was found that the performance characteristics were almost the same with hydrogen as with nitrogen. However, because of the lack of symmetry between the two sides of the servovalve, a small gain change results in a zero shift. Identical gain characteristics of both sides of the servovalve should eliminate the zero shift.

The output flow versus differential output pressure is shown in Figure 4-8. From this figure, it is seen that at rated input-signal the maximum load flows were 2.85 gm/sec (0.0063 pps) in one direction and 3.3 gm/sec (0.0073 pps) in the other. The maximum differential output pressures are 65.4 N/cm^2 (95 psi) and 70.3 N/cm^2 (102 psi). The supply flow remained at 6.18 gm/sec (0.0136 pps) during the test.

SECTION 5

GOALS FOR NEXT PERIOD

The next quarter goals will be to:

(1) Conduct developmental tests on the power stage vortex pressure amplifier to eliminate the excessive oscillation in the servovalve output and to improve the pressure recovery.

(2) Match gain characteristics of both sides of servovalve to eliminate zero offset, to improve linearity and to enable testing of pilot stage regenerative feedback.

(3) Conduct acceptance tests of breadboard servovalve.

(4) Begin the design of the prototype servovalve.

APPENDIX A

DESIGN SPECIFICATIONS FOR FLUERIC SERVOVALVE

1. SCOPE

The specification covers a valve to be designed to meet the requirements of NASA Contract Number NAS 3-7980, entitled "Design, Fabrication and Test of a Flueric Servovalve."

2. DESCRIPTION

The servovalve shall be a four-way valve with dynamic negative feedback of the output pressure. The servovalve shall contain no moving mechanical parts such as bellows, variable orifices, and jet-pipes. The principle of operation shall be the interaction of fluid streams.

3. SUPPLY AND EXHAUST SPECIFICATIONS

3.1 Phase 1 - Breadboard Model

3.1.1 Working Fluid: The working fluid shall be both nitrogen and hydrogen gas.

3.1.2 Temperature: Supply gas shall be room temperature.

3.1.3 Supply Pressure: The supply pressure shall be 148 ± 7 newtons per square centimeter, absolute (215 ± 10 psia).

3.1.4 Exhaust Pressure: The exhaust pressure shall be 34.5 ± 3.5 N/cm^{2}a (50 ± 5 psia).

3.1.5 Supply Flow: Under all operating conditions, the flow through the supply port shall be less than 1.82 times the rated no-load output flow. where "rated no-load output flow" is defined here as the mass flow through the wide open load-throttle for rated input signal. "Rated input signal" is defined in Paragraph 5.2.

3.2 Phase II - Breadboard Model and Prototype Servovalve

3.2.1 Working Fluid: The working fluid shall be dry hydrogen.

3.2.2 Temperature: Supply gas temperature shall be variable from 56 to 333 degrees Kelvin (100 to 600°R).

3.2.3 Supply Pressure: The supply pressure shall be 148 ± 7 N/cm^2a (215 ± 10 psia).

3.2.4 Exhaust Pressure: The exhaust pressure shall be 34.5 ± 3.5 N/cm^2a (50 ± 5 psia).

3.2.5 Supply Flow: Under all operating conditions, the flow through the supply port shall be less than 1.82 times the rated no-load output flow.

4. LOAD SPECIFICATION

The two output ports shall be connected to a load consisting of a series arrangement of a volume-throttle-volume combination. The load shall contain no vents. The load volumes shall be adjustable to the extent that the difference between the two volumes can vary between plus and minus 115 cubic centimeters (7 in^3). The total of the two volumes shall remain equal to 164 cm^3 (10 in^3). The load-throttle shall be a two-way valve adjustable from closed to wide open passageway. With wide open load throttle, the differential output pressure shall be less than 5 N/cm^2 (7 psi).

5. INPUT-SIGNAL SPECIFICATIONS

5.1 Input-Signal: The input-signal shall be a two-port differential pneumatic signal. The working fluid shall be the same as the supply gas for the servovalve. "Input-signal pressure" is defined here as the pressure difference between the two input ports.

5.2 Rated Pressure: The rated input-signal pressure shall be less than 7 N/cm^2 (10.2 psi) for flow in both directions through the load-throttle. "Rated input-signal" is defined here as the input signal that produces the rated no-load flow specified in Paragraph 6.2.

5.3 Quiescent Pressure: For zero input-signal, the pressure bias of the input-signal shall be less than 45 N/cm^2a (65.3 psia); where "pressure bias" is defined here as the average pressure of two lines.

5.4 Admittance: Variation in the admittance of each input port, resulting from changes in the load-throttle, shall be less than 10% of the maximum input admittance for the complete range from closed to wide open load-throttle; where "admittance" is defined here as the mathematical derivative of volumetric flow with respect to the absolute pressure in the input port. No specification is placed upon variation in the input admittance as a function of the input-signal.

5.5 Power: Under all operating conditions with dry hydrogen at 56°K (100°R), the combined power delivered to the input ports shall be less than 4 watts; where "power" is defined here as the product of the gage pressure (i.e., pressure relative to the exhaust pressure) and volumetric flow.

6. OUTPUT SPECIFICATIONS

6.1 Output: The servovalve shall have two output ports. "Differential output pressure" is defined here as the pressure difference between the output ports. "Output flow" is defined here as the mass flow through the load-throttle.

6.2 Rated No-Load Flow: With wide open load-throttle, the output flow of dry hydrogen at 56°K (100°R) shall be 2.1 grams per second (0.00463 lbs/sec) for the rated input-signal.

6.3 Pressure Recovery: With closed load-throttle, the differential output pressure shall be greater than 82 N/cm^2 (119 psi); i.e., 73% pressure recovery.

6.4 Pressure-Flow Characteristics: For all values of constant input-signal, the output flow shall be equal to or greater than

$$\dot{m}_o \left(1 - \frac{p}{p_o}\right)$$

where quantity $\dot{m}_o$ is a constant and equals the output flow for the given input signal with closed load-throttle; p_o is a constant and equals the differential output pressure for the given input-signal with closed load-throttle; and p is a variable term equal to the differential output pressure for the given input-signal and is a function of the load-throttle setting.

6.5 Linearity: Deviation from a straight line of input-signal pressure versus differential output pressure for closed load-throttle shall be less than 10% of the rated values. The pressure gain for all values of input-signal shall be less than two (2) times the average pressure gain, where "pressure gain" is defined here as the mathematical derivative of the differential output pressure with respect to the input-signal pressure during steady operating conditions with closed load-throttle.

6.6 Pressure Feedback: Dynamic negative feedback of the pressure of each output port shall be an integral part of the servovalve. The feedback gain at zero frequency shall be less than 1% of the rated input-signal. The feedback gain at the corner (break) frequency of 5 hertz shall be 8 ± 1% of the rated input signal. Construction of the servovalve shall allow easy exchange of components for changing the pressure feedback characteristics.

6.7 Stability: Peak to peak ripple of frequencies above 3 hertz shall be less than 0.4 N/cm^2 (0.58 psi) measured after filtering an electrical signal of the differential output pressure with a $1/(0.05S + 1)^2$ filter, for various load-volume settings and for all values of input signal with closed load-throttle.

6.8 Transient Response: From any initial value and for step input-signals that produce a 20 N/cm^2 (29 psi) change in the differential output pressure, the differential output pressure shall reach 62.5% of the step in a time period of less than 0.055 seconds and shall settle within 2 N/cm^2 (2.9 psi) of the final value in a time period of less than 0.210 seconds when tested with closed load throttle and with equal load-volumes.

6.9 Frequency Response: With zero load-volumes and blocked output ports, the phase shift of the differential output pressure for a 2% rated input-signal at 6 hertz shall be less than 20 degrees, and at 60 hertz the phase shift shall be less than 90 degrees. The differential output pressure amplitude variation for a constant input-signal shall be less than ± 2 db from 0 to 60 hertz.

6.10 Threshold: For all values of input-signal, the increment of input-signal required to produce a change in the output shall be less than 0.5% of the rated input-signal.

6.11 Hysteresis: The difference in the input-signal required to produce the same output during a single input cycle shall be less than 3% of the rated input-signal.

7. ENVIRONMENT SPECIFICATIONS

Items 7.2, 7.3, and 7.4 shall not apply to the breadboard model of the servovalve.

7.1 Ambient Temperature: The servovalve shall be capable of operation under ambient temperatures that vary between 56 and 333°K (100 and 600°R).

7.2 Vibration: The servovalve shall be operational when subjected to 6 g's amplitude from 0 to 20 hertz and then linear amplitude to 20 g's at 200 hertz and then constant at 20 g's to 2000 hertz along any axis.

7.3 Shock and Acceleration: The servovalve shall operate after a 6 g shock and/or a 8 g acceleration along any axis.

7.4 Radiation Field: The servovalve shall be operational under a total dose of 6×10^6 rads (ethylene) 1 hour; a fast neutron flux rate ($E > 1.0$ nev) of 3×10^{11} neutrons/cm^2-sec; a thermal neutron flux ($E < 1.86$ EV) of 1×10^{10} neutrons/cm^2-sec; and a gamma heating equivalent to 770 watts/kilogram aluminum (350 watts/lbm aluminum).