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Technical Report
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PROGRAM FOR THE CRITICAL COMPONENTS OF A FLY-BY-TUBE BACKUP FLIGHT CONTROL SYSTEM

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This report presents the results of a program to develop two of the critical components in an advanced fluidic backup primary flight control system defined as the fly-by-tube concept. Components developed include an input transducer, which converts pilot commands into hydraulic differential pressure signals, and fluidic resistor networks that sum these hydraulic signals together to provide the required servoactuator commands. Results show that this concept which uses signal levels up to +400 PSID is accurate, linear, quit, simple, low cost, relatively insensitive to changes in fluid viscosity, and has a stable null with adequate response.

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EXECUTIVE SUMMARY

This report presents the results of a program to develop two of the critical components in an advanced fluidic backup primary flight control system. The system will function as a dissimilar backup to a Digital Fly-by-Wire (DFBW) flight control system for a V/STOL type aircraft or other advanced aircraft.

Dissimilar flight control systems, which are not susceptible to any form of electromagnetic rediation or loss of electrical power, are mechanical linkages and fluidic flight controls. Fluidic systems are lighter, easier to route through the aircraft, and offer the option of added stability augmentation.

A new design approach was selected for this program and the resulting performance was far superior to that obtained on previous fly-by-tube systems. Two design features account for this improved performance:

1. Signal levels (scale factors) throughout the system were increased by a factor of one hundred or more. Larger signals are less susceptible to most error sources.

2. Fluid amplifiers used for summing of signals were replaced with simple orifice networks. Development of these summing networks is the most significant accomplishment of this program. Problems associated with null shift and gain change as a function of fluid temperature changes have been virtually eliminated. Networks, which are designed using the procedures outlined in this report, will be linear to within ±1 percent. This is much better than required for most applications.

Performance of the system over the design temperature range of 40°F to 180°F using MIL-H-83282 was satisfactory for most applications. Gain change was less than ±12 percent, which is close to the design objective of ±10 percent. Cross axis coupling was measured to be ±2.7 percent as compared to design objectives of 2.0 percent. Remaining characteristics of threshold, linearity, response, and null stability all were well within design objectives. The most impressive characteristics of this system were its stable null and its low noise.

Response of the signal transmission lines was excellent over the entire temperature range. Signal propagation velocity in hydraulic oil was about 4,000 ft/sec, giving a response approximately four times as fast as could be obtained with the best pneumatic system. A line size of 0.125 inch appears adequate for most applications resulting in a low system weight.

Major risk areas in developing a hydraulic backup flight control system have been overcome as a result of this program. A satisfactory non-augmented backup system can be produced with existing state-of-the-art technology. Growth versions of this system, designed to interface with fluidic stability augmentation systems or direct drive servoactuators, will require additional development in the area of high-pressure fluid amplifier cascades.

PREFACE

This document is the final report of a program to develop two of the critical components in an improved fly-by-tube backup primary flight control system concept. Work covered in this report was performed from January 1978 to December 1978 by the Avionics Division of Honeywell Inc. under Navy contract N62269-78-C-008. The sponsoring agency was the Naval Air Development Center, Warminster, Pennsylvania. Mr. Ralph McGiboney was the Project Monitor.

Publication of this report does not constitute approval by the Naval Air Development Center of the findings and conclusions contained herein. It is published for the exchange and stimulation of ideas.

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SECTION I
INTRODUCTION

Fluidic Technology appears to be a promising and low-risk method of providing an effective and dissimilar backup for digital fly-by-wire (DFBW) flight control systems to be used on V/STOL type aircraft and other advanced aircraft.

The basic technologies of fluidic components have been demonstrated and proven. Fluidic stability augmentation systems (SAS) have accumulated more than 8,000 flight hours in the Navy TH-57 Helicopters and an equivalent amount of time in other military aircraft.

Fly-by-tube, an extension of fluidic technology, is a control concept that provides a hydraulic control signal link between the pilot's controls (stick and pedals) and the control surface actuators. It provides a third alternative to mechanization of primary flight controls; the other alternatives are conventional mechanical flight controls and the growing fly-by-wire technology. Fly-by-tube, however, offers potential weight, cost, and versatility advantages over conventional mechanical systems, while protecting against catastrophic electronic failures that might occur in a fly-by-wire system from lightning, radiation, or other common mode electrical failures. Fly-by-tube is also compatible with current fluidic flight control techniques, making the addition of stability augmentation relatively simple.

Two existing fly-by-tube concepts were evaluated and a third concept was generated on a previous program reported on in Reference 1.* The low pressure passive system, which used levers and bellows for summing of signals, demonstrated excessive null shift and unpredictable gain changes in its existing state of development. The second system evaluated on this previous program was a low signal level active fly-by-tube system, which used fluidic amplifiers for summing of signals. This system had problems of low gain, poor linearity, and excessive null shift with temperature. Analysis of these concepts as applied to a UTTAS/LAMPS class helicopter resulted in the recommendation of a third configuration: a high signal level active fly-by-tube system using resistor network summing, which provides improved linearity, gain stability, and null stability.

This report presents the results of a program to develop two of the critical components required in the above recommended high signal level fly-by-tube concept. These components--an input transducer and a summing network--were designed, fabricated, and tested. This report thoroughly documents the program's findings, from detailed design data (with a step-by-step procedure for designing a summing network) to system test results, including the effects of fluid temperature and vibration.

*"Design Study of a Fluidic Flight Control System," Contract No. N00019-76-C-0272 (January 1977).

Development status of all components in typical fly-by-tube systems is summarized in Section VII.

Because of the excellent performance and simplicity of this design approach, the final section of this report recommends the development of a flightworthy fluidic fly-by-tube system.

SECTION II

SYSTEM DESCRIPTIONS AND GENERAL REQUIREMENTS

This section briefly describes each major component. Figure 1 shows a simplified schematic of a single axis fly-by-tube backup primary flight control system.

1. INPUT TRANSDUCER

The input transducer converts pilot commands from a mechanical displacement to a fluidic differential pressure signal. In some applications this transducer also has an electrical input to be used for built-in-test (BIT).

Stringent requirements on null stability, gain stability, and tolerance to moderate changes in load impedance dictate the use of pressure feedback within this transducer.

Transducer output range is ±400 psid, which is several orders of magnitude greater than the previous active fly-by-tube system in which the input transducer had a range of less than ±1 psid. The use of larger signals simplifies mechanization of negative pressure feedback and greatly improves overall system performance.

The input transducer is one of the two major critical components developed on this program. Section III details the input transducer design requirements and performance data.

2. SUMMING NETWORK

Each input transducer supplies signals to two or more summing networks in a typical fly-by-tube system. In addition to the mixing of command signals, the summing network is also the logical point for introducing stability augmentation system (SAS) signals in many applications. Analysis has indicated that linearity of properly designed resistor summing networks should be better than ±1 percent if inputs are designed to have a gain of 0.25 or less. Fixed geometry resistor summing networks are the second critical component developed on this program.

A variable geometry resistor summing network can be used as a "gain changer" or programmer/scheduler, which changes the characteristics of the primary flight control system as a function of flight condition. Most of the advancements made on the development of fixed geometry summing networks can be applied directly to the design of more complex variable geometry devices in the future.

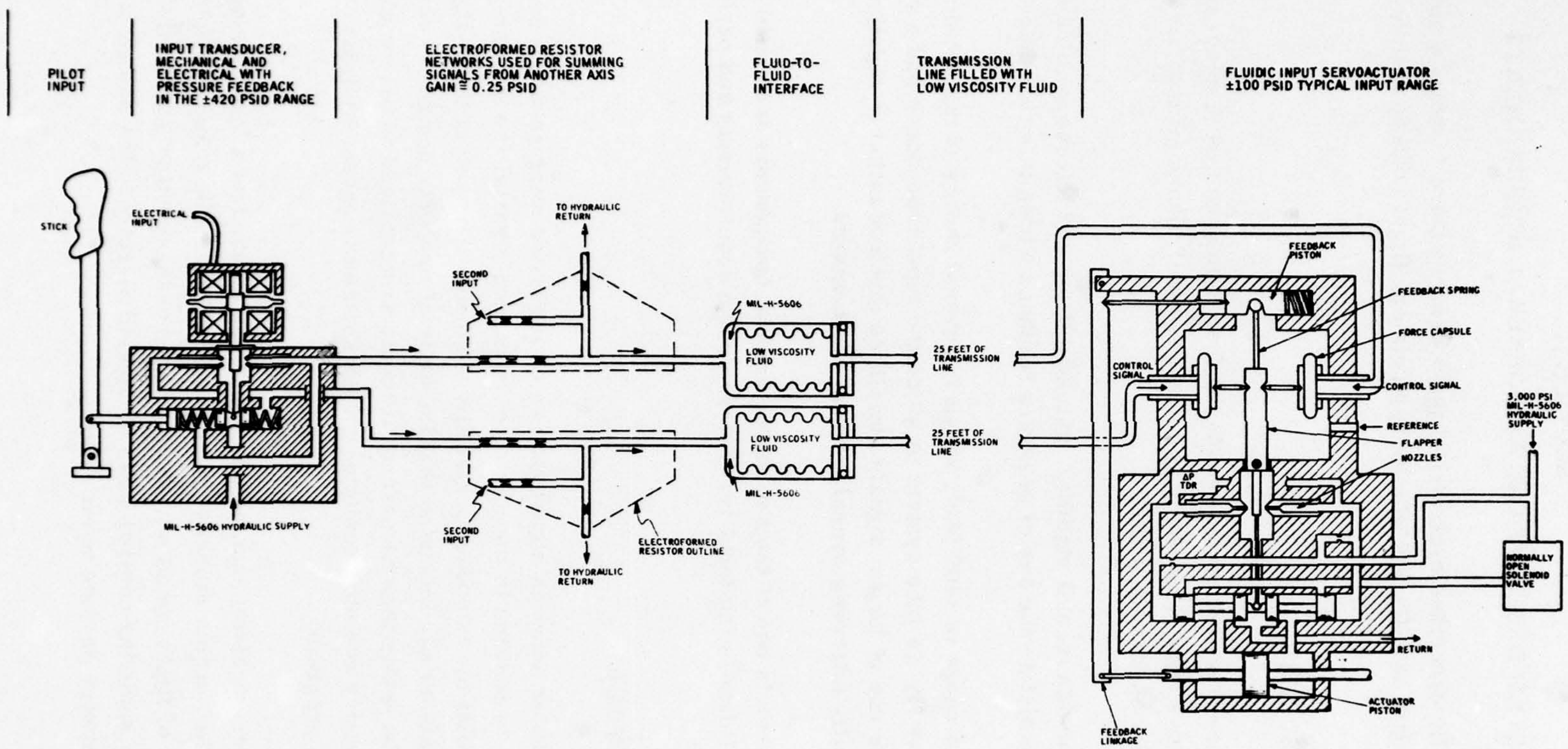


Figure 1. Single-Axis Schematic of a High Signal Level Active Fly-by-Tube Backup Primary Flight Control System

Section IV presents details of the design and development of fixed geometry resistor summing networks.

3. FLUID-TO-FLUID INTERFACE - OPTIONAL (use with sealed lines only)

Sealed fluid filled transmission lines were previously used with pneumatic stability augmentation systems because compressibility and time delay associated with air in long transmission lines greatly reduced system response.

When used with hydraulic systems, not only do sealed lines eliminate air entrainment problems, but much smaller lines can be used when the lines are filled with a low viscosity fluid. Systems with sealed transmission lines usually weigh substantially less than those with flowing transmission lines.

This optional fluid-to-fluid interface uses a low spring rate bellows or rolling diaphragm to separate the aircraft hydraulic oil from the low viscosity fluid in the transmission lines. There is essentially zero differential pressure across the interface under all conditions; differential thermal expansion in the transmission lines will not cause a null offset. Self-bleeding features, not shown in the schematic, are incorporated into the input side of the bellows.

4. TRANSMISSION LINES

Transmission line response is determined by fluid viscosity, line diameter, line length, source impedance, and load impedance. The design approach depicted in the schematic incorporates a low viscosity fluid and a high input impedance (low input capacitance) load that greatly improve transmission line response.

Only two sealed transmission lines are required per actuator, but flowing lines require a third return (or reference) line. Maximum flow through each flowing signal line will be about 0.2 cis, which is insufficient to keep the lines significantly warmer than ambient unless the lines are insulated from the structure and the ambient. Temperature of the fluid in either type of line will be close to that of the ambient.

In applications where the input transducers and summing network are widely separated, the long lines between them are also transmission lines. These lines will be flowing but a third reference line is not required. The development program described in this report includes analysis and test of the transmission lines between the input transducer and summing network. Transmission lines between the summing network and actuator are not part of this development program.

5. SERVOACTUATOR

Performance capabilities of the type of fluidic input servoactuator shown in Figure 1 have been demonstrated in many previous applications, accumulating over 20,000 flight test hours. This design, modified for the higher ±100 psid signal levels, will have an extremely low input capacitance resulting in improved transmission line response. Refinement of this servoactuator concept or the development of additional concepts is not a part of this development program.

SECTION III

INPUT TRANSDUCER

1. INPUT TRANSDUCER REQUIREMENTS

Nominal performance requirements for the input transducer were defined in the previous study contract, Reference 1. Transducer configurations in this previous program included various combinations of mechanical, electrical, and fluidic inputs. A configuration with a full authority mechanical input and a 25 percent authority electrical input was selected for this program. Appendix A presents a revised specification for the VG1005 Input Transducer.

2. INPUT TRANSDUCER CONFIGURATIONS

Five general configuration concepts were evaluated prior to the selection of the Diverter Jet concept. These concepts are summarized in Table 1.

a. Concept 1 -- Reverse Flow Nozzle Flapper

This concept, shown in Figure 1, was used in establishing the original input transducer specification requirements. This concept delivers all of the supply flow to the load (summing resistor networks) and does not require a separate reference or return line. This not only reduces flow requirements but minimizes system weight by using fewer lines and fittings.

A spool and feedback wire arrangement (shown in Figure 1) provides negative pressure feedback. Negative feedback greatly reduces null offset variations and makes the transducer more tolerant to changes in loading, thereby reducing cross-axis coupling. Mechanical input signals can be "force summed" at the feedback as shown or summed at the torque motor. Mechanical inputs can be either linear or rotary. Linear inputs would, of course, be balanced to prevent the net displacement of fluid; however, these details are not shown in the simplified schematic.

b. Concept 2 -- Pressure Control Servovalve

One expedient way to fabricate the input transducer is to modify an off-the-shelf pressure control servovalve similar to the one shown in Figure 2. In this case, the mechanical input would probably be "force summed" at the torque motor.

TABLE 1. TRANSDUCER CONCEPTS SUMMARY

Concept	Discussion	Advantages and Disadvantages
(1) Reverse Flow Nozzle Flapper (Initial Concept)	Has problem with "negative spring rate" and requires a separate device for negative feedback.	• Minimum Flow • Few Lines x Separate negative feedback required
(2) Pressure Control Servovalve Output	Use output from second stage spool to drive circuit. Requires controlled underlap or network bias flow to provide nominal flow.	• Little Modification required x More complex--2 stages x More lines
(3) Forward Flow Nozzle Flapper on Supply to Network	Use nozzle flapper in its normal configuration. Two supply resistors are required to provide nominal flow; resistors can be in the network.	• Little Modification required • Can get negative feedback x 5 x flow required x Requires more lines
(4) Jet Pipe	Movable jet pipe with two receivers which become output. Separate return may not be required but negative pressure feedback is required.	• Low to moderate flow • Considered very reliable by some x Separate negative feedback required
(5) Forward Flow Nozzle Flapper on Return Side of Network	Similar to configuration (3) except transducer is on return side of network.	• Minimum flow and lines • Transducer at low pressure • Can be designed with inherent feedback x Transmission lines at high pressure

In order for the valve to provide an effective output signal flow of 0.8 cis at null, it will be necessary to either undercut the supply lands or provide a bias flow through some parallel resistor network.

Use of off-the-shelf hardware results in a more complex design than is necessary, because two stages are used in an application where one would be satisfactory. Concept 2 uses two to three times the flow of Concept 1 and will also require a return line.

c. Concept 3 -- Forward-Flowing Nozzle Flapper on Supply to Network

If the nozzles in this configuration (Figure 3) are properly sized, it is possible to obtain negative pressure feedback into the flapper. This concept requires at least 50 percent more flow than Concept 1 and requires a return line.

d. Concept 4 -- Jet Pipe

This configuration resembles that of Concept 1, except that a jet pipe is used in place of the nozzle-flapper. If no separate return is used, the movable jet pipe has the same advantages as Concept 1. It may, however, produce more noise, but it is usually considered more reliable. A separate feedback piston similar to that used in Concept 1 is required with the jet pipe.

e. Concept 5 -- Forward-Flowing Nozzle Flapper on the Return Side of Network

If inputs are introduced into the summing network by "bleeding off" flow rather than adding flow, a nozzle flapper can be used in its forward-flowing direction similar to that of Concept 3. This configuration (Figure 4) has all the attributes of Concept 3; moreover, it is more flow efficient and requires one less line. Network tests have shown that the network performance is identical in the reverse flow direction.

3. SELECTED INPUT TRANSDUCER CONFIGURATION

Moog Inc. was selected to develop the input transducer using their deflector jet concept. Although mechanized differently, this concept has characteristics similar to that of the jet pipe valve. Appendix B describes this valve and the Moog Inc. development.

4. INPUT TRANSDUCER 120°F PERFORMANCE

Figure 5 shows a gain curve of S/N 01 output as a function of mechanical input position using MIL-H-83282 at 120°F and with a differential supply pressure of 1000 psid. Non-

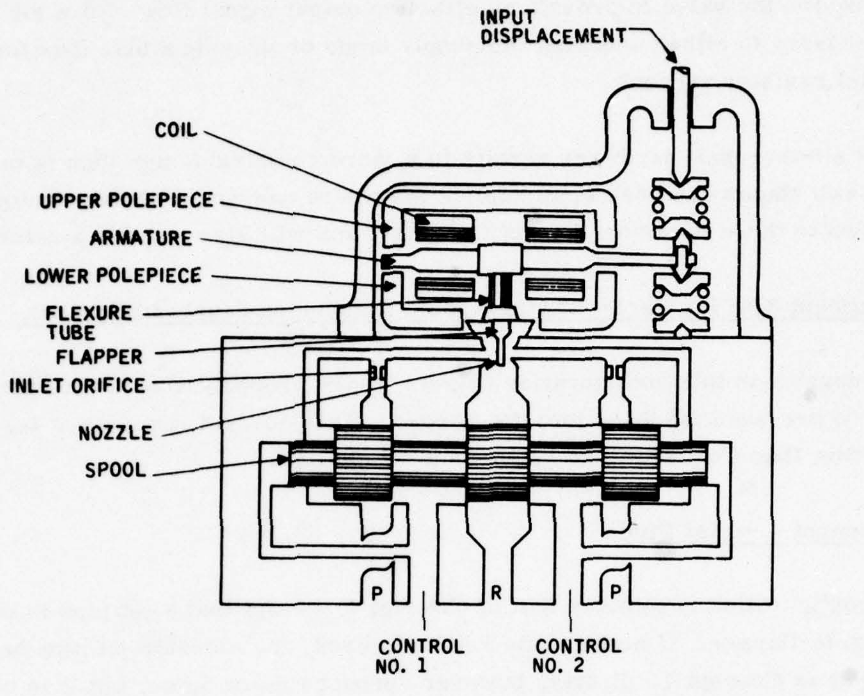


Figure 2. Modified Pressure Control Servovalve

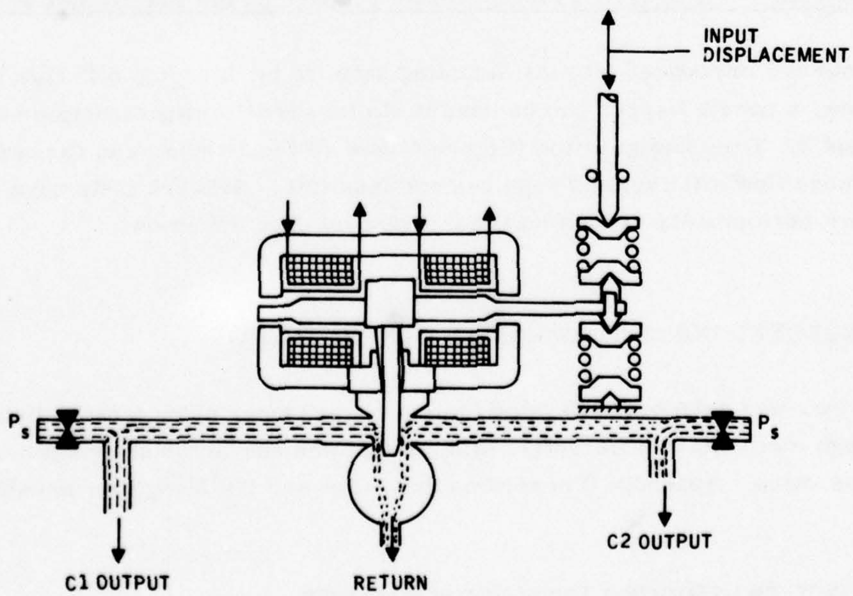


Figure 3. Forward Flowing Nozzle Flapper on Supply to Network

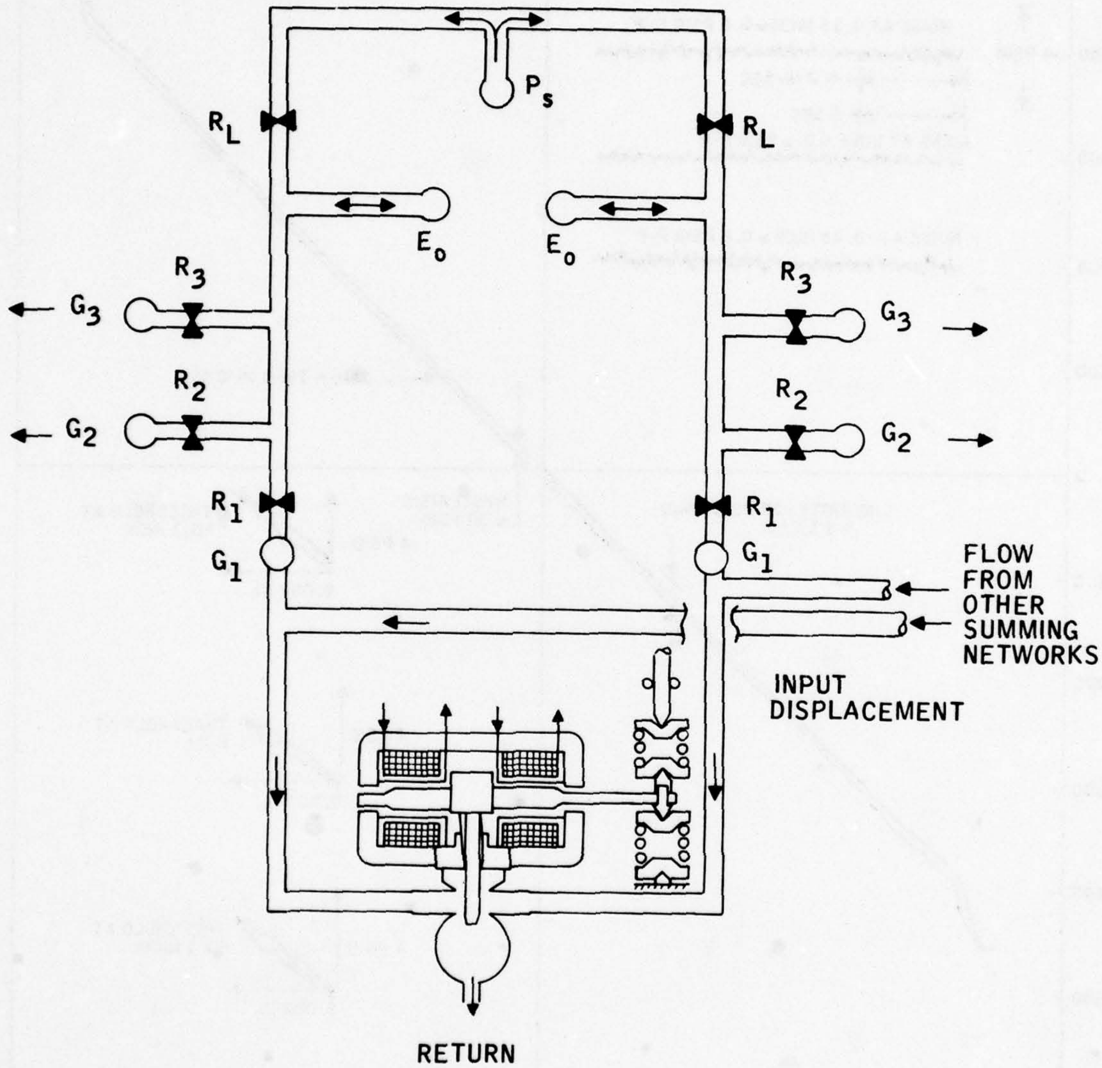


Figure 4. Forward Flowing Nozzle Flapper on Return Side of Network

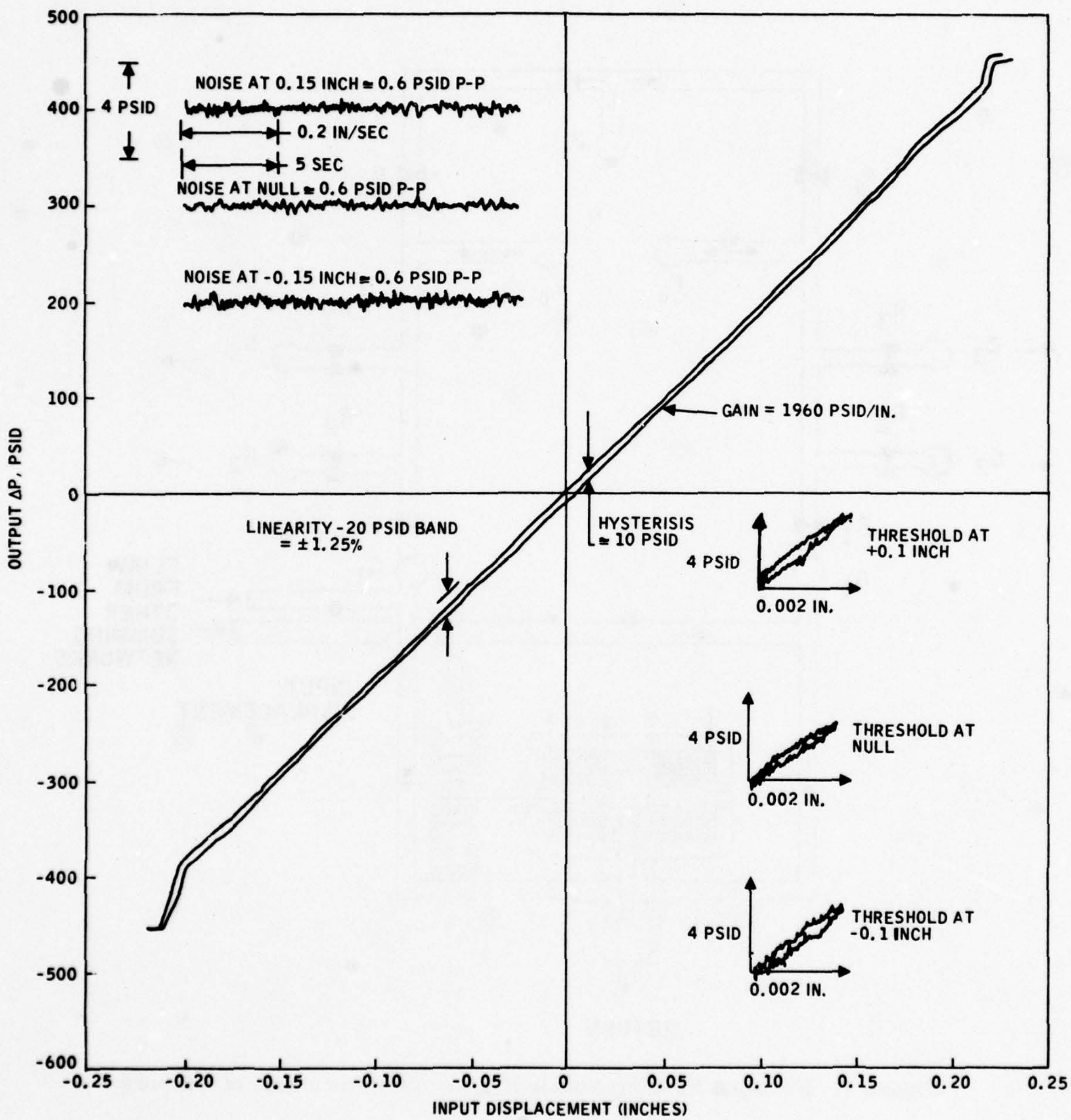


Figure 5. Mechanical Input Performance of Input Transducer at 120°F

linearities at the ends of the gain curve are outside of the nominal ±0.2 inch input range and, therefore, are not included in valve performance calculations. This curve shows acceptable linearity and hysteresis. Noise is exceptionally low and threshold is far below the 0.5 percent tolerated by the specification.

Electrical input performance (Figure 6) is also within specification limits. Frequency response to electrical inputs (Figure 7) shows the valve has a simple first order lag at a frequency of about 17.6 Hz. Frequency response with the mechanical input is nearly identical to the electrical response. Table 2 summarizes input transducer performance at 120°F.

TABLE 2. INPUT TRANSDUCER PERFORMANCE SUMMARY

Parameter	Specification Requirements	Transducer Performance
Noise	8.0 PSID peak to peak max	0.6 PSID peak to peak
Linearity	±2.0 percent or less	±1.25 percent
Hysterisis	16 PSID max	10 PSID
Threshold	0.5 percent or less	Less than 0.1 percent
Gain (Mechanical)	2,000 PSID/IN	1960 PSID/IN
Gain (Electrical)	3.33 PSID/MA	3.36 PSID/MA
Freq Response	15 degree phase at 30 RAD	15 degree phase at 30 RAD

5. INPUT TRANSDUCER COLD TEMPERATURE PERFORMANCE

Transducer performance becomes less linear as the MIL-H-83282 hydraulic fluid temperature is reduced. The worst performance was obtained at 76°F, as shown in Figure 8. At this condition, the valve is probably in the transition region between laminar and turbulent flow.

At colder temperatures the curve becomes smoother, but the gain continues to decrease and the output range decreases (Figures 9 and 10). Nominal operating differential pressure for this transducer is 1000 psid; increasing it to 1140 does improve both gain and range.

This input transducer is operable down to 40°F, but either an improvement in performance or a very large increase in supply pressure is required in order to meet specification requirements.

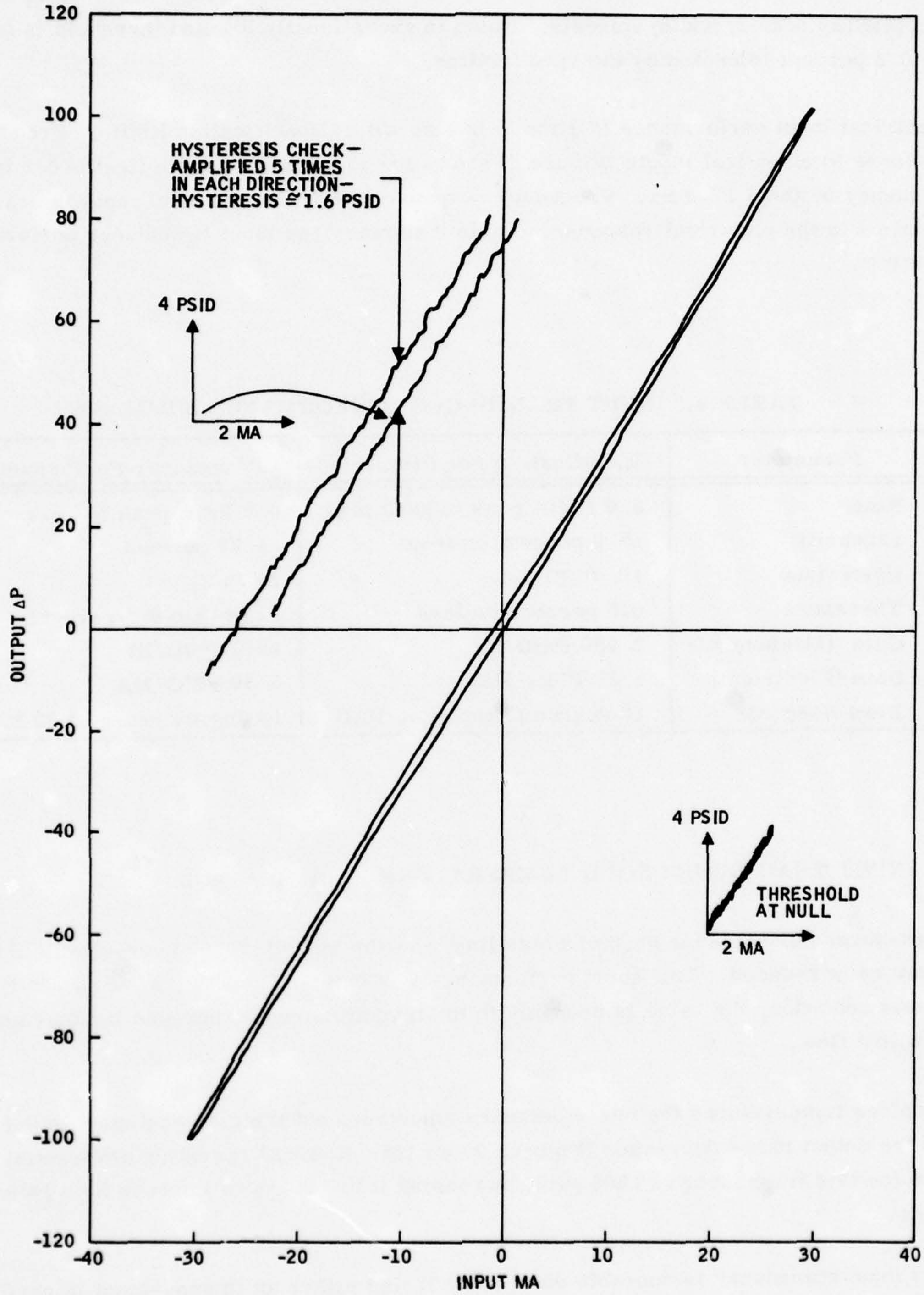


Figure 6. Input Transducer Performance with Electrical Input

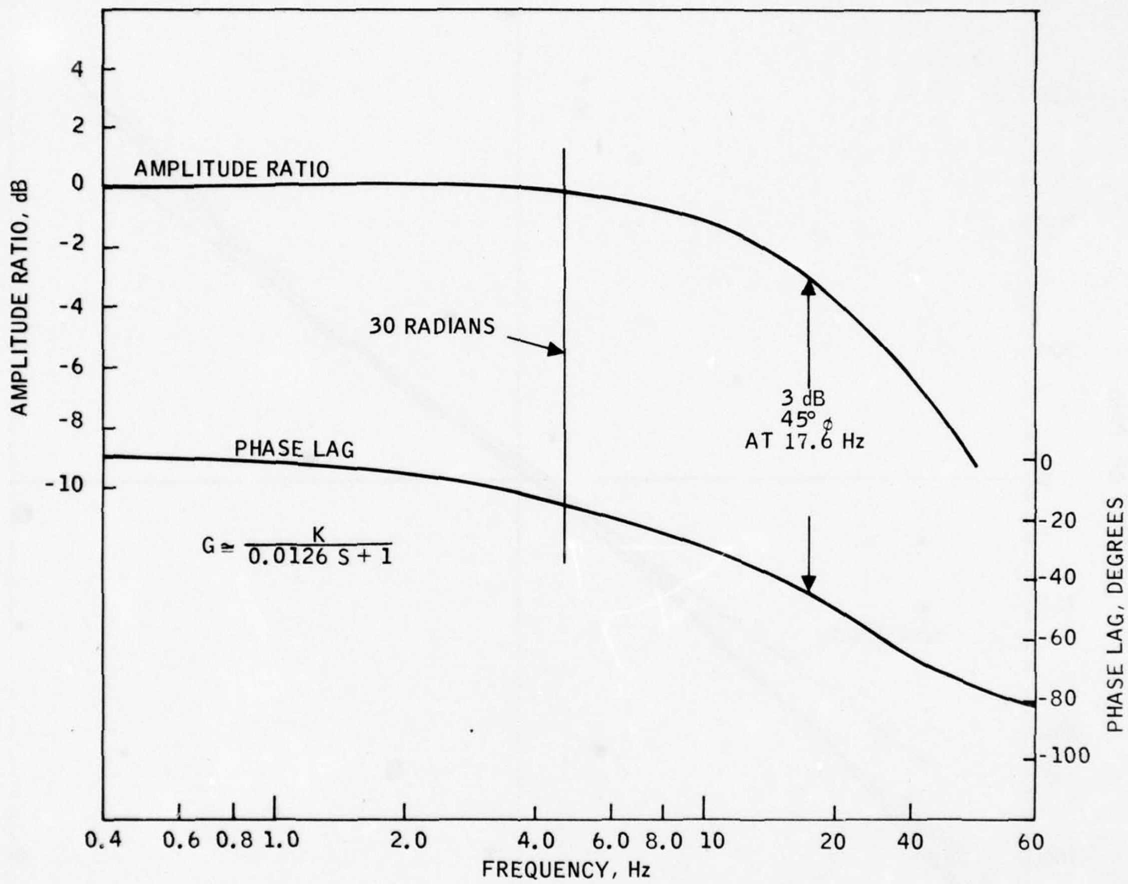


Figure 7. Electrical Input Frequency Response at 120°F

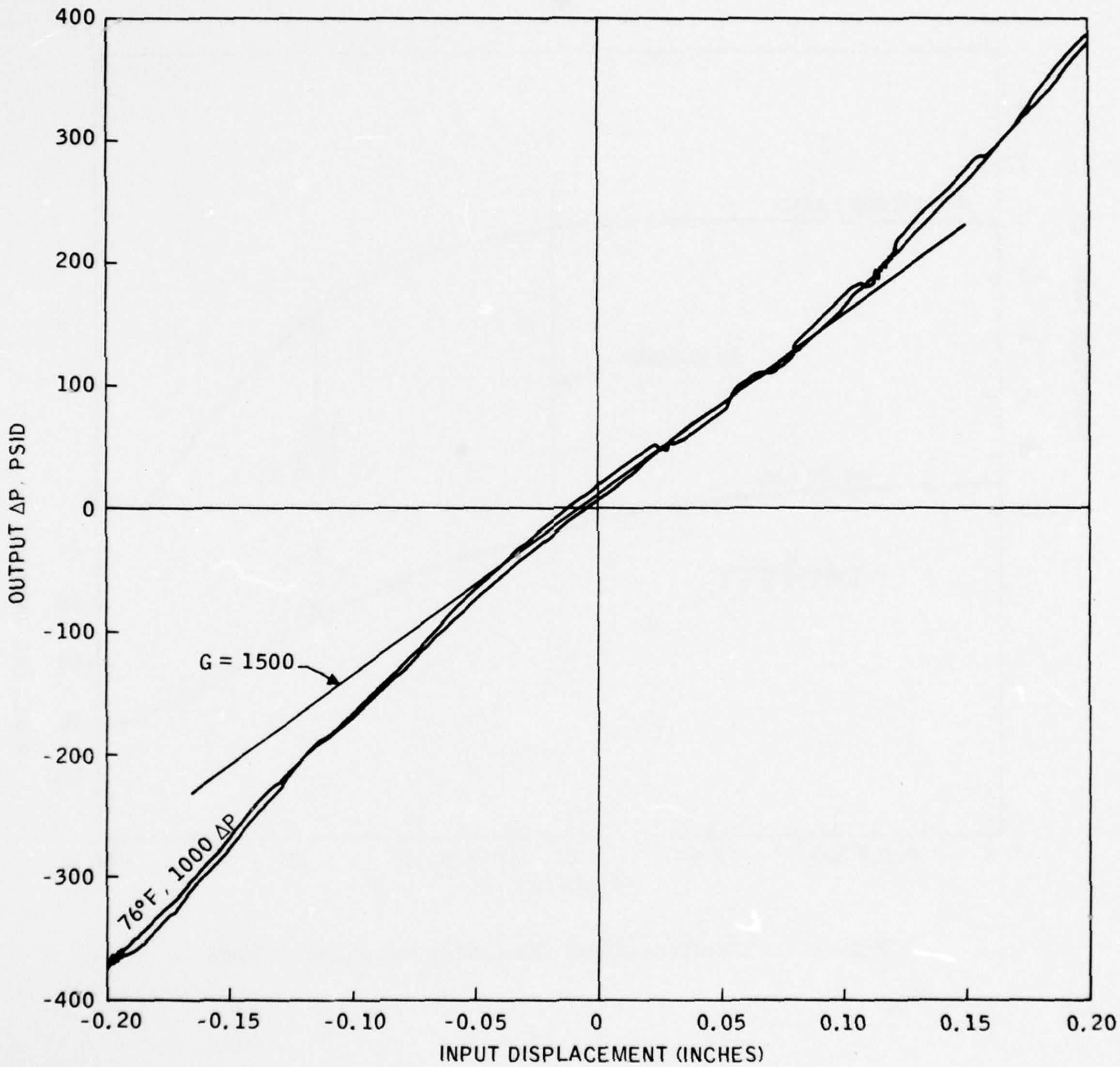


Figure 8. Input Transducer Performance at 70°F

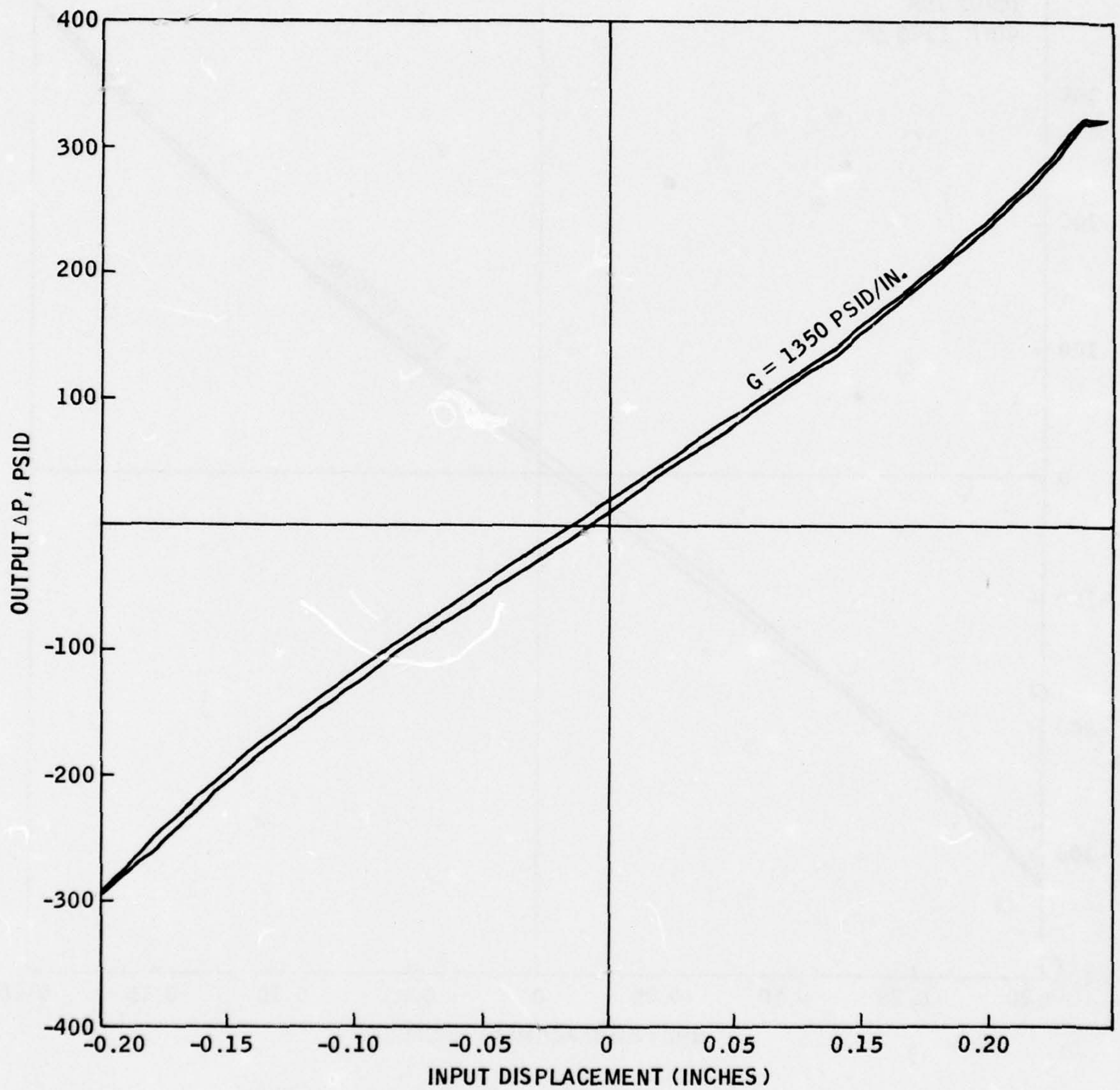


Figure 9. Input Transducer Performance at 40°F and 890 PSID Supply

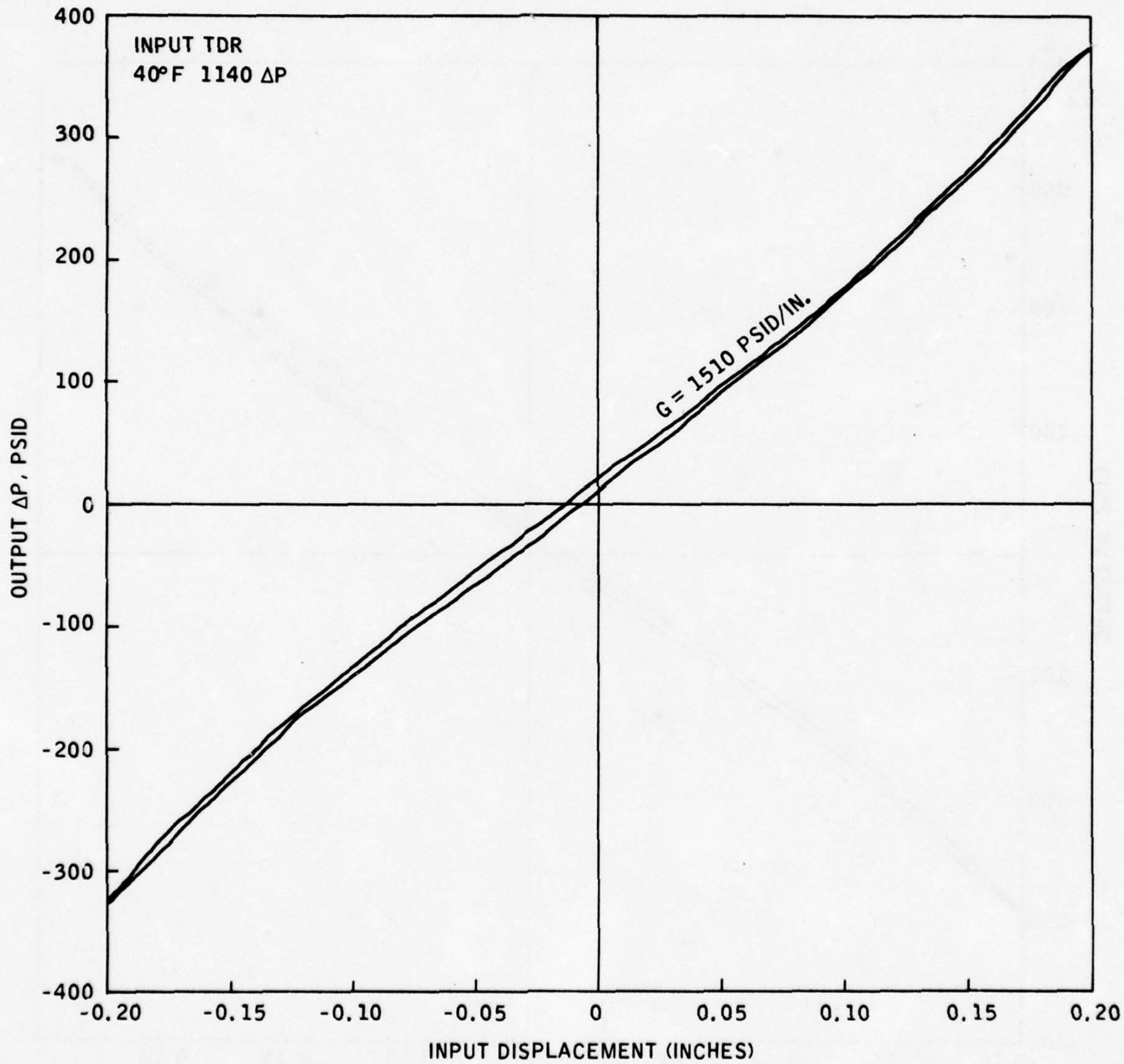


Figure 10. Input Transducer Performance at 40°F and 1140 PSID Supply

SECTION IV
SUMMING NETWORK

1. DESIGN OBJECTIVES--NETWORK REQUIREMENTS

All but the most simple flight control systems require signal summing. At the start of this program, the general requirements for the summing network were the following:

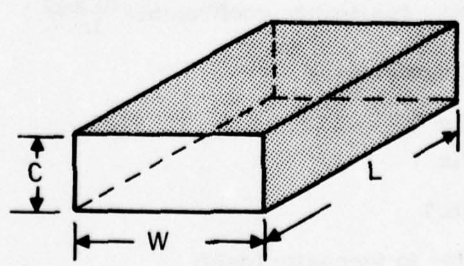
- Number of inputs - 3
- Input range - ±400 psid
- Input impedance - Compatible with input transducer
- Gain - 0.2 psi/psi nominal
- Linearity - 5 percent
- Accuracy - 2 percent
- Fluid - MIL-H-83282 from 40°F to 180°F

As a result of studies during this development program, design objectives were further defined to include:

- Input port gains - 0.1, 0.15 and 0.25 psi/psi
- Total flow/network - 0.4 cis
- Design linearity - 1 percent
- Minimum orifice dimension - 0.01 inch

2. ORIFICE RESISTANCE CALCULATIONS

Restrictors used in summing networks are short rectangular channels similar to the one sketched below. This restrictor is the equivalent of a sharp edged orifice in series with a viscosity sensitive laminar restrictor.



Characteristics of a sharp-edged orifice operating with hydraulic fluid are approximated by the following equations:

$$R_s = \frac{1.94 \times 10^{-2} \sqrt{\Delta P_s}}{A} \qquad (1)$$

$$Q_s = 103A \sqrt{\Delta P_s} \qquad (2)$$

$$R_s = \frac{2\Delta P_s}{Q_s}$$

where:

R_s = sharp-edged orifice resistance (ohms)

ΔP_s = pressure drop across sharp edged orifice (psid)

A = cross sectional area of orifice (in.^{2})

Q_s = flow through sharp edged orifice (cis)

Characteristics of a laminar restrictor operating with hydraulic fluid are approximated by the following:

$$R_v = K\nu \qquad (4)$$

$$K = \frac{1.325 \times 10^{-6} L}{C^3 W \left(\frac{W}{C+W}\right)^2} \qquad (5)$$

$$R_v = \frac{\Delta P_v}{Q_v} \qquad (6)$$

where:

R_v = viscosity sensitive resistance (ohms)

K = viscosity sensitive resistance coefficient $\left(\frac{\text{lb sec}^2}{\text{in.}^7}\right)$

ν = fluid viscosity (centistokes)

L = channel length (in.)

C = channel height (in.)

W = channel width (in.)

ΔP_v = pressure drop due to viscosity (psid)

Q_v = flow through viscosity sensitive resistor (cis)

For example, calculate the resistance of a channel 0.0194 inches wide, 0.01 inches deep, and 0.06375 inches long. Total pressure drop is 500 psid and the fluid viscosity is 10 centistokes (MIL-H-83282 at 120°F).

Substituting in Equations (4) and (5),

$$R_v = K\nu = \frac{1.32 \times 10^{-6}\, L\nu}{C^3 W \left(\frac{W}{C+W}\right)^2} = \frac{(1.325 \times 10^{-6})\,(0.06375)\,(10)}{(0.01)^3\,(0.0194)\,\left(\frac{0.0194}{0.01 + 0.0194}\right)^2} = 100\Omega \quad (7)$$

Substituting in Equation (1)

$$R_s = \frac{1.94 \times 10^{-2}\,\sqrt{\Delta P_s}}{A} = \frac{1.94 \times 10^{-2}\,\sqrt{\Delta P_s}}{(0.01)\,(0.0194)} = 100\,\sqrt{\Delta P_s}\,\Omega \quad (8)$$

The total pressure drop given above is the sum of the two pressure drops:

$$\Delta P_s + \Delta P_v = 500 \text{ psid} \quad (9)$$

Flow is the same through both restrictors:

$$Q_s = Q_v \quad (10)$$

Substituting in Equation (2),

$$Q_s = 103A\,\sqrt{\Delta P_s} = (103)\,(0.01)\,(0.0194)\,\sqrt{\Delta P_s} = 0.02\,\sqrt{\Delta P_s} \quad (11)$$

Substituting data from Equation 7 in Equation 6 and rearranging,

$$Q_v = 0.01\ \Delta P_v \quad (12)$$

Combining (10), (11), and (12),

$$2\,\sqrt{\Delta P_s} = \Delta P_v \quad (13)$$

Solving Equations (9) and (13) simultaneously yields

$$\Delta P_s = 457 \text{ psid} \quad (14)$$

$$\Delta P_v = 43 \text{ psid} \quad (15)$$

Combining Equations (7), (8), and (14),

$$R_{T(10\ cs)} = R_s + R_v = 100\sqrt{\Delta P_s} + 100 = 2138 + 100 = 2238\ \Omega \quad (16)$$

When Equations 7 through 15 are solved for a 40°F temperature condition where the viscosity of MIL H 83282 is 60 centistokes, Equation (16) becomes

$$R_T\ (60\ cs) = R_s + R_v = 100\sqrt{294} + 600 = 1715 + 600 = 2315\ \Omega \quad (17)$$

If viscosity were somehow reduced to zero centistokes,

$$R_{T(0\ cs)} = R_s + R_v = 100\sqrt{500} + 0 = 2236\ \Omega \quad (18)$$

Equations (17) and (18) show that an increase in viscosity sensitive resistance of 600 Ω results in a total resistance increase of only 79 Ω. This inherent compensation is caused by the fact that an increase in viscosity reduces the flow through the network branch, thereby reducing the pressure drop across the sharp-edged orifice resistance. Conversly, there is very little compensation when the viscosity sensitive resistance is very large. Restrictors fabricated on this program were designed to have a relatively small viscosity sensitive component; this is one reason why the networks are relatively insensitive to temperature.

Total pressure drop across the restrictor was assumed to remain constant at 500 psid in the above simplified example. In complex networks, it is cometimes necessary to perform several iterations in order to establish the pressure drop that will occur across each circuit element.

Optimum network performance is obtained when the load impedance is equal to the impedance of all the input ports in parallel. In this case the effective network gain is 0.5 and its linear output range is maximum. Overall effect of fluid viscosity changes will be negligible if the ratio of viscosity sensitive resistance to sharp-edged orifice resistance is the same for all branches in the network.

The following simplified example will clarify the above statements. Assume that a summing network is made by using the previous resistor as a load resistor and that the parallel combination of all three input resistors has an impedance equal to that of the load resistance. Further assume that the fluid viscosity is 10 centistokes and the same signal is put into all three inputs. An equivalent circuit for this example is shown below:

P_{in}, Pressure Input

R_{in}, Input Resistors

P_{out}, Output Signal

R_L, Load Resistor

1000 psig, typical

$R_{in} = 2138 + 100 = 2238\,\Omega$

500 psig typical

$R_L = 2138 + 100 = 2238\,\Omega$

Gain of this network is

$$\frac{P_{out}}{P_{in}} = \frac{R_L}{R_L + R_{in}} = \frac{2238}{2238 + 2238} = 0.5 \qquad (19)$$

If the fluid viscosity is increased to 60 centistokes, the gain will be

$$\frac{P_{out}}{P_{in}} = \frac{R_L}{R_L + R_{in}} = \frac{2315}{2315 + 2315} = 0.5 \qquad (20)$$

Next, consider the case where the input resistors are completely insensitive to viscosity and the load resistor is twice as sensitive as it was in the previous case. Equivalent circuits for the 10-centistoke and 60-centistoke cases are shown below:

P_{in} = 1,000 psig

R_{in} = $2138\,\Omega$

P_{out} = (1,000 -457) = 543 psig

R_ℓ = 2138 + 200 = $2338\,\Omega$

10 centistokes

P_{in} = 1,000 psig

R_{in} = $1715\,\Omega$

P_{out} = (1,000-294) = 706 psig

R_ℓ = (1715 + 1200) = $2915\,\Omega$

60 centistokes

Gain at 10 centistokes for this network is

$$G = \frac{R_\ell}{R_\ell + R_{in}} = \frac{2338}{2338 + 2138} = 0.522 \qquad (21)$$

Gain at 60 centistokes

$$G = \frac{R_\ell}{R_\ell + R_{in}} = \frac{2915}{2915 + 1715} = 0.630 \qquad (22)$$

Network gain increased by about 21 percent at the colder temperature when only the load resistor was sensitive to viscosity. Similar calculations shown that network gain decreases by nearly 30 percent when only the input resistors are sensitive to viscosity.

The above calculations show that fluid viscosity changes must be considered when designing a summing network; however, it is relatively easy to design a network that is nearly insensitive to viscosity changes.

3. SUMMING NETWORK CONFIGURATIONS

Use of series orifices

A major consideration in the design of summing networks is that the orifices should be large while the required flow is small. It is also desirable for the output impedance to be low. Several orifices in series will be larger in diameter than the single orifice that they replace. Relationships between the number of orifices in series and the diameter increase is calculated below.

Modifying Equation (1) to show orifice diameter,

$$R_s = \frac{1.94 \times 10^{-2} \sqrt{\Delta P_B}}{A} = \frac{2.47 \times 10^{-2} \sqrt{\Delta P_B}}{D_o^{\,2}} \tag{23}$$

where

A = orifice area (in.^{2})

D_o = orifice diameter (in.)

ΔP_B = pressure drop across the network branch

If the branch resistance is constant but N resistors are used in series, they will each have a pressure drop of $\Delta P_B/N$, and the brach resistance will be N times the resistance of each new orifice:

$$\frac{2.47 \times 10^{-2} \sqrt{\Delta P_B}}{D_o^{\,2}} = \frac{N \times 2.47 \times 10^{-2} \sqrt{\Delta P_B/N}}{D_n^{\,2}} \tag{24}$$

which reduces to

$$D_n = D_o \sqrt[4]{N} \tag{25}$$

where:

D_n = diameter of the new resistors (in.)

D_o = diameter of the original resistors (in.)

N = number of new resistors in series

For example, this equation shows that 16 orifices in series that are 0.010 inches in diameter will have the same resistance as a single 0.005-inch resistor. The larger resistors in series will be much less sensitive to contamination than the single small resistor. When networks are fabricated using electroforming, fabrication costs will be about the same for both configurations, but the tooling cost will be higher when more resistors are used.

4. REQUIREMENTS ASSUMED FOR NETWORK ANALYSIS

Three network configurations, single-point summing, ladder network, and single-point summing with bridge network on the low gain input were analyzed using the following ground rules for all configurations. Figure 11 shows a black box schematic of the network.

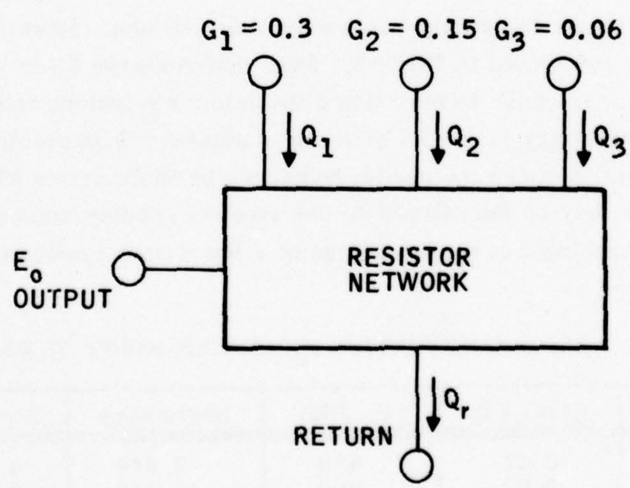


Figure 11. Black Box Schematic

- Signal levels at G_1, G_2, and G_3 are 1000 psig.
- Signal level at E_o is 500 psig.
- Pressure level at return is zero psig.
- Ratio of gains between inputs is 5/1 as shown above.
- Minimum orifice diameter is 0.01 inch.
- Total input flow is 0.30 cubic inches per second.

Requirements used in this network configuration analysis are somewhat more stringent than the final network requirements presented in the first part of this section. The most difficult requirement is the large ratio between the maximum gain the minimum gain inputs.

Flows, pressures, resistances and orifice diameters were all calculated using the equations for sharp-edged orifices presented in this section. Network gains were calculated using the calculated resistances and conventional electrical network equations. Calculations defining the detailed configurations of each network are tedious, and include substantial iteration due to the non-linear characteristics of orifices. As a result, these equations are not presented in this report. Calculation results, however, are presented so that the merits of each configuration can be compared.

a. Single-Point Summing

Figure 12 illustrates the single-point summing network. Results of the analysis on this circuit are presented in Table 3. Note that resistor R3 is very small in diameter -- 0.00448 inches. In order to maintain a minimum equivalent orifice diameter of 0.01 inches, it is necessary to use 25 orifices in series. With electroformed networks, this requirement is still reasonable; however, in applications where the low gain input is even less, it may be unrealistic to use an even greater number of orifices in series. Single-point summing has the advantage of a low output impedance, which was calculated to be 1,633 ohms.

TABLE 3. CHARACTERISTICS OF SINGLE POINT SUMMING NETWORK

Resistor	Flow, CIS	ΔP, PSID	Resistance	Equiv. Dia.	N*
R1	0.18	490	5,444	0.01002	1
R2	0.09	490	10,889	0.00708	4
R3	0.036	490	27,222	0.00448	25
RL	0.306	510	3,333	0.01293	1

* Number of orifices in series required to maintain minimum diameter above 0.01 inch.

b. Ladder Network

Minimum resistor size can be increased significantly by using the ladder network shown in Figure 13.

Each of the three inputs, whether low gain or high gain, receives nearly the same steady state flow. (In the single-point summing network the low gain input received only 20 percent of the flow into the high gain input.) The ladder network, like all other networks analyzed, interfaces well with a fluid-to-fluid transducer for use with passive transmission lines. With flowing (active) transmission lines the load resistor, R_L, must be located downstream of the E_o port. Unlike single-point summing, the ladder network cannot deliver flow out of the E_o port without a significant change in circuit design.

Table 4 summarizes the flows, pressures, and resistor sizes for the ladder network. Physical size of the low gain input resistors has increased substantially to more than 0.007 inches in diameter. Four 0.010-inch diameter resistors in series are approximately equivalent to a 0.007-inch diameter resistor. Output impedance of the ladder network is 2,935 ohms -- the highest of all configurations investigated.

c. Single-Point Summing with Bridge Network on Low-Gain Input

Figure 14 illustrates a compromise between the single-point summing network and the ladder network. Like single-point summing, the load resistor, R_L, can be located remotely at the actuator if desired.

Table 5 summarizes the performance of this network. Minimum resistor size is only slightly smaller than that required on the ladder network, and its output impedance of 2,042 ohms is only slightly larger than that of the single-point summing network.

5. COMPARISON OF NETWORK CHARACTERISTICS

Table 6 summarizes significant characteristics of the three network configurations. All three networks are satisfactory for the specified application. Since a 31-resistor electroformed network is almost as easy to produce as a 16-resistor network, the low output impedance characteristic of the single-point summing network makes it a slightly better choice than the ladder network. The addition of a bridge network to the low-gain input of a single-point summing network begins to become advantageous when the ratio of gains between the maximum and minimum inputs exceed five.

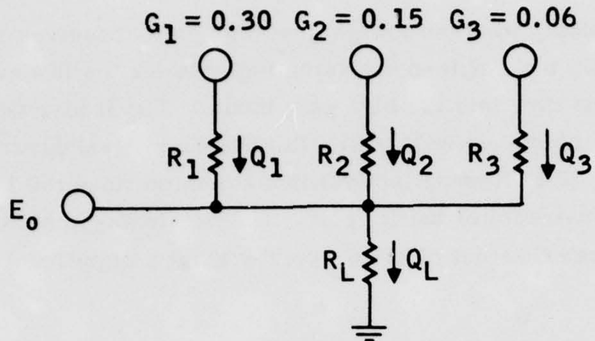


Figure 12. Single Point Summing Network

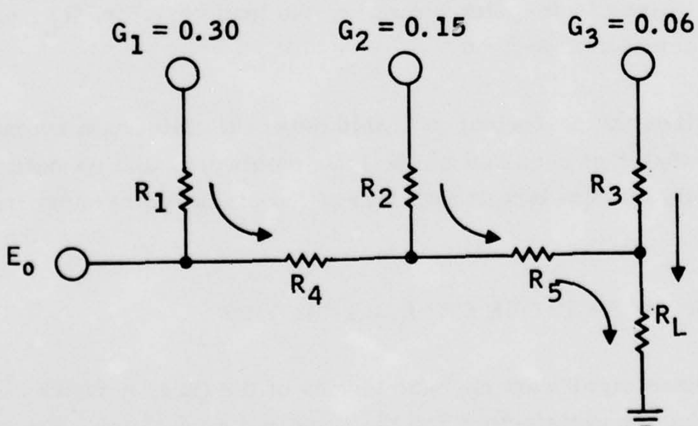


Figure 13. Ladder Network

TABLE 4. CHARACTERISTICS OF LADDER NETWORK

Resistor	Flow, CIS	ΔP, PSID	Resistance	Equiv. Dia.	N*
R1	0.100	490	9,800	0.00747	4
R2	0.0976	574	11,760	0.00709	4
R3	0.1083	743	13,720	0.00700	5
R4	0.100	84	1,681	0.01606	1
R5	0.1976	169	1,709	0.01370	1
RL	0.306	257	1,680	0.01521	1

TABLE 5. CHARACTERISTICS OF SINGLE POINT SUMMING NETWORK WITH BRIDGE NETWORK ON LOW-GAIN INPUT

Resistor	Flow, CIS	ΔP, PSID	Resistance	Equiv. Dia.	N*
R1	0.144	490	6,805	0.00896	2
R2	0.072	490	13,611	0.00634	7
R3	0.091	616	13,603	0.00671	5
R4	0.041	126	6,126	0.00673	5
RL	0.175	510	5,836	0.00977	2
RLL	0.132	383	5,819	0.00912	2

TABLE 6. SUMMARY OF NETWORK CHARACTERISTICS

Network Type	Output Impedance, Ohms	Min. Resistor Size	N*
Single Point Summing	1,663	0.00448	31
Ladder Network	2,635	0.00700	16
Single Point with bridge	2,042	0.00634	23

* Number of orifices in series required to maintain minimum diameter above 0.01 inch.

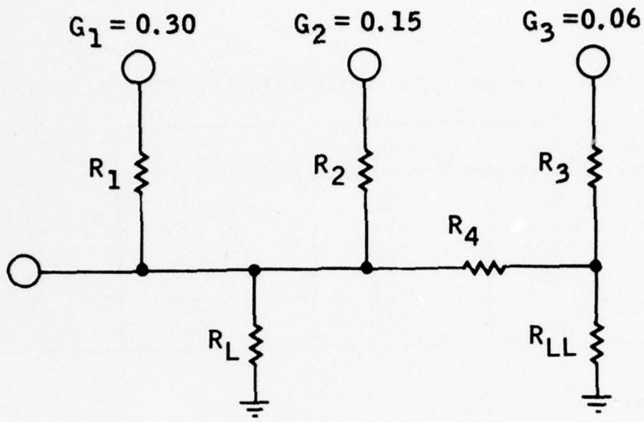


Figure 14. Combined Single Point Summing and Ladder Networks

6. SAS INTERFACE

Many fly-by-tube applications need a fluidic stability augmentation system (SAS) or command augmentation system (CAS) to provide the required aircraft handling characteristics. Present fluidic SAS systems have an output range of about ±2 psid, but at least ±75 psid is required into an orifice summing network if the SAS is to have 25 percent authority. A typical requirement is that the SAS have an output range of ±150 psid at a level of 1500 psig.

Four configurations can provide the necessary interface between the SAS and summing network.

a. Configuration 1 - Use Electrical Input into the Input Transducer

Configuration one (Figure 15) would use a differential pressure transducer with electrical amplification to drive the existing electrical input on the input transducer. This approach is inconsistant with the objectives of fly-by-tube systems; however, this approach can be used in closed-loop simulations in order to demonstrate overall system performance before the prototype interface hardware is developed.

b. Configuration 2 - Replace Input Transducer Torque Motor with Force Capsules

The current method of interfacing between a fluidic SAS and a servoactuator is to replace the electrical torque motor with a pair of force capsules (Bellows). Several manufacturers have developed these fluidic input servovalves. Replacing the torque motor on the input transducer with force capsules is an interfacing approach that involves negligible design risk. A schematic of this approach is shown in Figure 16. Output from the SAS is small (±2 psid) as compared to the ±400 psid range of the input transducer. This type of interface isolates the SAS pressure level from that of the primary flight control system, eliminating the need to match pressure levels for proper operation. Matching pressure levels between the SAS and the primary control can be difficult with Configuration 4 (described later) especially in a three-axis system when the three SAS controllers are usually connected in series to conserve flow.

c. Configuration 3 - Mechanical to High-Pressure Interface

In this approach, a low-pressure to high-pressure interface is used between the SAS and the summing network. The interface device is similar to that used in Configuration 2, except the position input and the SAS inputs go to two separate servo valves rather than one common unit. Orifice summing is used to combine the various signals in the system summing networks. This approach provides the same level isolation between the SAS and the primary flight control as does Configuration 2. It has the advantage of allowing the SAS to be located in the optimum position in the aircraft without requiring that SAS signal lines be routed back to the position transducer for summing. The mechanical-to-high-pressure interface is similar to the position input transducer, consisting of a bellows-actuated nozzle-flapper valve that transforms the low pressure SAS output to a signal compatible in both level and magnitude with the other primary control loops (Figure 17). (Jet pipe or deflector jet concepts are also satisfactory for this interface.)

d. Configuration 4 - Fluidic Amplification

In this configuration, the SAS signal is amplified using fluidic amplifiers and then orifice summed with the position input similar to Configuration 3. Although this is the simplest approach, it has several disadvantages: 1) it does not provide the level isolation of the other configurations, 2) development is required for the high pressure fluidic amplifiers and 3) this approach probably requires the most flow. Figure 18 shows a schematic of this configuration.

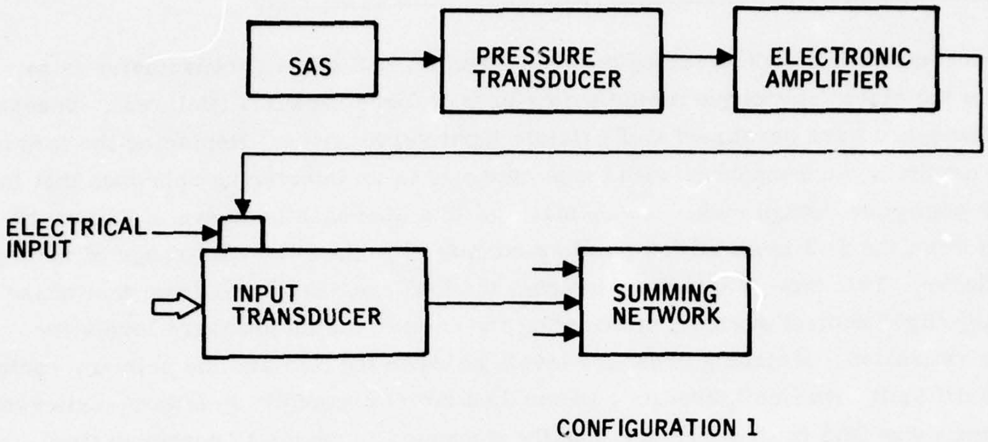


Figure 15. SAS Interface--Configuration 1

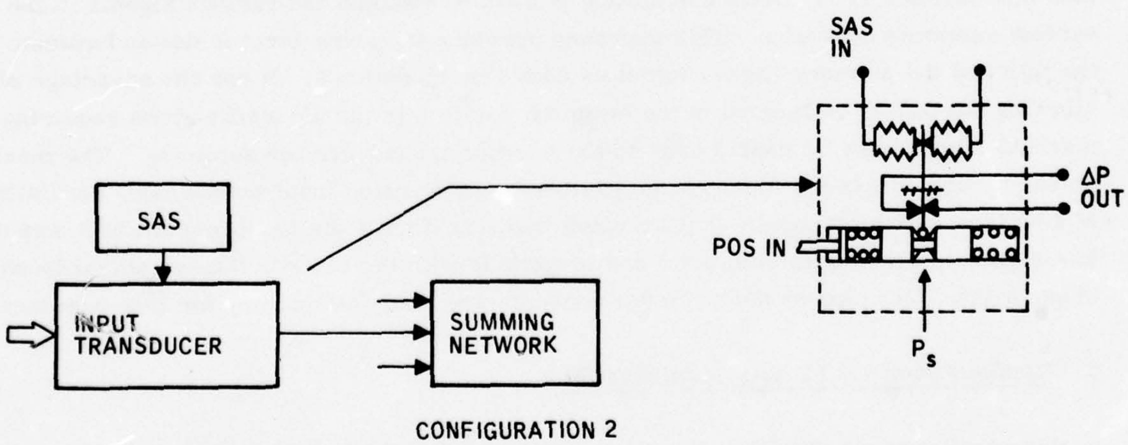
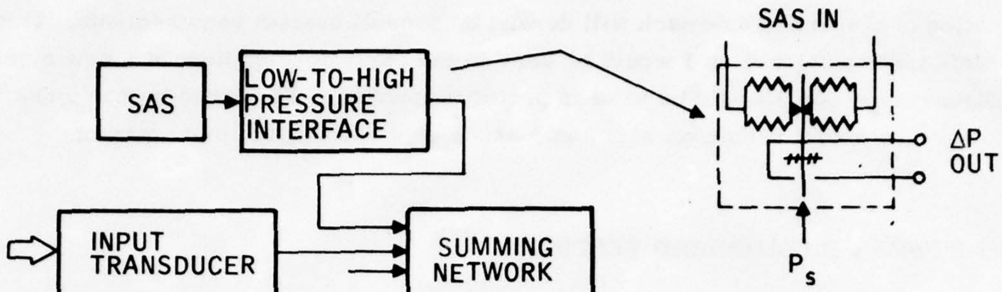
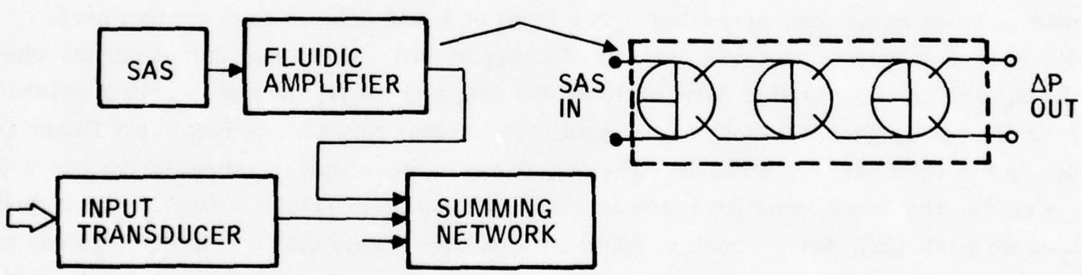


Figure 16. SAS Interface--Configuration 2



CONFIGURATION 3

Figure 17. SAS Interface--Configuration 3



CONFIGURATION 4

Figure 18. SAS Interface--Configuration 4

7. INTERFACE COMPARISON

Table 7 includes a list of advantages and disadvantages of the four configurations. The selection of a specific approach will depend on overall system requirements. It is possible that configuration 1 would be used in the early development of a new aircraft configuration, 2 or 3 would be used in prototype production followed by configuration 4 developed as a cost reduction with some associated reliability improvement.

8. NETWORK BREADBOARD TESTING

A breadboard single-point summing network similar to that defined in Table 3 was tested. Flow through the network was increased by a factor of four (all orifice diameters were doubled) in order to simplify the measurement of orifice diameters. Diameter of the load resistor was increased further in order to reduce the output pressure level to remain within the operating pressure range of the output pressure transducer. It should be noted that the network tested is only half of a push-pull network pair shown on Figure 1.

Performance of the high-gain port of this breadboard network is shown on Figure 19 along with a schematic of the test setup and a listing of the theoretical gains (revised to reflect the decrease in load resistance). From this curve it can be seen that a pair of these resistors, operating with a level of 1,000 psig on each control port, would have an output pressure level of 420 psig at null. Maximum output occurs when the G_1 port of one resistor network is at 800 psig and the G_1 port of the other network is at 1200 psig for a ΔP input of 400 psid. The output curve looks relatively linear in the 800 to 1200 psig input range; however, it can be seen that the slope of the curve is greater at the lower input pressure and less at the high pressure. When two networks operate push-pull, the network at 800 psig will have a gain that is slightly high and the network at 1200 psig will have a low gain. The average gain of the two networks will be very close to their gain at null. In other words, the probability of obtaining a 1 percent linearity with this network is very good.

Figures 20 and 21 show the gains of the other two ports. Test data shows that the projected characteristics of resistive summing networks are valid.

Similar tests were conducted simulating a system where the input transducer was mounted on the return side of the summing network (see Section III, concept 5). Figure 22 shows the test results and a schematic of the test setup. In this case the

TABLE 7. SAS INTERFACE COMPARISON

Configuration	Advantages	Disadvantages
(1) Electrical Input into input transducer	• Can be accomplished with present hardware. • Ideal for closed loop simulations. • No additional flow required.	• Requires electrical power for SAS Operation. • Inconsistent with objectives of fly-by-tube.
(2) Replace Input transducer with force capsules	• Combines 2 functions in one device (amp and summing). • Existing SAS approach directly applicable. • SAS and pos. transducer pressure levels do not require matching. • Requires no additional flow.	• SAS signal must be routed to input transducer. • May be difficult to incopo-rate mechanical fluidic and electrical inputs in single device if all three are required. • Requires added position transducer development.
(3) Mechanical to High Pressure Interface	• Existing SAS approach directly applicable. • Does not effect position transducer design. • SAS can be located remote from pos. transducer. • SAS and pos. transducer pressure levels do not require matching.	• Requires both low-to-high pressure interface and additional orifice summing. • Requires low-to-high pressure interface development. • Requires added flow for low-to-high pressure interface.
(4) Fluidic Amplification	• No additional moving parts. • Simplest approach. • Does not effect pos. transducer design. • SAS can be located remote from pos. transducer.	• SAS and position transducer pressure levels must be matched. • Requires added flow for fluidic amps. • Requires some modification to SAS design. • Requires both fluidic amps and additional orifice summing. • Noise and gain change with fluid temperature may be problem.

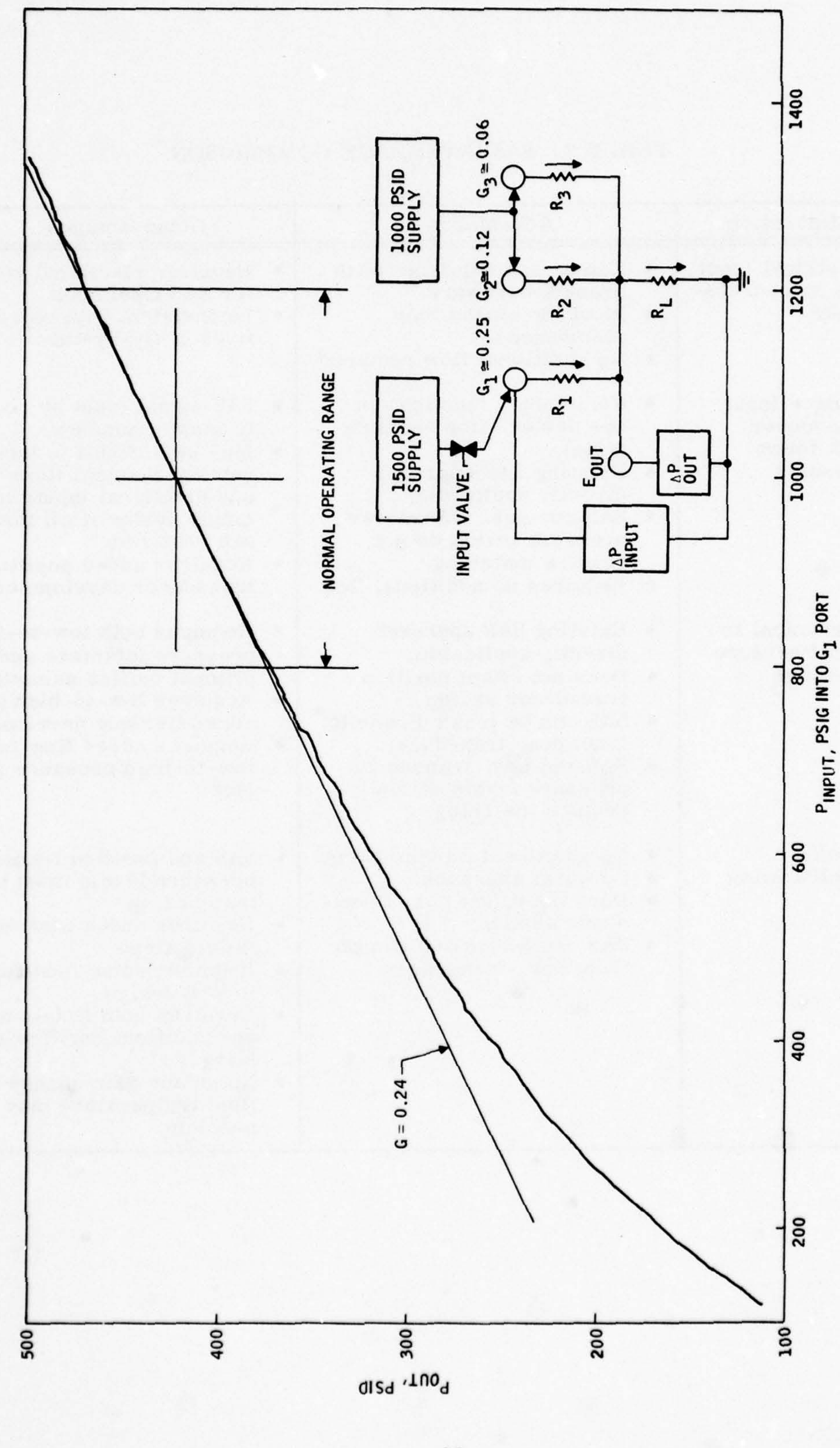


Figure 19. Breadboard Summing Network--High Gain Port

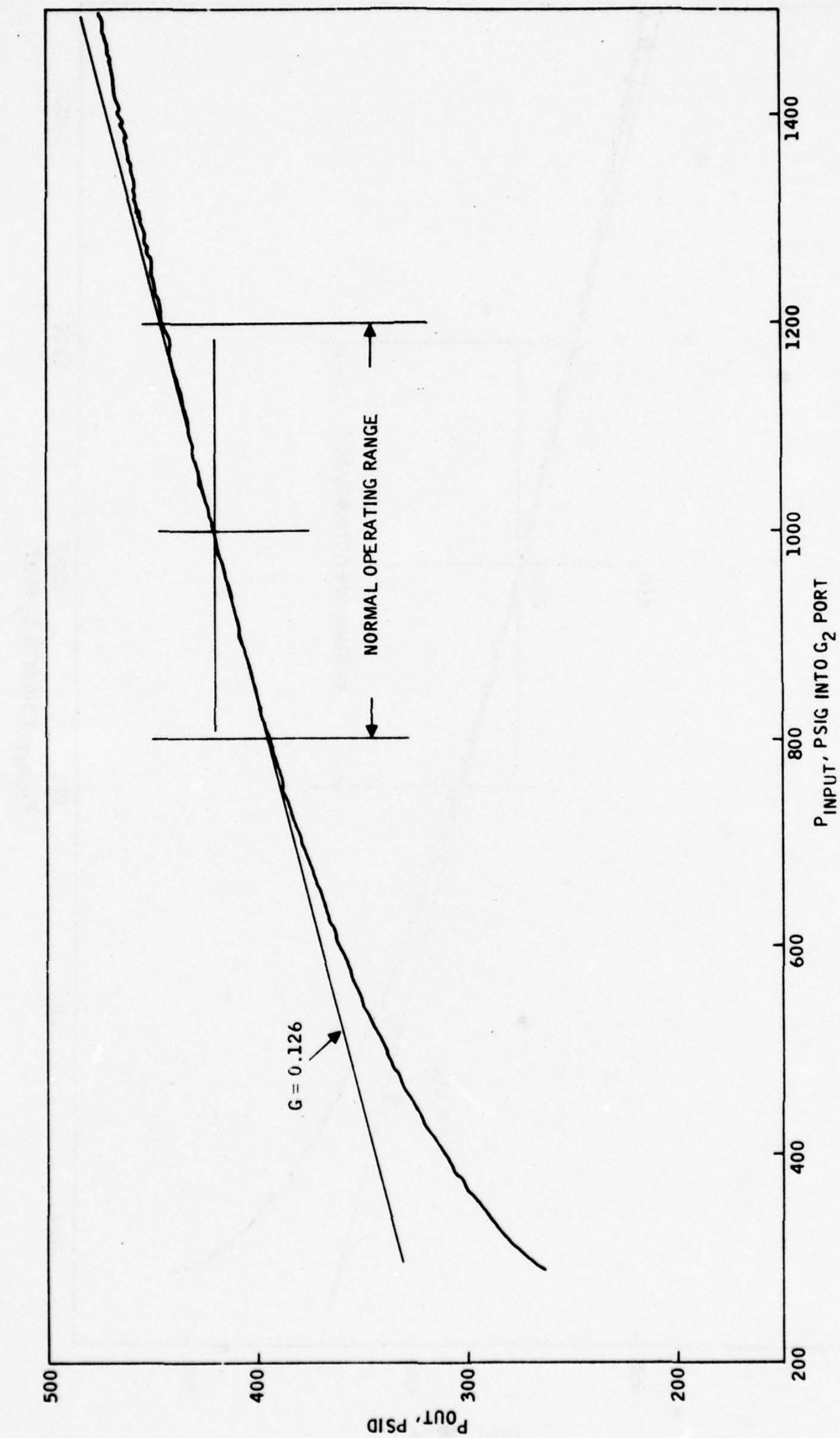


Figure 20. Breadboard Summing Network--Medium Gain Port

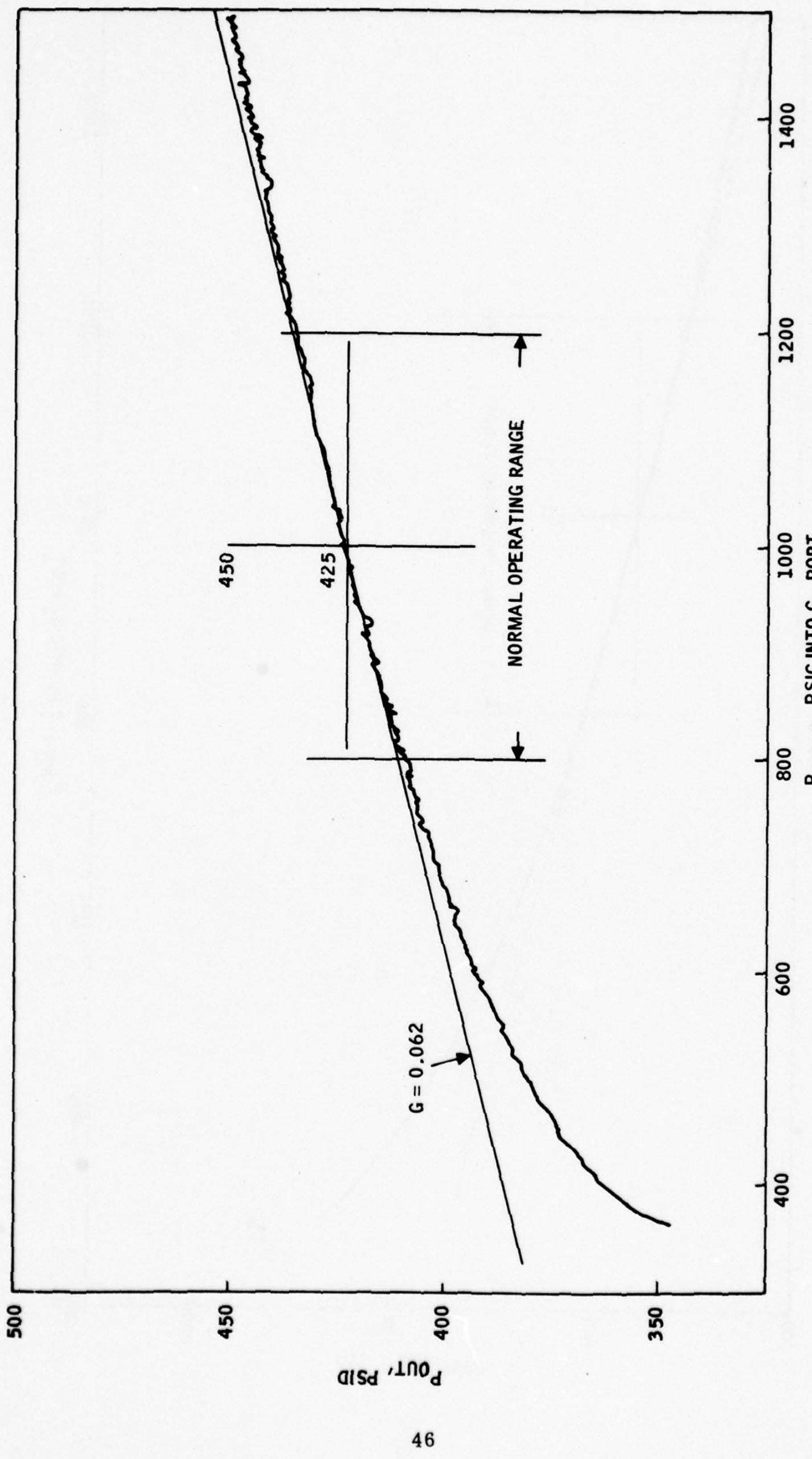


Figure 21. Breadboard Summing Network--Low Gain Port

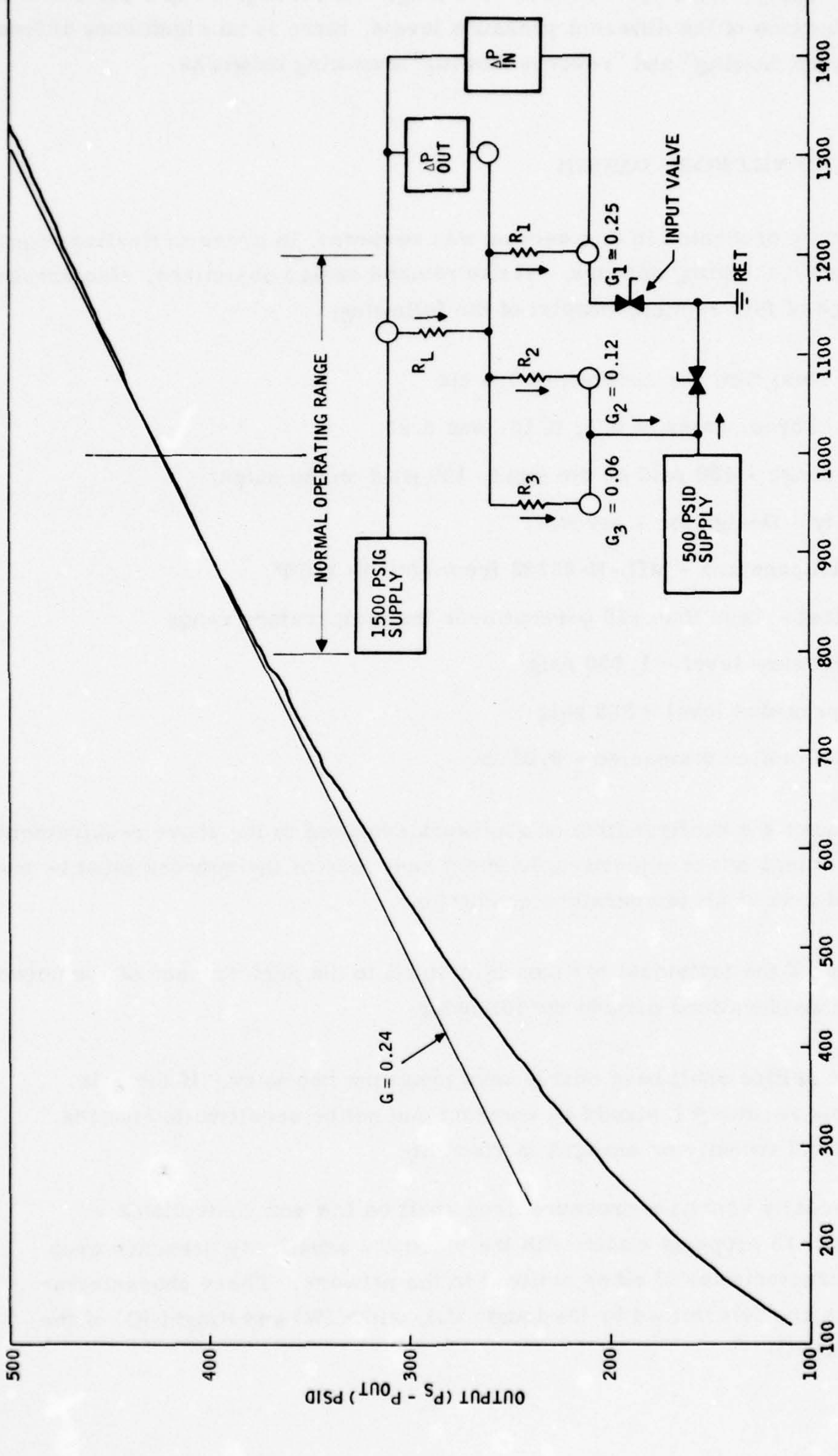


Figure 22. Breadboard Summing Network--Reverse Flow

flow through the network is in the opposite direction. The load resistor is connected to a 1500 psig supply, the output level is 1000 psig, and the signal input ports are at 500 psig. With the exception of the different pressure levels, there is no significant difference between "forward flowing" and "reverse flowing" summing networks.

9. DETAILED NETWORK DESIGN

Data previously presented in this section was reviewed in order to finalize requirements for the resistor summing network. These revised design objectives, also presented on the first page of this section, consist of the following:

Flow - Total flow per network of 0.4 cis

Inputs - Three, gains of 0.1, 0.15, and 0.25

Linear range - 400 psid on the input, 100 psid on the output

Linearity - Design for 1 percent

Fluid/temperature - MIL-H-83282 from 40°F to 180°F

Null offset - Less than ±10 percent over the temperature range

Input pressure level - 1,000 psig

Output pressure level - 500 psig

Minimum orifice dimension - 0.01 in.

Figure 23 shows the configuration of a network designed to the above requirements. In order to meet null offset objectives the right hand side of the network must be matched to the left-hand side at all temperature conditions.

Configuration of the individual orifices is critical to the performance of the network pair. The major considerations include the following:

1. The orifice shall have nearly zero pressure recovery. If there is some recovery it should be constant and not be sensitive to changes in fluid velocity or changes in viscosity.

2. Viscosity sensitive pressure drop shall be low and controllable in order to properly match with the viscosity sensitivity pressure drop characteristics of other orifices in the network. These characteristics are determined by the length (L), width (W) and Height (C) of the orifice.

3. Flow exiting the orifice chamber shall be uniform, with nearly zero velocity head.

An orifice configuration previously designed to meet the above considerations is shown in Figure 24. This configuration has demonstrated consistant performance and low noise.

Reference 2, an Army sponsored program ("Production Suitability of an Electroform Conductive-Wax Process for the Manufacture of Fluidic Systems")* produced a total of 35 feedback resistor networks of a design similar to the above with a yield of 100 percent. Matching of the right and left hand side of the network pair can best be accomplished by fabricating both networks using the same mold. Electroforming was selected because it is both consistant and capable of producing the somewhat unusual orifice geometry.

Orifices were designed to have a viscosity sensitive pressure drop equal to about 8 percent of the total pressure drop at 120°F. Each branch is required to have the same viscosity sensitive characteristics.

Network design calculations are tabulated in Table 8. The following is a discussion of each entry on the table along with selected sample calculations.

1. This line defines each resistor branch and its required gain where appropriate.

2. Flow through each branch where the total flow is 0.4 cis and the flow in each branch determines its gain. Flow through R_1 is:

$$Q_1 = \frac{Q_{TOT}(G_1)}{G_1+G_2+G_3} = \frac{0.4\ (0.25)}{0.25+0.15+0.10} = 0.2 \text{ cis} \tag{26}$$

3 and 4. Since the total gain of all inputs is 0.5 the total pressure drop across each branch will be 500 psid. Eight percent or 40 psid, will be viscosity sensitive drop, and the remaining 460 psid will be orifice drop at the 120°F condition.

5. Sharp-edged orifice resistance was defined in Equation (3). For Resistor 1 this is

$$R_S = \frac{2\Delta P_S}{Q_S} = \frac{2 \times 460}{0.2} = 4,600\Omega \tag{27}$$

*Contract No. DAAJ02-74-C-0012 (April 1977).

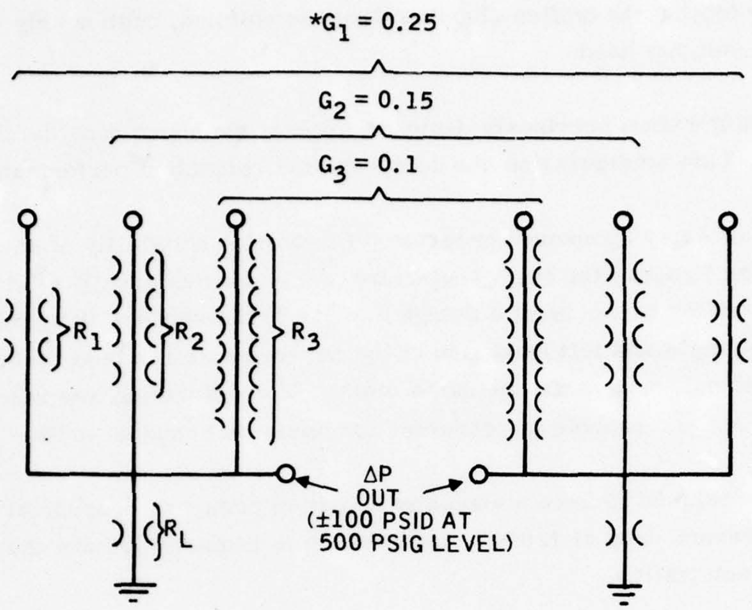


Figure 23. Resistor Summing Network--General Configuration

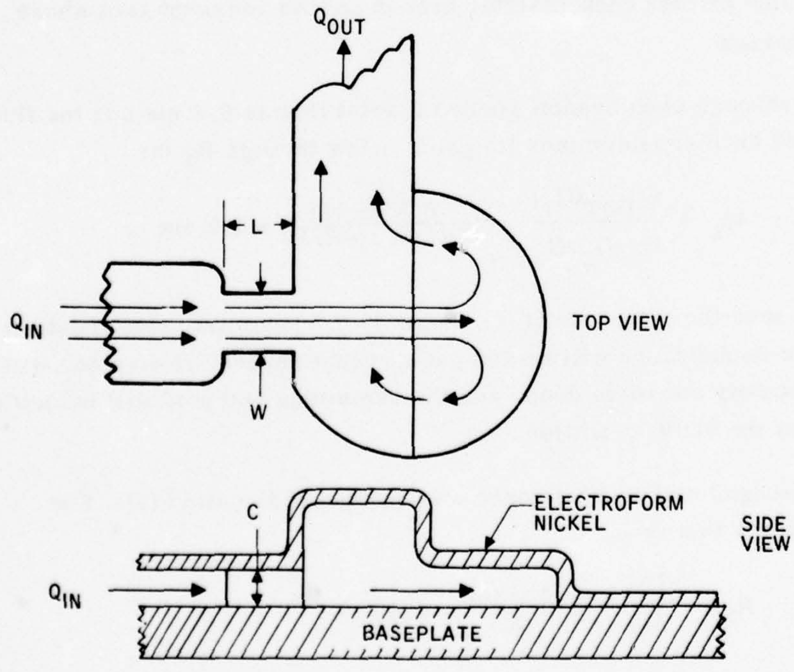


Figure 24. Network Orifice Configuration

TABLE 8. RESISTOR NETWORK DESIGN CALCULATIONS

Parameter	R_1	R_2	R_3	R_L
(1) Resistor/Gain	0.25	0.15	0.10	-
(2) Flow (In.^{3}/Sec.)	0.20	0.12	0.08	0.40
(3) ΔP_s, 120°F (PSID)	460	460	460	460
(4) ΔP_v, 120°F (PSID)	40	40	40	40
(5) R_s, 120°F (Ohms)	4,600	7,667	11,500	2,300
(6) R_v, 120°F (Ohms)	200	333	500	100
(7) R_{tot} 120°F (Ohms)	4,800	8,000	12,000	2,400
(8) Resistor Area (In.^{2})	9.05×10^{-5}	5.43×10^{-5}	3.62×10^{-5}	1.81×10^{-4}
(9) $\sqrt{\text{Area}}$ (In.)	9.51×10^{-3}	7.37×10^{-3}	6.02×10^{-3}	1.35×10^{-2}
(10) $(.01/\sqrt{\text{Area}})^4$ (In.)	1.22	3.39	7.60	0.31
(11) Number Required	2	4	8	1
(12) ΔP_s Each (PSID)	230	115	57.5	460
(13) Area Each (In.^{2})	1.28×10^{-4}	1.09×10^{-4}	1.02×10^{-4}	1.81×10^{-4}
(14) Width for 0.01 Deep (In)	0.0128	0.0109	0.0102	0.0181
(15) Required K, $\frac{\text{Lb Sec.}^2}{\text{In}^7}$	19.05	31.75	47.62	9.52
(16) K per Unit Length, K/L	328	447	506	176
(17) Length Required (In.)	0.058	0.071	0.094	0.054
(18) Length/Resistor (In.)	0.029	0.018	0.012	0.054
(19) Length/Resistor after Layout (In.)	0.0249	0.0157	0.0103	0.0426

6. Viscosity sensitive resistance per Equation (6) as applied to R_1 is

$$R_V = \frac{P_V}{Q_V} = \frac{40}{0.2} = 200\,\Omega \tag{28}$$

7. Total resistance is the sum of columns 5 and 6.

8. Required orifice area for a single resistor derived from Equation (2) and applied to R_1 is:

$$A = \frac{Q_S}{103\sqrt{\Delta P_S}} = \frac{0.2}{103\sqrt{460}} = 9.05 \times 10^{-5} \text{ in.}^2 \tag{29}$$

9. Width of a square channel designed to provide the above area (i.e., $\sqrt{A}$). Note that all except R_L are smaller than the 0.01-inch minimum, and therefore several orifices in series will be required in all input branches.

10. Number of orifices required to maintain a minimum dimension of 0.01 inches. An equation derived from Equation (25) is applied to R_1 as follows:

$$N = \left(\frac{0.01}{\sqrt{\text{area}}}\right)^4 = \left(\frac{0.01}{9.51 \times 10^{-3}}\right)^4 = 1.22 \tag{30}$$

11. Number of orifices required, rounded up to the next full integer.

12. Sharp-edged orifice pressure drop across each resistor in the specified branch. For R_1 this is

$$\Delta P_{each} = \frac{460}{N} = \frac{460}{2} = 230 \text{ psid} \tag{31}$$

13. Area of each restrictor is calculated using the flow from column 2 and the pressure drop from column 12. Applying Equation (2) to the data on R_1 yields:

$$\text{Area} = \frac{Q}{103\sqrt{P_S}} = \frac{0.20}{103\sqrt{230}} = 1.28 \times 10^{-4} \text{ in.}^2 \tag{32}$$

14. Depth of all restrictors was selected to be 0.01 inches. Resistor width is easily calculated for this depth using the area in column 13.

15. Required viscosity sensitive coefficient, K, for each network branch can be calculated from column 6 and Equation (4) using a viscosity of 10.5 cs for MIL-H-83282 at 120°F. For the R_1 Branch,

$$K = \frac{Rv}{\nu} = \frac{200}{10.5} = 19.05 \qquad (33)$$

16. Viscosity sensitive coefficient per unit length will differ slightly for each resistor branch because all branches have different widths as defined in column 14. Substituting 0.01 for C in equation 5 results in

$$K = \frac{1.325L}{W\left(\frac{W}{0.01+W}\right)^2} ; \quad K/L = \frac{1.325}{W\left(\frac{W}{0.01+W}\right)^2} \qquad (34)$$

Resistors in R_1 have a width of 0.0128 inches, giving a K/L of 328.

17. Total required length of all resistors in a given branch is the ratio of column 15 divided by column 16.

18. Length of each resistor is determined from columns 11 and 17.

19. A preliminary layout was made of the above network and calculations showed that the interconnecting channels between the resistor elements introduced a significant viscosity sensitive pressure drop. Layout measurements show that R_1 has 0.25 running inches of 0.030 x 0.030-inch channels. Calculated K for these channels is 1.63. Calculated K for 0.43 inch of 0.050 x 0.030-inch channels in R_1 is 1.08. Total K of the channels is 2.71; therefore, the required K for the resistors stated in column 15 for R_1 is too high by this amount. Reducing the required K to 16.34 reduces the required length of each R_1 resistor to 0.0249 inches.

Gains of this network will remain constant for all fluid viscosities because the ratio of viscosity sensitive resistance to sharp-edged orifice resistance is the same for all channels at any given temperature. In order to obtain this ratio it was necessary for the length of each resistor configuration to be different. If, for example, the length of R_L were increased, network gain would increase at the cold temperature condition.

10. NETWORK FABRICATION

A mold was fabricated to the configuration shown on Figure 25. After polishing, the resistors in the mold were optically measured. These dimensions in thousandths of an inch are shown on Figure 26 in the order of length, width, and depth. For example, resistor D on the drawing (R_L) was measured to be 0.038 inches long, 0.017 inches wide, and only 0.008 inches deep. Average channel size is smaller in all branches; however, the greatest size reduction is R_L. This increased load impedance will cause all gains to be higher than originally predicted.

Gains of the network as measured were calculated using the same equations used to design the mold; however, some iteration is required. Since the size of the load resistor is smaller, its resistance and pressure drop will be greater than it was on the original design. When the pressure drop across the network is 1,000 psid, the drop across the input resistors will be about 400 psid and the drop across the load resistor will be about 600 psid. Equation (1) shows that the resistance of R_L will be much higher than its design value, because not only is its area smaller but its ΔP is higher.

Preliminary calculations neglected to include the secondary effect of changes in pressure drops on network resistances and the effect of measured dimensional changes appeared to be less significant than they actually are. When the effects of changes in pressure drop are included in resistance calculations the gains are as shown in Table 9. All gains are substantially higher than the design value due to the large increase in load resistance because this element is only 0.008 inches deep rather than the design value of 0.010 inches deep. Viscosity sensitive resistance was higher than the design value for all paths, and the calculated gains of the network at 40°F are only slightly lower than they were at 120°F. Later test results indicated that the 120°F gains are nearly identical to the calculated values on Table 9; however, there was a significant decrease in gain at 40°F. This decrease could have been due to the connecting lines rather than the network itself.

TABLE 9. CALCULATED NETWORK GAINS BASED ON MOLD MEASUREMENTS

Input Port Designation	Design Gain	Calculated Gain 120°F	Calculated Gain 40°F	Actual Gain 120°F	Actual Gain 40°F
G_1	0.25	0.325	0.322	0.32*	0.29*
G_2	0.15	0.166	0.157	0.18	Not tested
G_3	0.10	0.108	0.102	0.11	Not tested

* Component test data; system test data showed a gain of 0.34 at 120°F and 0.28 at 40°F.

ELEMENT TAB.

DESIGNATION	WIDTH ±.0005	LENGTH ±.0005	QTY
A	.0130	.0249	2
B	.0110	.0157	4
C	.0100	.0103	8
D	.0180	0426	1

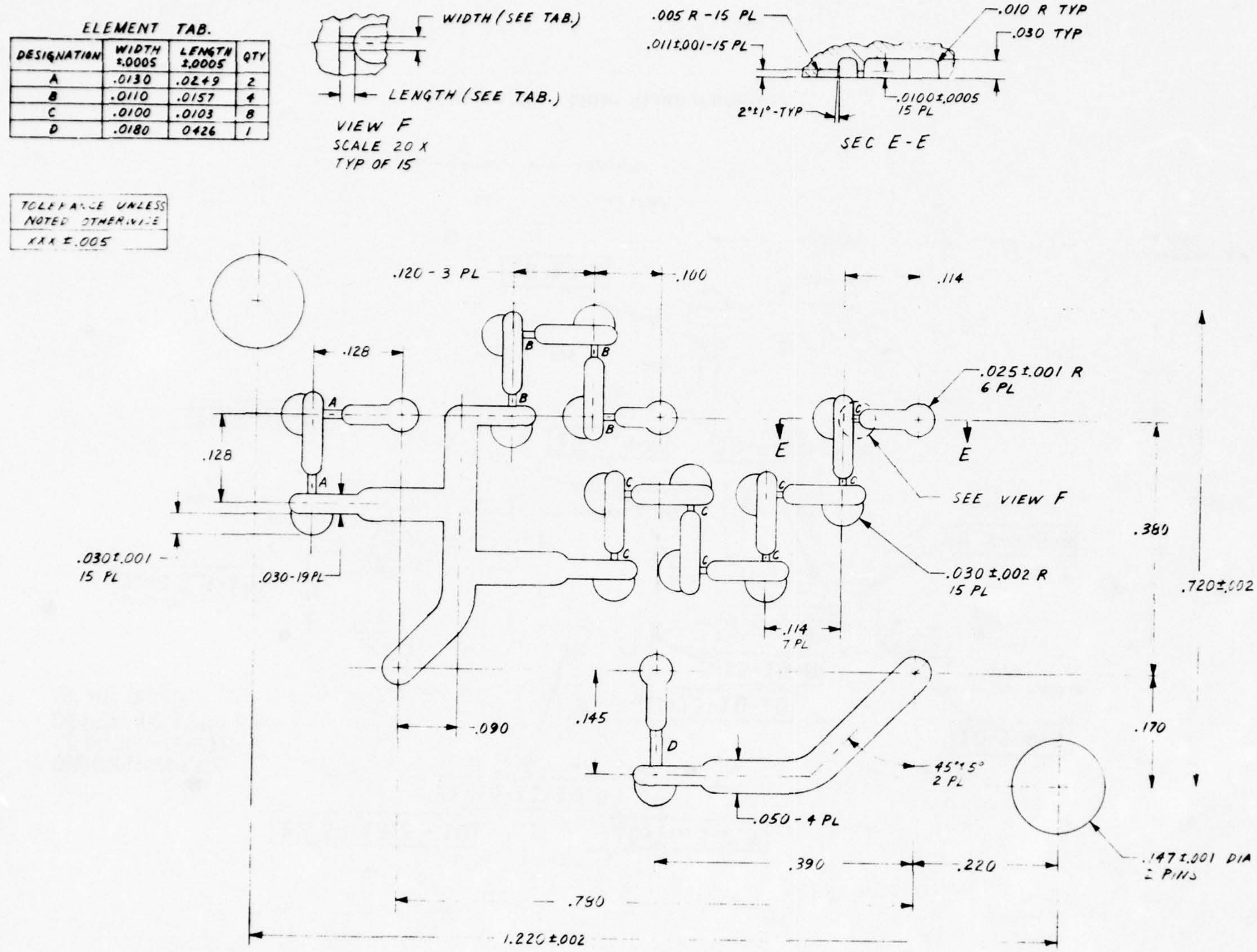


Figure 25. Resistor Network Layout

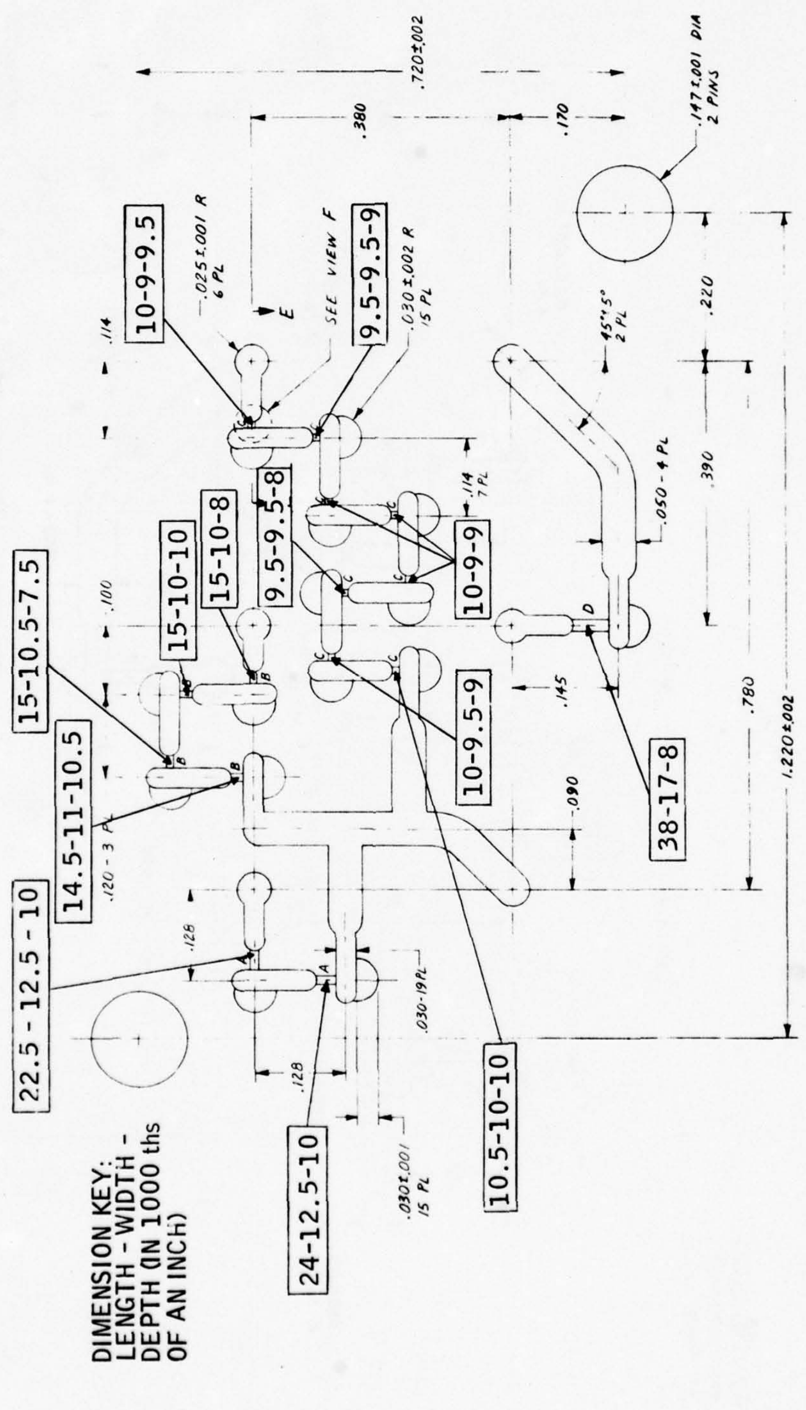


Figure 26. Mold Measurements

11. NETWORK TEST

After electroforming, the conductive wax is removed by pumping hot solvent through the network. Networks were initially cleaned for a period of about 5 minutes in each direction.

Network matching tests were performed where all input ports are connected to a 1,000 psid supply and the load resistor is connected to return. Two parallel networks are used in this test with SN899 arbitrarily selected as a reference. Differential pressure between each network and the reference was recorded as shown in Table 10. By definition the reference network has zero offset. Deviation between networks was nominally ±5 psid which corresponds to a 5 percent null offset in an operating system if the networks are not matched. Another problem which occurred during these tests was that the data was not always repeatable.

The network cleaning fixture was modified and all networks were cleaned for an additional 7 minutes in each direction. Serial numbers 901 through 904 received an additional half hour of cleaning in each direction. Matching tests were repeated and these data are also tabulated in Table 10. These results were repeatable.

TABLE 10. NETWORK MATCHING TESTS

Resistor Serial Number	Offset After First Cleaning PSID	Offset After Final Cleaning PSID	
897	+ 5.2	+32.5 (Suspect)	
898	-33.0	+0.2	
899	0	+0.8	
900	- 1.8	+9.3 (Suspect)	
901	+ 0.8	-0.9	These four units were given an additional hour of cleaning.
902	- 0.3	+0.4	
903	- 3.6	+2.1	
904	+ 4.0	0	

The electroforming on SN897 and SN900 was partially removed by grinding in order to determine the cause of their offset. No evidence of conductive wax was found in any of the channels. Each of the networks had an electroformed obstruction (curtain) on one of its resistor elements in the areas shown in Figure 27. Curtains have occurred previously on amplifiers and were reported on in Reference 2; however, this is the first case of a curtain in a resistor network. Curtains are caused by a hairline crack in the wax mandrel. The electroforming process is capable of plating down into the crack, creating a fence or curtain in this area. The hairline cracks probably occurred when the injected part was removed from the mold. This problem can probably be eliminated entirely by polishing the surfaces of the mold and adding slight additional draft, if required. The mold used on this program was substantially less expensive than that used on production programs, and the yield was substantially less than the 100 percent reported for resistor networks in Reference 2.

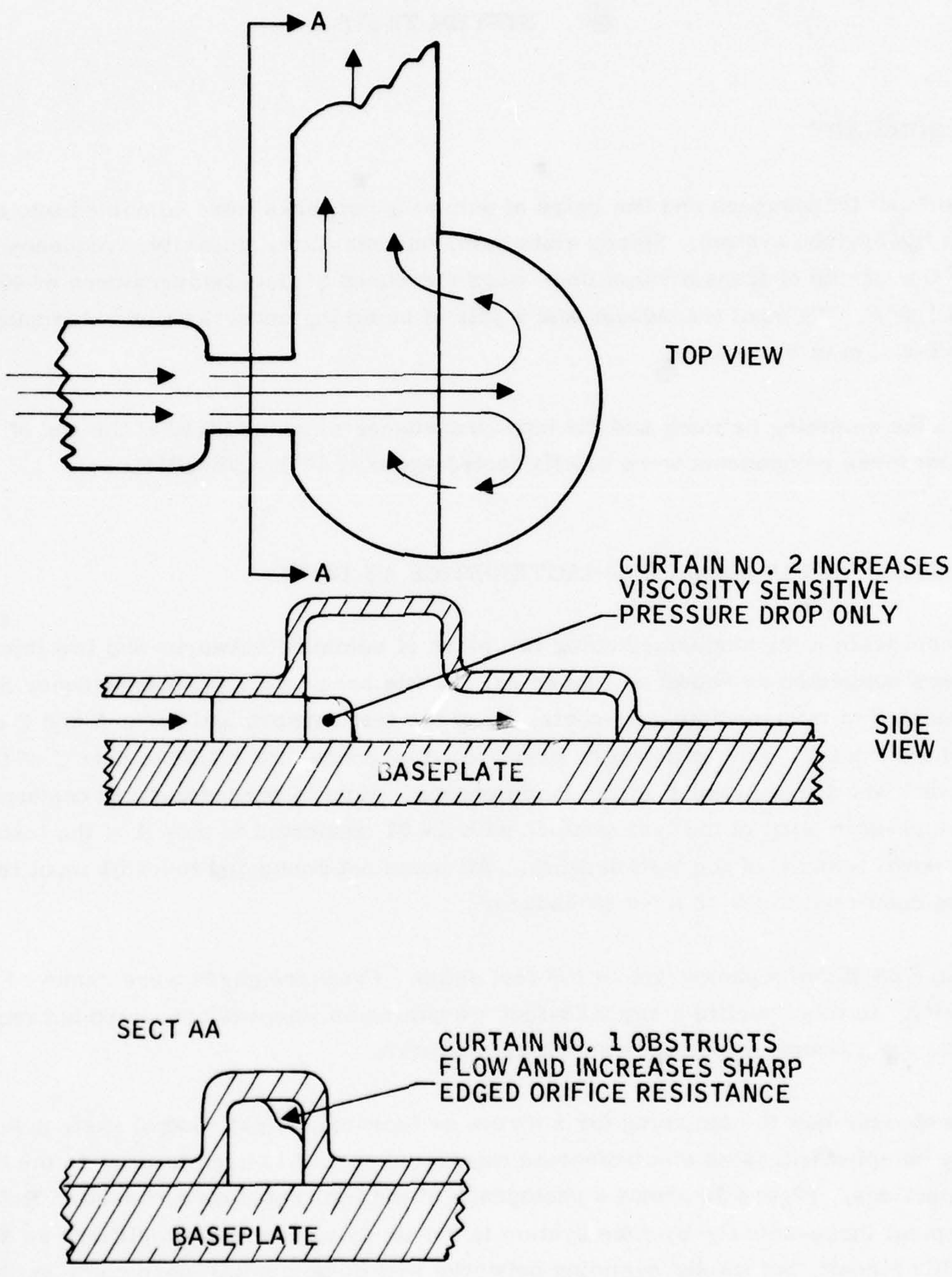


Figure 27. Location of Electroformed Curtains

SECTION V
SYSTEM TESTS

1. SUMMARY

Two input transducers and two pairs of summing networks were combined into a simplified fly-by-tube system. Steady state gain, null stability, linearity, frequency response, and the effects of transmission lines were measured at fluid temperatures of 40°F, 120°F, and 180°F. An input transducer and a pair of summing networks were also subjected to 5g vibration in three axes.

Both the summing network and the input transducer were modified at the end of the program; these components were briefly tested again at 40°F and 120°F.

2. STEADY STATE GAIN CHARACTERISTICS AT 120°F

System tests were performed using two pairs of summing networks and two input transducers connected as shown on Figure 28. In this schematic, input transducer SN 01 is connected to intermediate gain ports, B, of the test network and ports A and C of the load transducer. Low gain inputs were tested by connecting SN 01 to port C of the test network and ports A and B of the load network. Most of the testing was conducted on the high-gain input of the test network with SN 01 connected to port A of the test network and ports B and C of the load network. All ports not connected to SN 01 input transducer were connected to SN 02 input transducer .

Figure 29 shows a photograph of the test setup. Pressure gages were removed for clarity. In this specific setup a 25-foot transmission line was connected between the SN 01 input transducer and its summing networks.

It is obvious that the plumbing for a three- or four-axis flight control system will be very complex unless an electroformed integrated circuit is used to provide the hydraulic connections. Figure 30 shows a photograph of the integrated circuit used in Reference 2. A typical three-axis fly-by-tube system is not likely to use fluid amplifiers as shown on this circuit, but its six summing networks will be somewhat more complex than those shown on this photograph. Overall complexity of the integrated circuit shown in the photograph is approximately equivalent to that of the manifold circuit required for a complete three-axis fly-by-tube system.

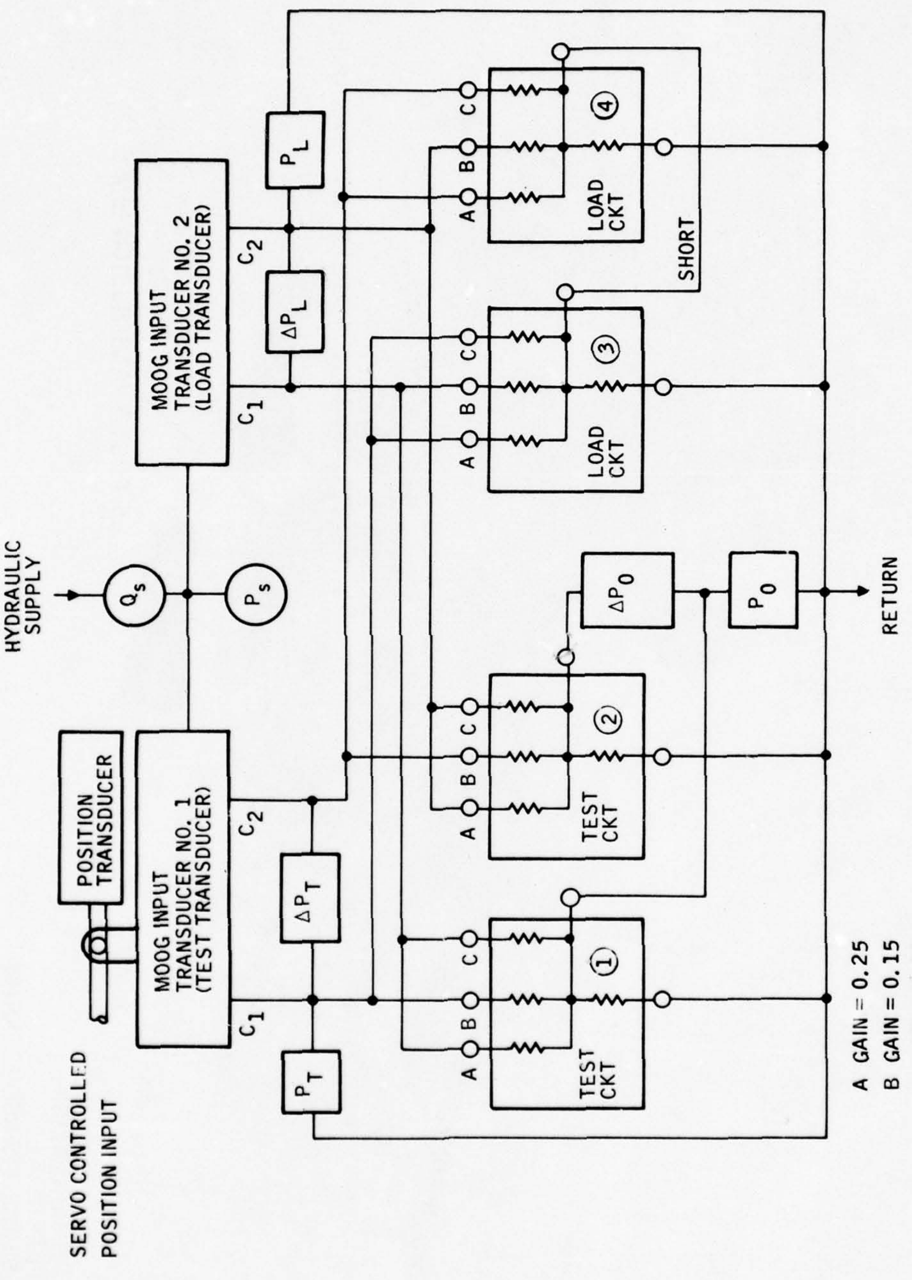


Figure 28. System Test Setup

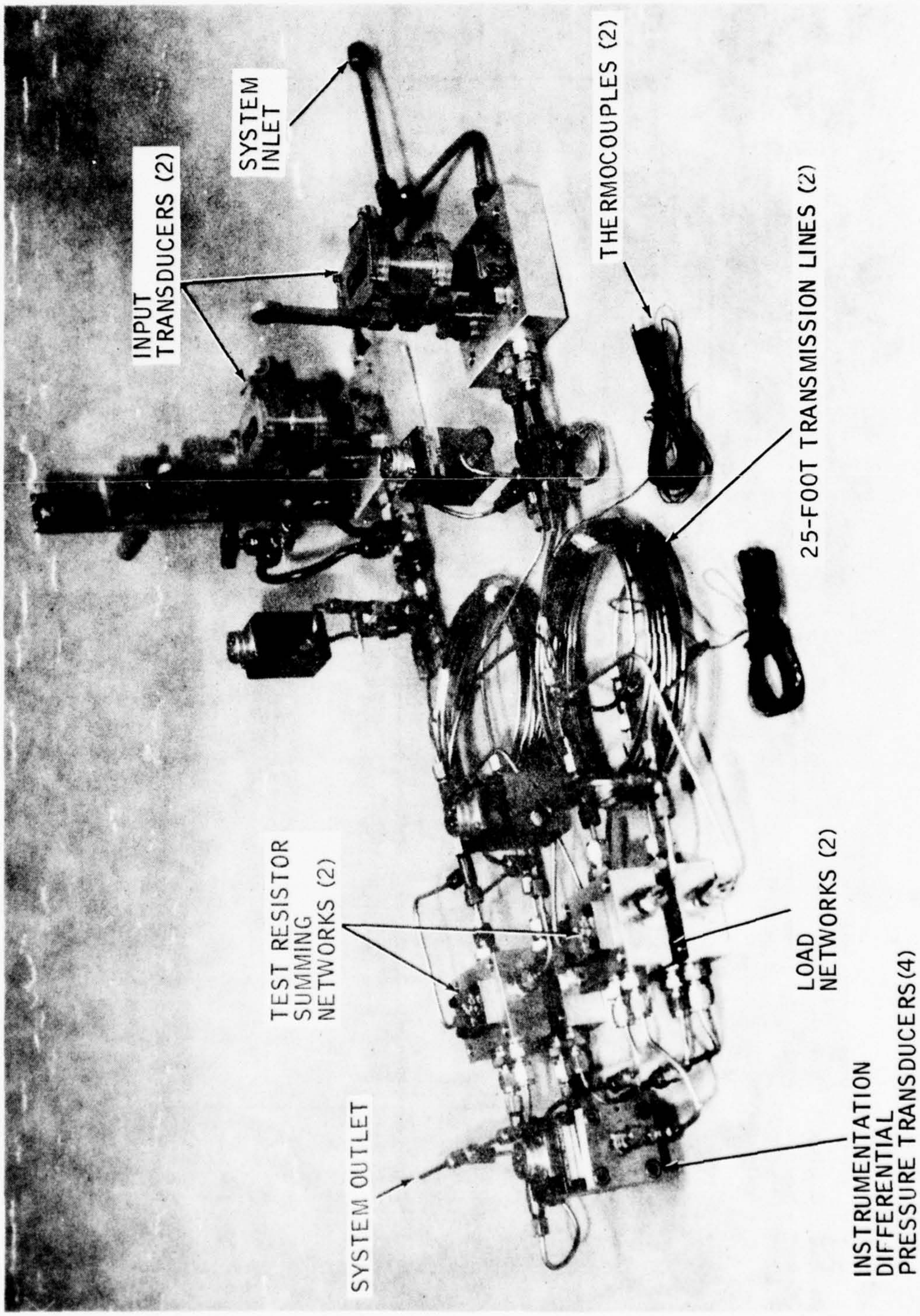


Figure 29. Fly-by-Tube Test Setup

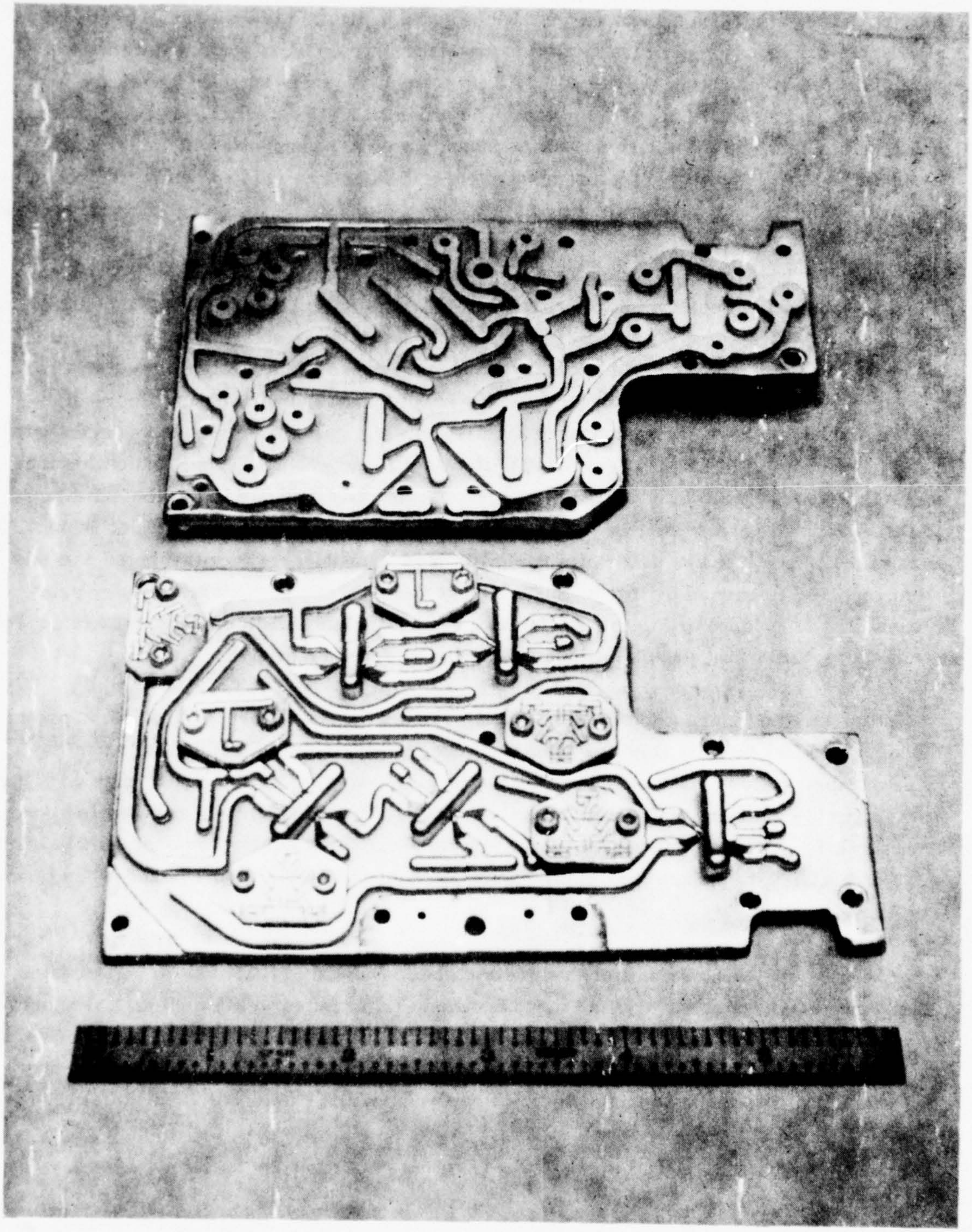


Figure 30. An Electroformed Integrated Circuit with Replaceable Resistor Networks

Figure 31 gives the characteristics of the input transducer operating in the system test setup at 120°F. Position input range on this setup is limited to its normal range of ±0.2 inch; the overtravel characteristics are not shown. Cross axis sensitivity was demonstrated by changing the output of SN 02 transducer over its complete range and monitoring the output of SN 01 transducer. Figure 32 shows the expanded output of SN 01 under this condition. Cross axis sensitivity of 3.5 percent is higher than the 2 percent required in many applications however this characteristic can be improved by the use of higher loop gain in the input transducer.

System end-to-end characteristics were obtained with the test transducer (SN 01) connected to the high gain ports of the test network and the load transducer connected to the other two ports. Figure 33 shows an operating map of these characteristics in which test network output was plotted against test transducer position for various values of load transducer position. Lines on this map should be linear (indicating linear high-gain port characteristics), parallel (indicating that the gain of the test transducer path does not change when the load transducer is offset), and evenly spaced (indicating that summing through the other two ports is linear). Spacing between lines is even except in the upper left hand corner of the curve when the test transducer is changed from 0.15 inch to 0.20 inch. It was determined that the load transducer was mis-rigged and this wider spacing is caused by the discontinuity at the ends of the input transducer gain curves that is evident in Figure 5. Some of the hysterisis shown on Figure 33 is caused by the output instrumentation differential pressure transducers.

Summing network characteristics are extremely linear, as Figure 34 depicts. Spacing between parallel lines is even for load transducer signals out to ±400 psid. For the sake of clarity, hysterisis characteristics were shown only for the center curve. This hysterisis is caused by the instrumentation. Gain of the high gain input ports is approximately 0.34. Similar curves, obtained for the other input ports, demonstrated gains of 0.18 and 0.12. It appears that the projected linearity of better than 1 percent has been realized.

Operating at off-design conditions is one method for investigating system deficiencies. The system was operated with the input transducer connected to the high gain test network ports as before, but the supply pressure to the system was reduced 50 percent. Overall system performance shown in Figure 35 is good despite a reduction in gain, linearity and range, when compared to the nominal performance of Figure 32. Null offset remains small at all supply pressures.

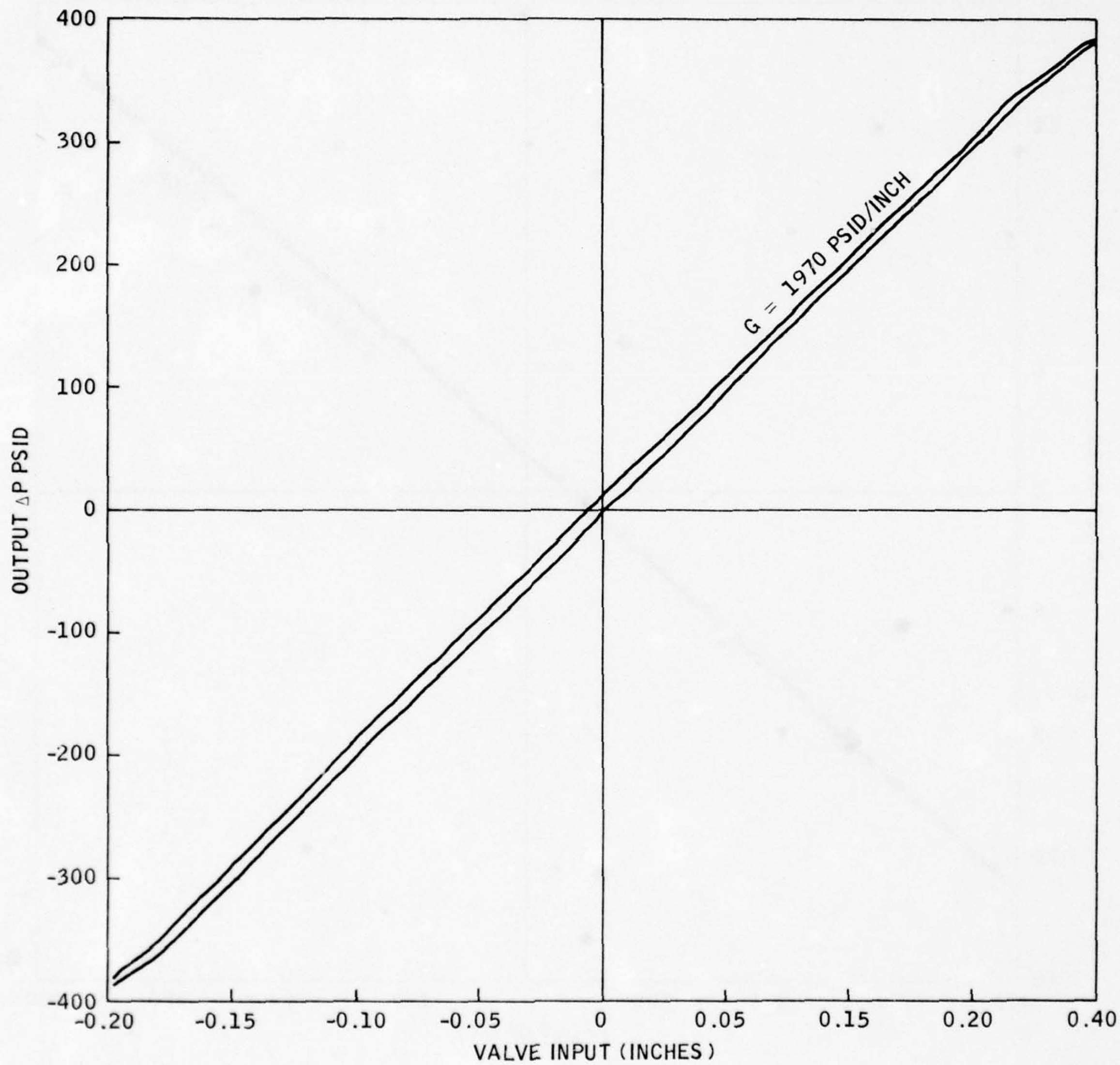


Figure 31. Input Transducer Characteristics at 120°F When Loaded into Summing Networks

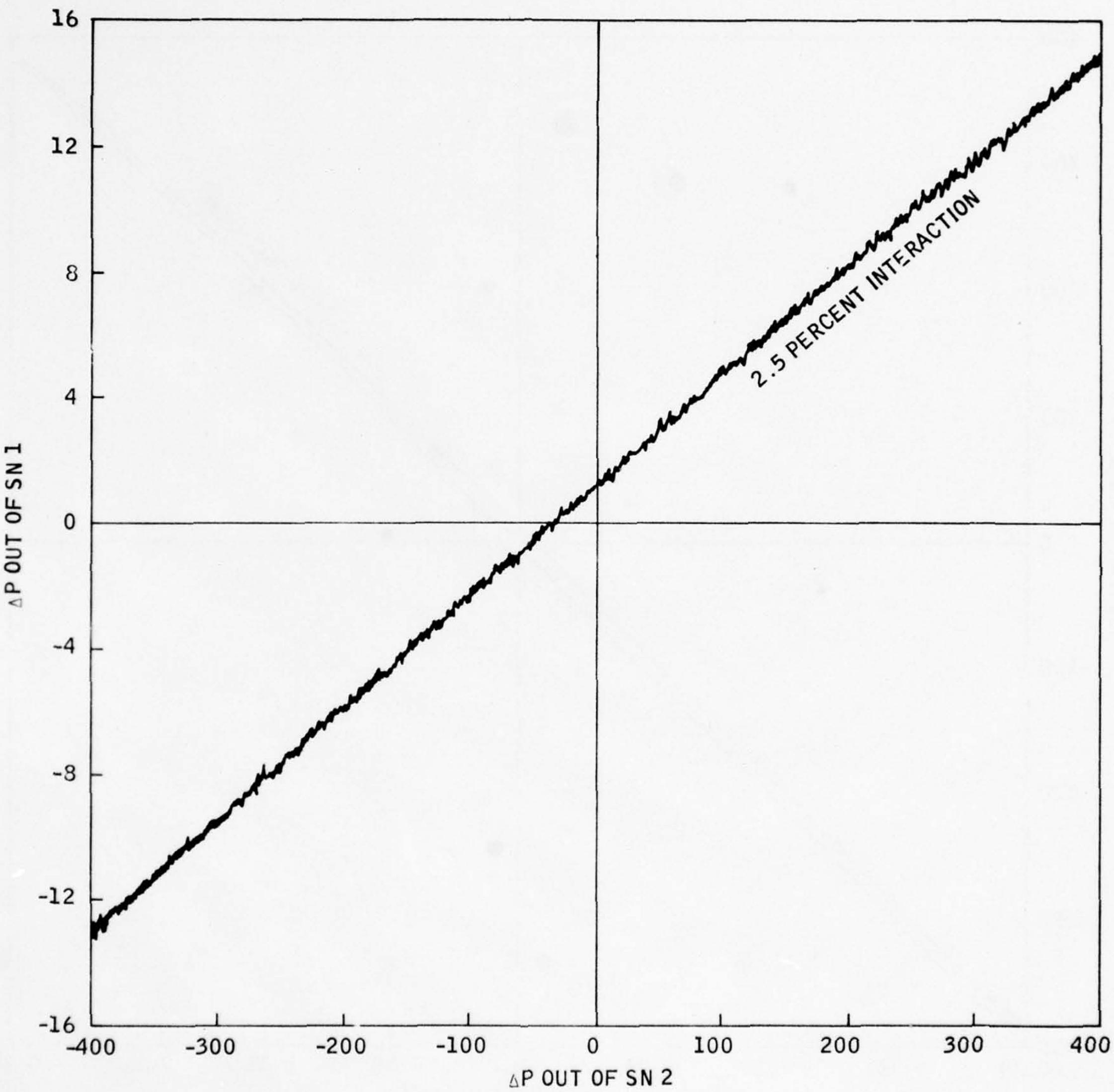


Figure 32. Cross Axis Coupling Characteristics

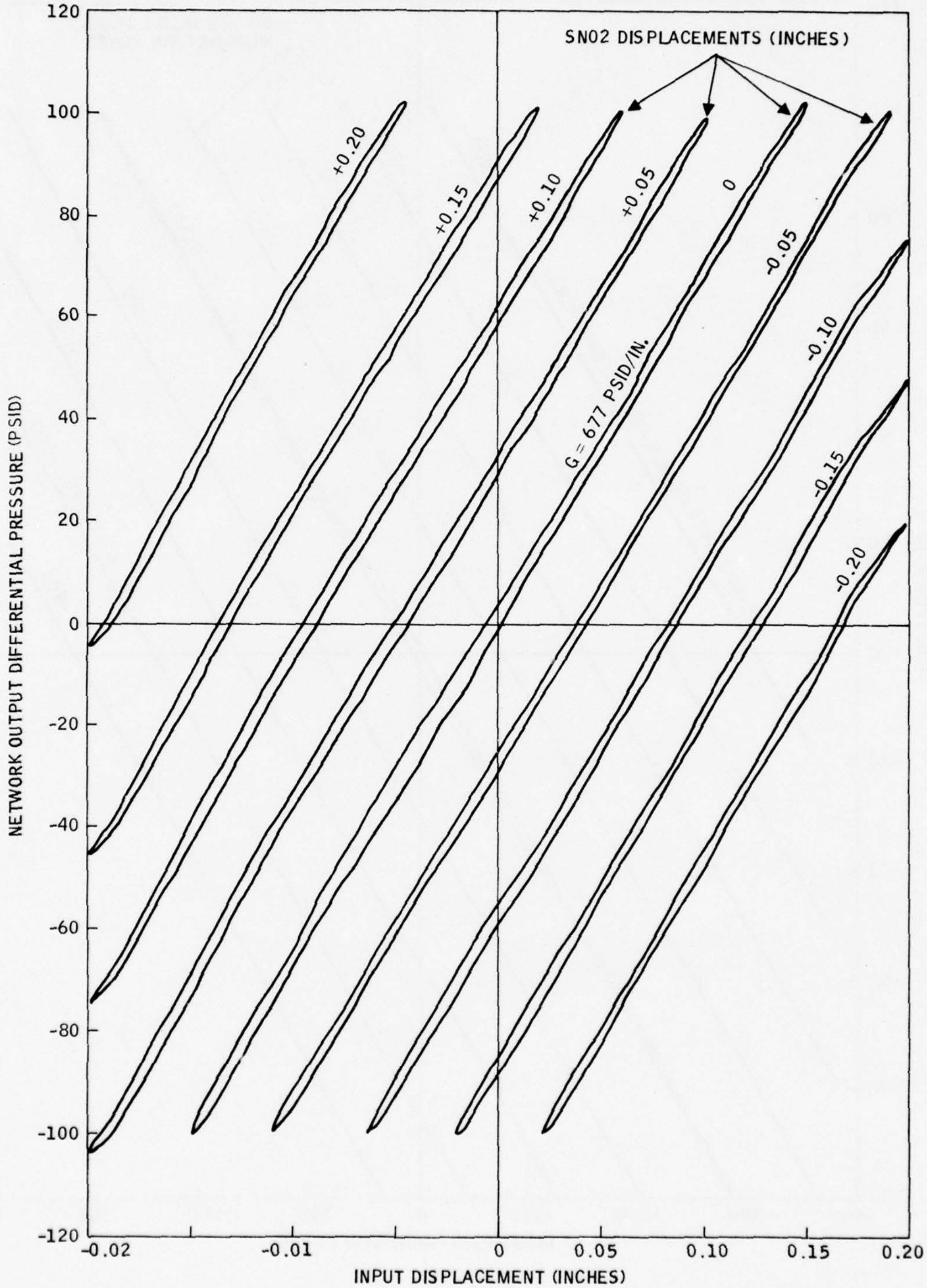


Figure 33. Operating Map of System Characteristics

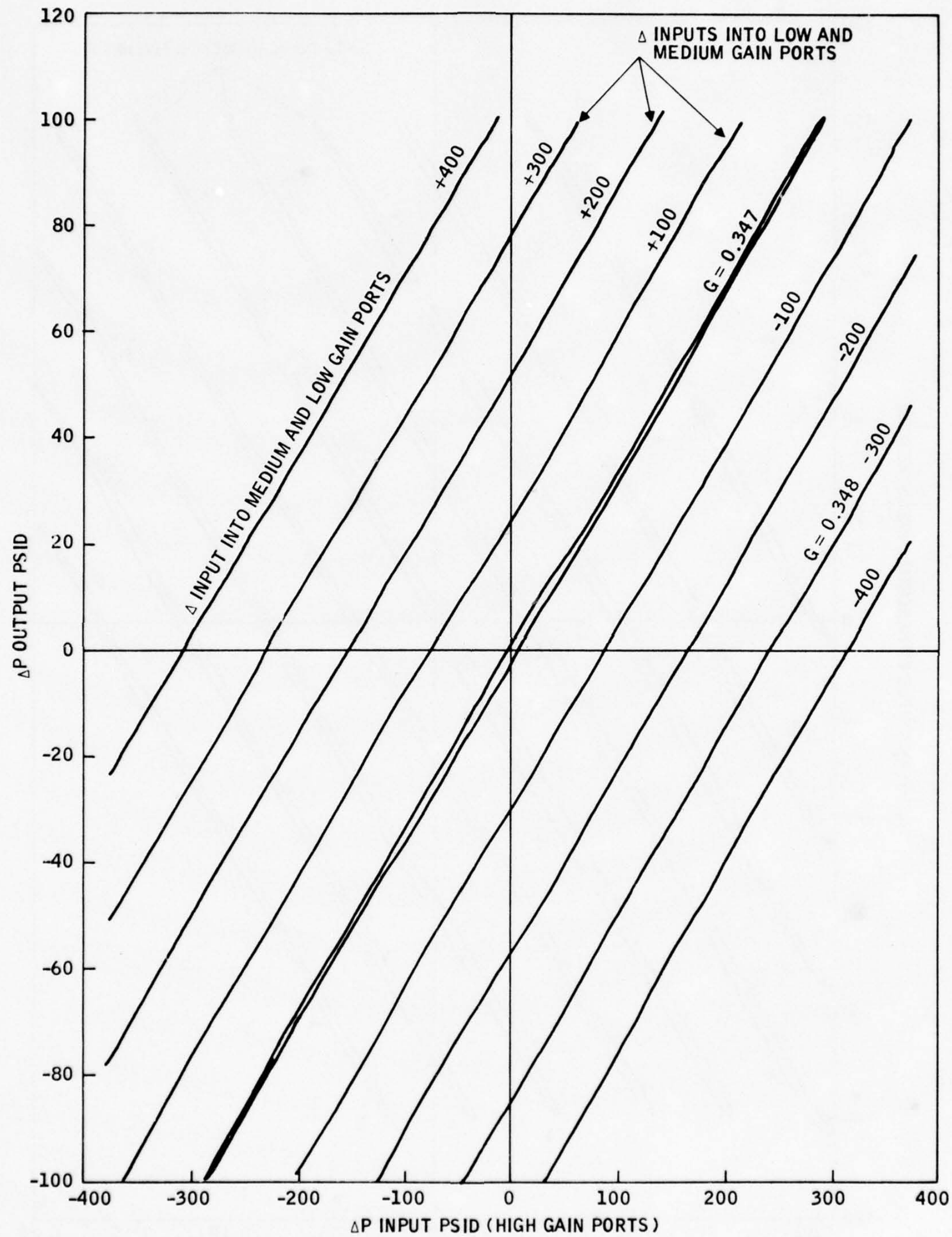


Figure 34. Operating Map of Summing Network Characteristics

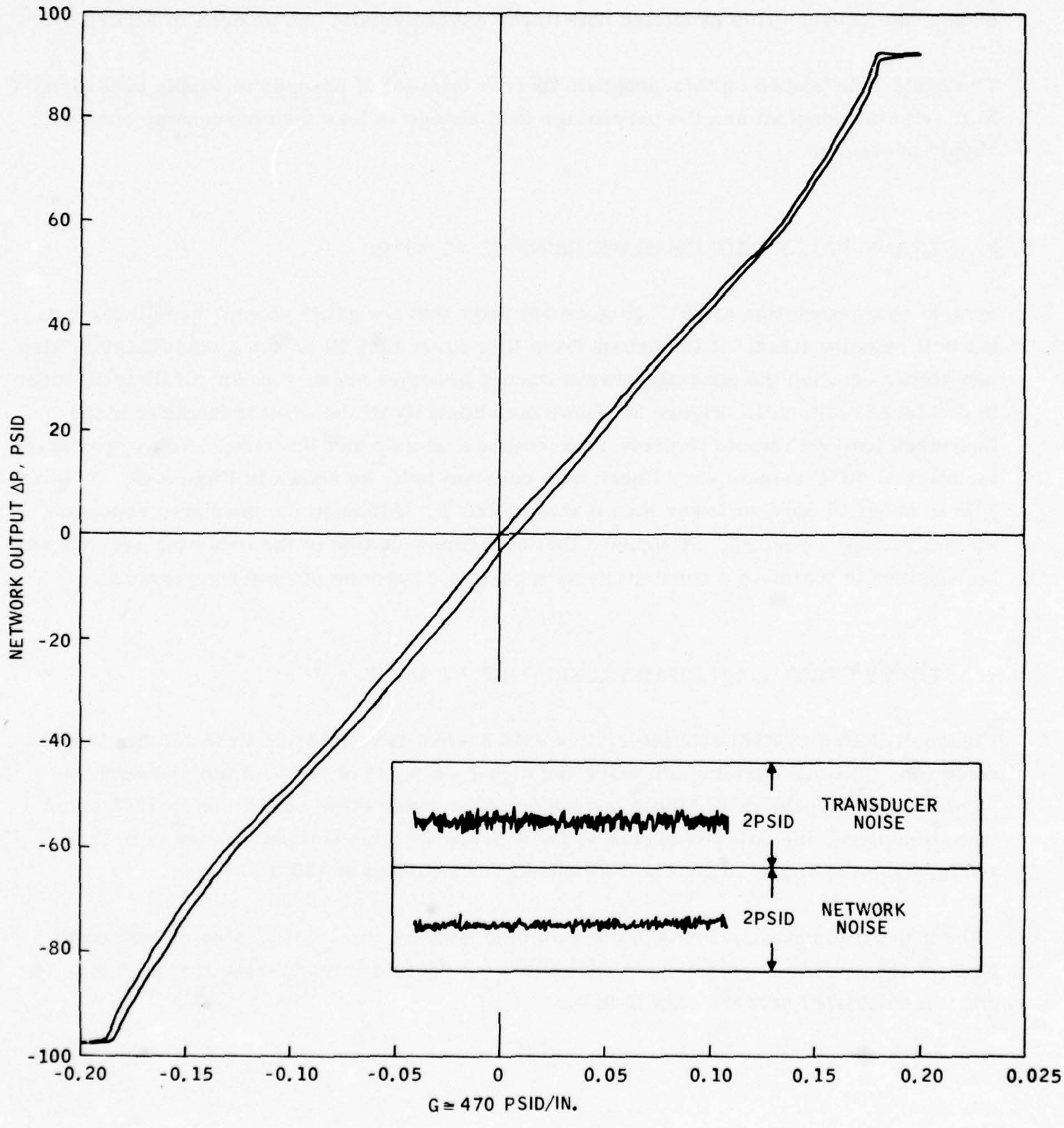


Figure 35. System Characteristics at 50 Percent Supply Pressure

Characteristics of the input transducer and summing networks at 50 percent supply pressure are shown in Figure 36 and 37 respectively. Linear output range for the summing network should be ±50 psid at 50 percent supply pressure. Theoretically the non-linearity should increase as the output is driven above 50 psid in the direction of high gain at the ends of the curve. This predicted non-linear characteristic can be seen in Figure 37.

The system developed on this program is very tolerant of changes in supply pressure. Null remains constant and the percentage gain change is less than percentage change in supply pressure.

3. STEADY STATE GAIN CHARACTERISTICS AT 40°F

System characteristics at 40°F (Figure 38) show that the gain becomes non-linear but the null remains fixed. It is obvious from this curve that SN 02 input transducer is also non-linear because the spacing between curves becomes greater as the SN 02 transducer is displaced from null. Figure 39 shows non-linearity of the input transducer alone. Increased loop gain would improve input transducer gain and linearity. Network characteristics at 40°F remain very linear with constant null, as shown in Figure 40. Network gain is about 15 percent lower than it was at 120°F. Although the predicted reduction was only about 1 percent. It appears that overcompensation of the summing network will be required to maintain a constant system gain as a function of fluid temperature.

4. STEADY STATE GAIN CHARACTERISTICS AT 180°F

Figure 41 shows system characteristics with 25-foot transmission lines for the 180°F condition. Overall system gain using the high-gain ports of the summing network is shown to be 616 psid/inch. Input transducer gain under these conditions is 1902 psid/inch; therefore, the calculated gain of the network with transmission lines is 0.32. Performance at 180°F is nearly identical to that obtained at 120°F.

Gain of the transmission line and the summing network in series is also measured to be 0.32 (Figure 42). This Figure shows that the 25-foot transmission line gain is 0.94 and the calculated network gain is 0.34.

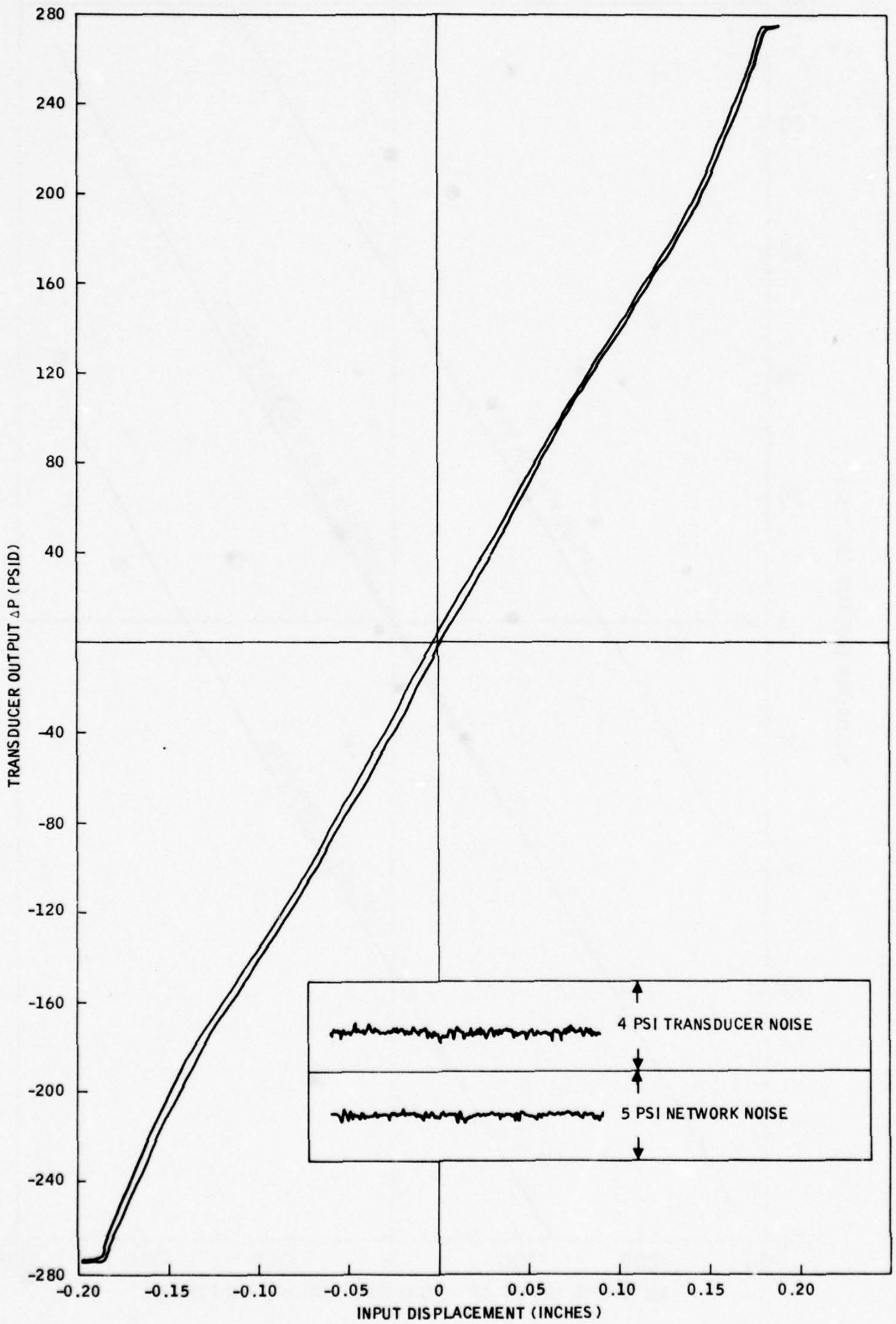


Figure 36. Input Transducer Characteristics at 50 Percent Supply Pressure

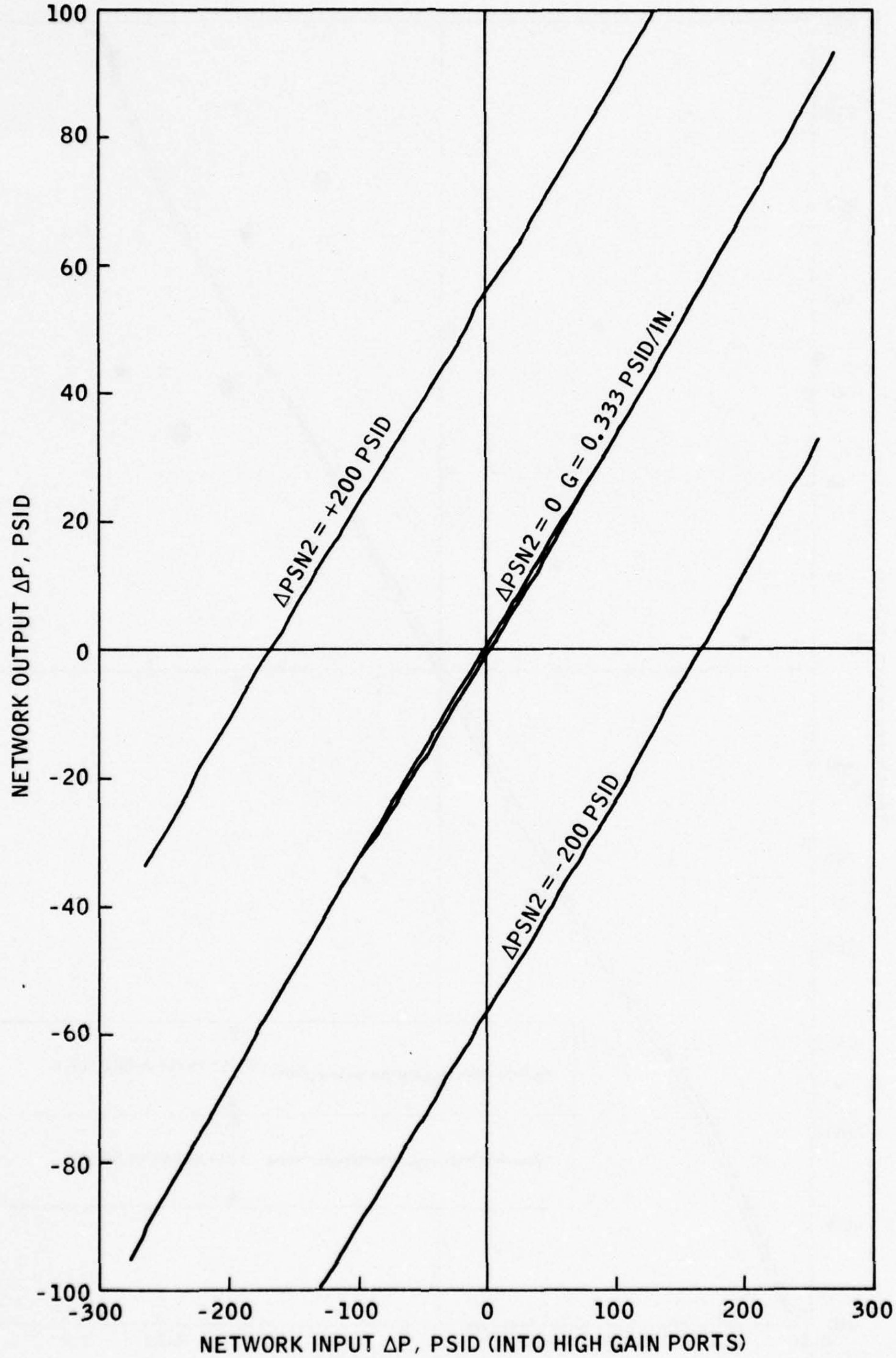


Figure 37. Summing Network Characteristics at 50 Percent Supply Pressure

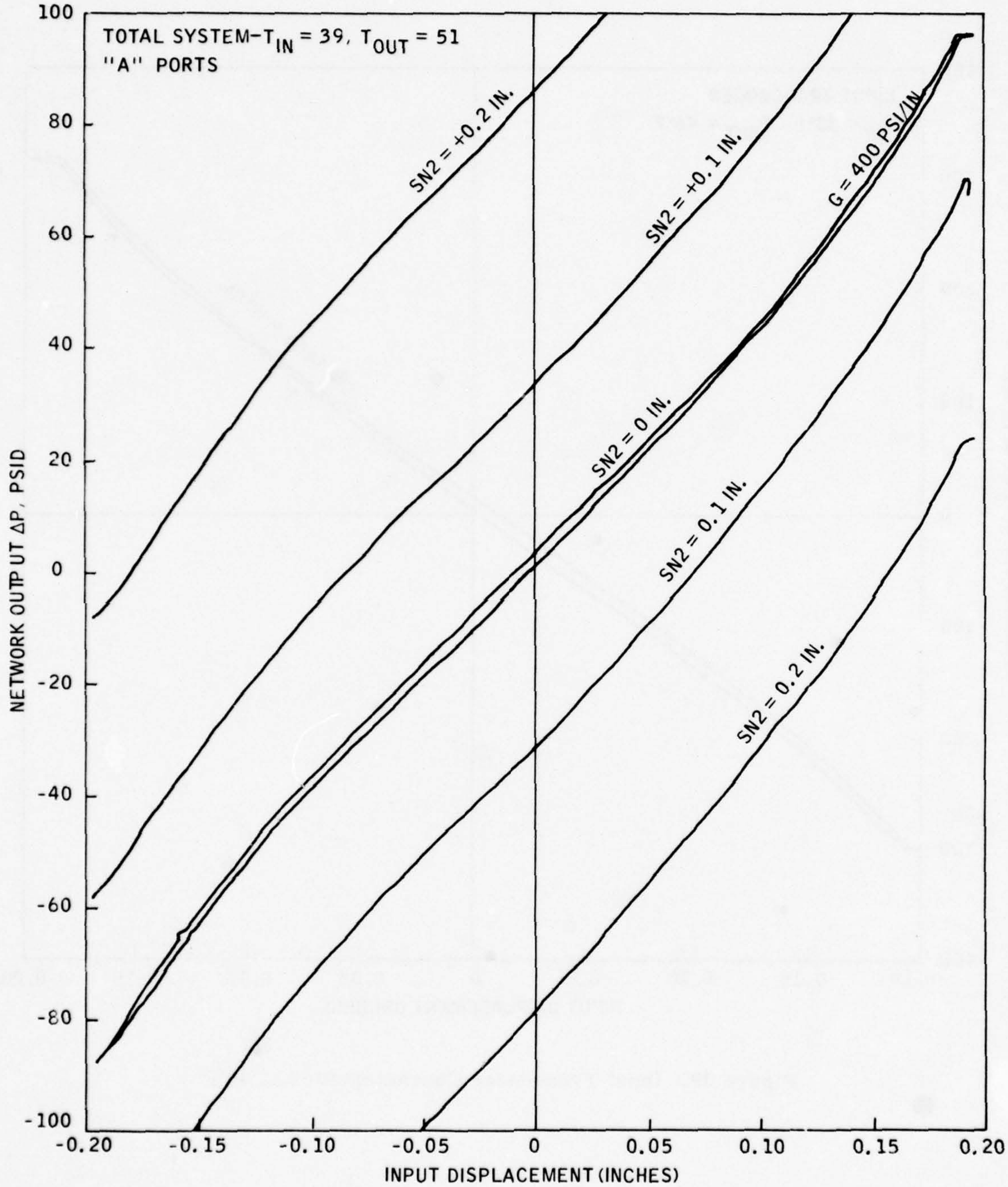


Figure 38. System Gain Characteristics at 40°F

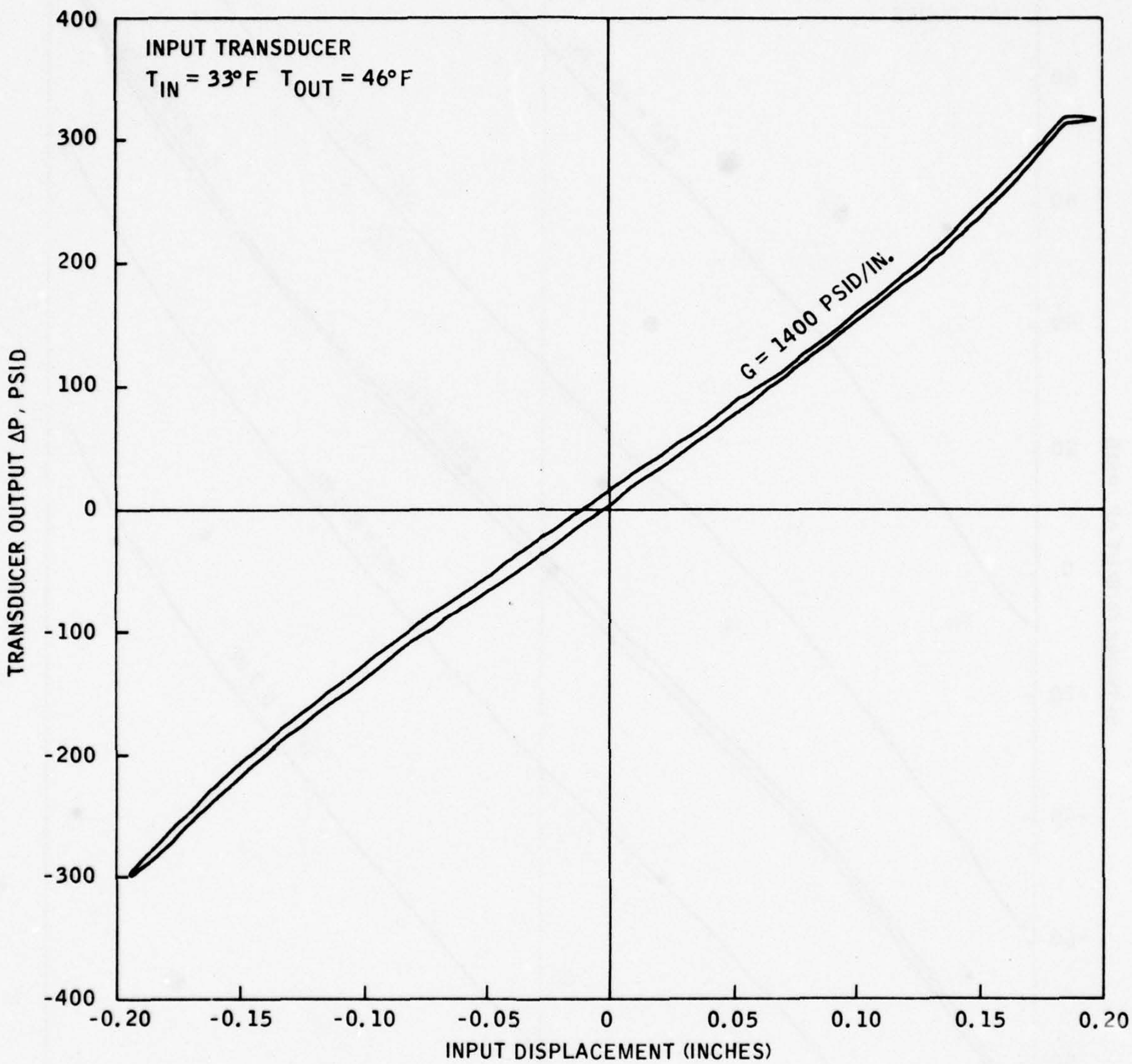


Figure 39. Input Transducer Characteristics at 40°F

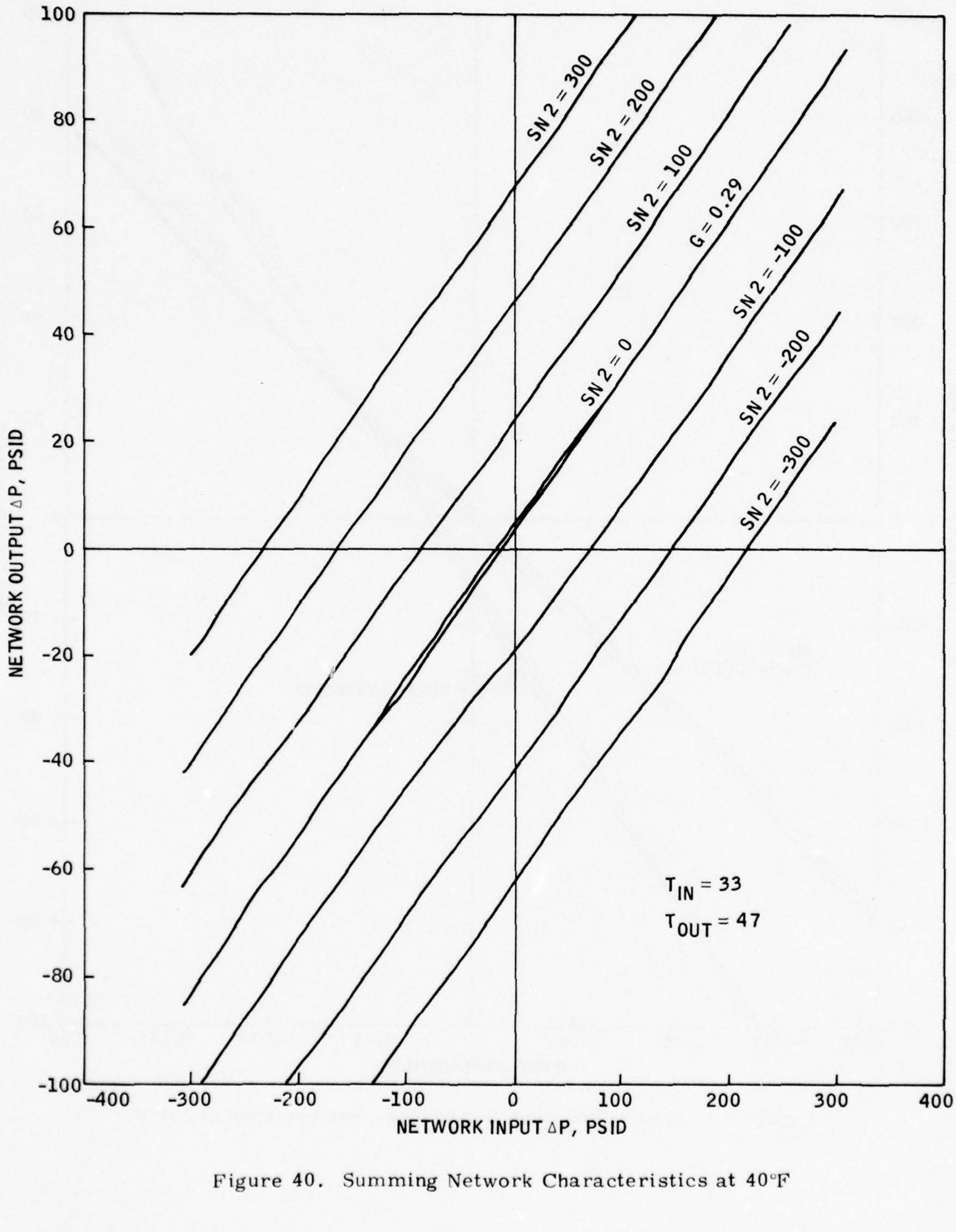


Figure 40. Summing Network Characteristics at 40°F

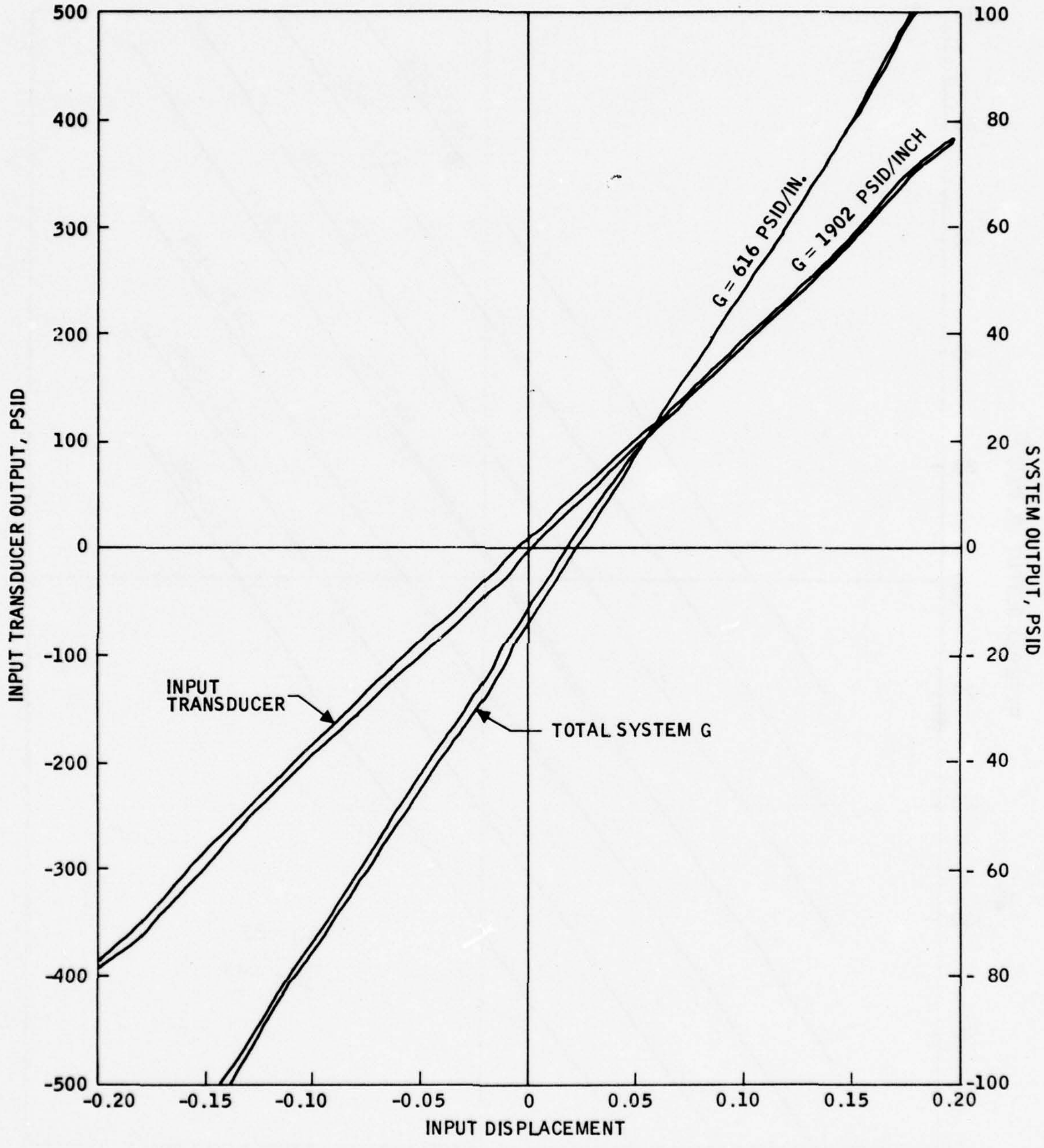


Figure 41. System and Input Transducer Performance at 180°F

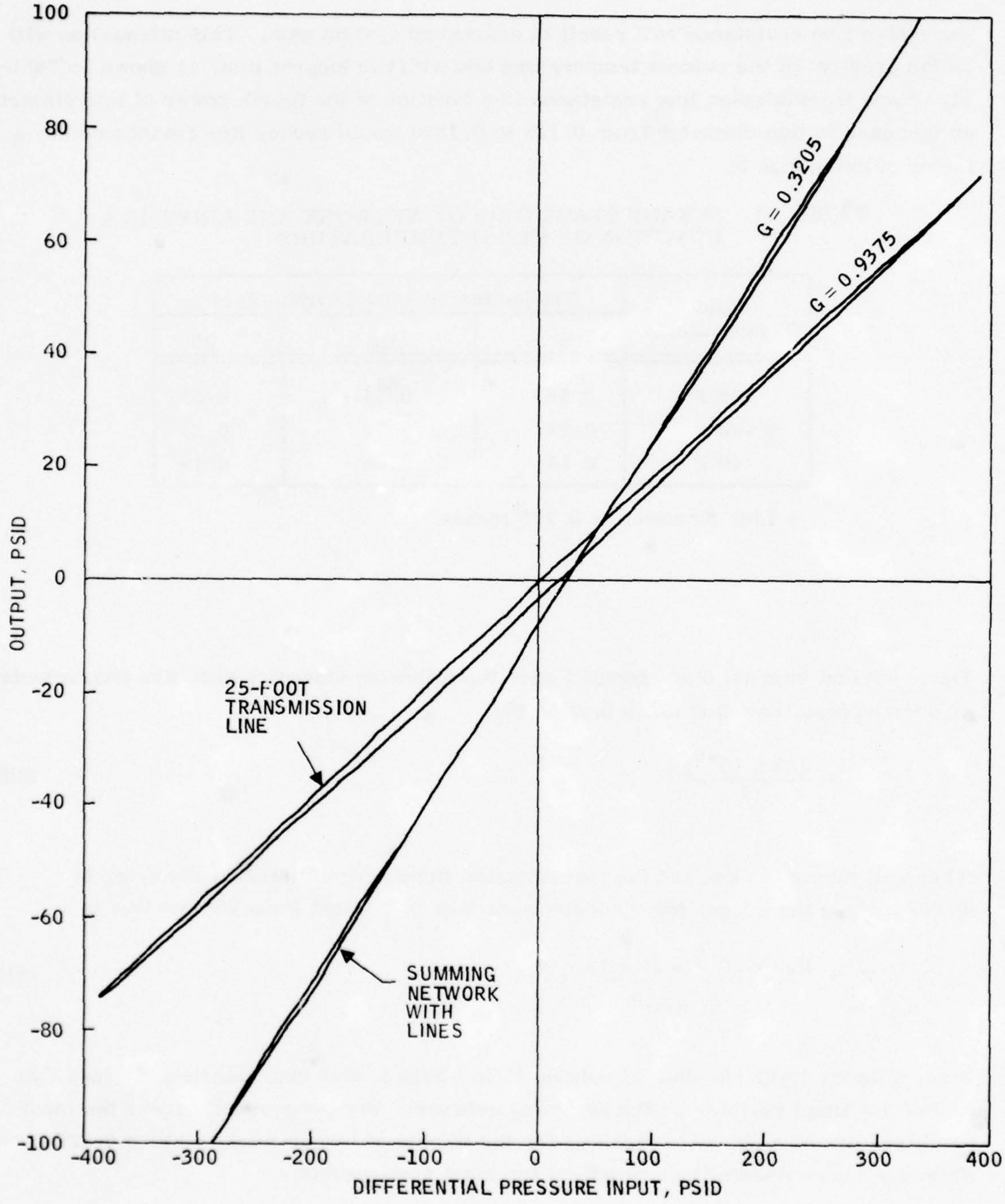


Figure 42. Transmission Line and Summing Network Characteristics at 180°F

5. EFFECTS OF TRANSMISSION LINES ON STEADY STATE GAINS

Excessive line resistance will result in decreased system gain. This attenuation will be the greatest at the coldest temperature and with the longest line, as shown in Table 11. Since transmission line resistance is a function of the fourth power of line diameter, an increase in line diameter from 0.125 to 0.1875 would reduce line resistances by a factor of more than 5.

TABLE 11. STEADY STATE GAIN OF NETWORK AND LINES AS A FUNCTION OF FLUID TEMPERATURE

Fluid Temperature	Transmission Line Length, Feet*		
	0	10	25
180°F	0.36	0.34	0.32
120°F	0.34	0.32	0.31
40°F	0.28	0.24	0.19

* Line diameter is 0.125 inches.

Tubes with an internal diameter of d have the following viscosity sensitive characteristic as derived from Equation (5) in Section IV:

$$K = \frac{5.3 \times 10^{-6} L}{d^4} \tag{30}$$

Thin wall tubing is used and the transmission lines have an internal diameter of 0.097 inches; therefore, the viscosity sensitive coefficient for a 25-foot line is

$$K = \frac{5.3 \times 10^{-6} \times 25 \times 12}{(0.097)^4} = 18.0 \tag{31}$$

When compared with the data of column 15 in Table 8, this characteristic is less than that of any input resistor on the summing network. Viscosity sensitivity of the input resistors can be reduced to make up for the effects of longer lines, making 0.125-inch diameter transmission lines practical for most applications.

6. SYSTEM FREQUENCY RESPONSE CHARACTERISTICS AT 120°F

Frequency response tests were conducted with the test input transducer connected to the high-gain inputs of the test networks and the other two gain ports of the load networks. The system was tested with no transmission lines, 10-foot transmission lines, and 25-foot transmission lines. Diameter of the transmission lines was 0.125 inch.

Figure 43 shows the input transducer response characteristics. Input transducer response is slightly better with the shorter lines, and some unusual resonance is noted with the long lines at 40 Hz. Higher valve loop gain would improve valve response; however, its present response is satisfactory for most applications.

Transmission line frequency response was obtained with the line loaded into the summing networks with a 100 psid transducer at the output of the network. This transducer capacitance, combined with the output resistance of the summing network, results in an R-C time constant of about 0.017 second. Transmission line response characteristics (including the summing network and transducer) are plotted in Figure 44. Note that a resonance occurs with the 25-foot lines at about 30 Hz. This resonance is well beyond the response of most systems. Data at 10 Hz for each of the three line lengths was used in calculations in order to approximate the transfer function, which is a time delay with a first order lag. The increase in phase shift with increasing line length is very small and if changes im amplitude response were not included, the calculated signal propagation velocity would be about 6700 feet per second. This is higher than the velocity of sound in hydraulic oil. For this reason changes in amplitude response were included in the calculations, resulting in the transfer functions shown in Figure 44. Calculated propagation velocity is 5300 feet per second; however, it should be noted that 0.5 db error in the amplitude ratio data will result in a change of 1,000 feet per second in computed propagation velocity.

7. SYSTEM FREQUENCY RESPONSE CHARACTERISTICS AT 40°F

Figure 45 shows input transducer characteristics when loaded into a 10-foot transmission line at 40°F fluid temperature. Transducer response was slightly better with short lines, similar to the performance at 120°F, but there was no apparent resonance with the 25-foot lines at high frequencies.

Transmission line amplitude response, as shown in Figure 46, was nearly identical for all line lengths. Phase shift increased as a function of line length. Transfer functions of the transmission line, summing network, and 100 psid instrumentation transducer are

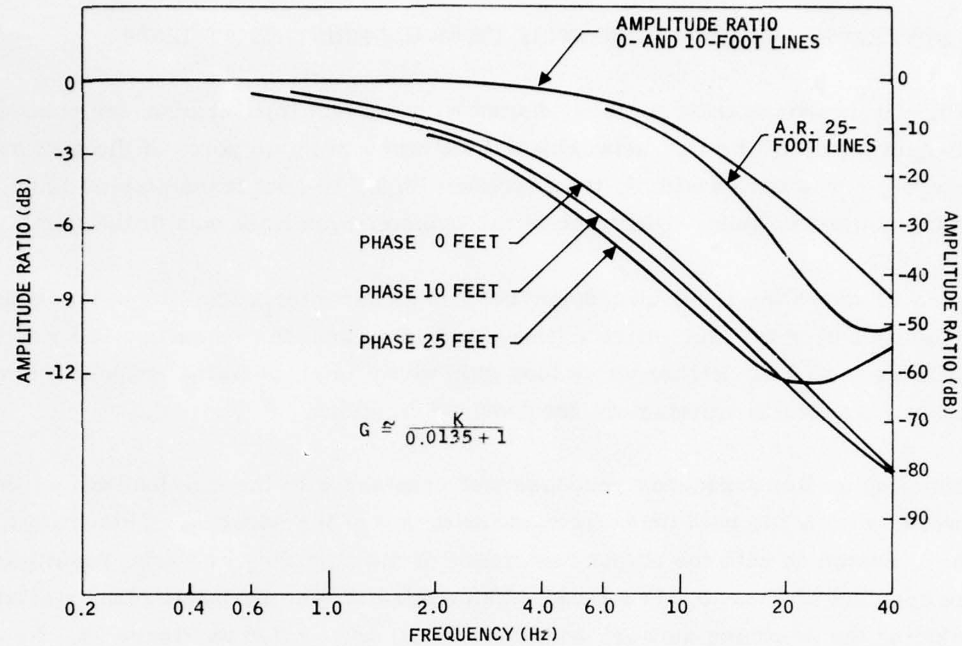


Figure 43. Input Transducer Response at 120°F Loaded into Transmission Lines

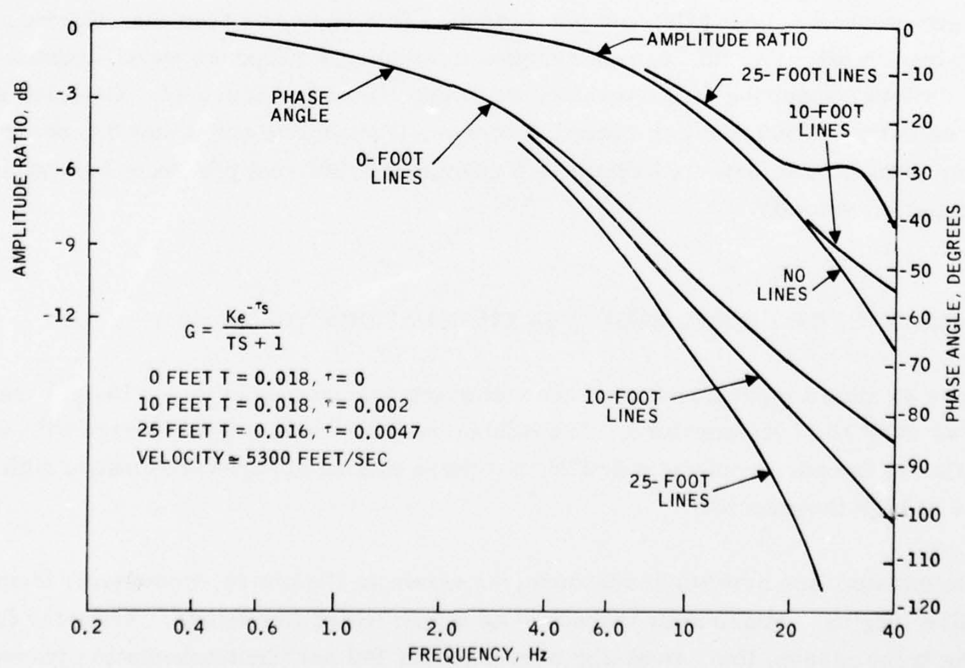


Figure 44. Transmission Line Response at 120°F Loaded into a 100 PSID Transducer

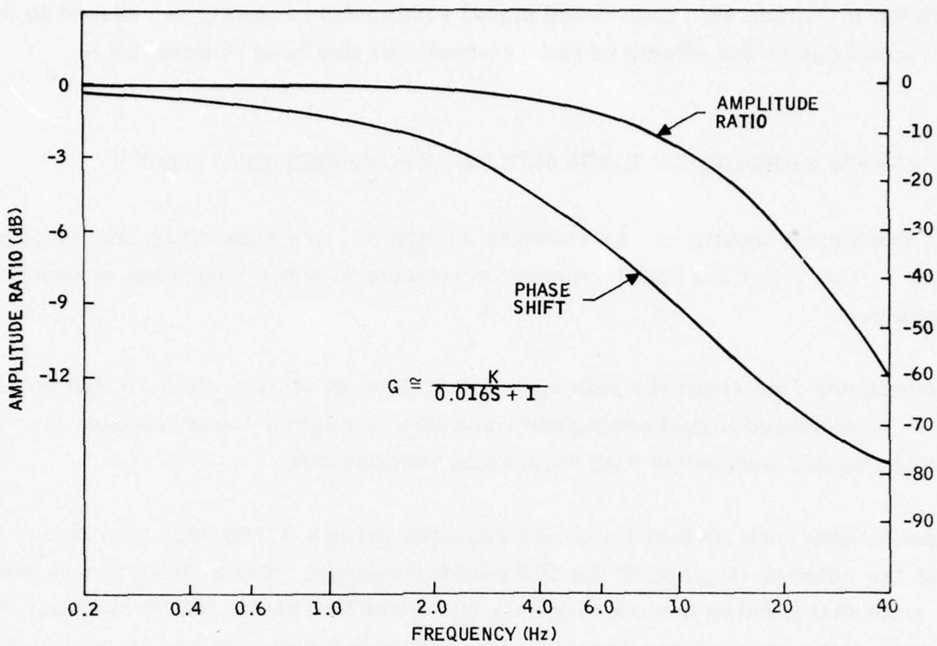


Figure 45 Input Transducer Response at 40°F and a 10-Foot Transmission Line

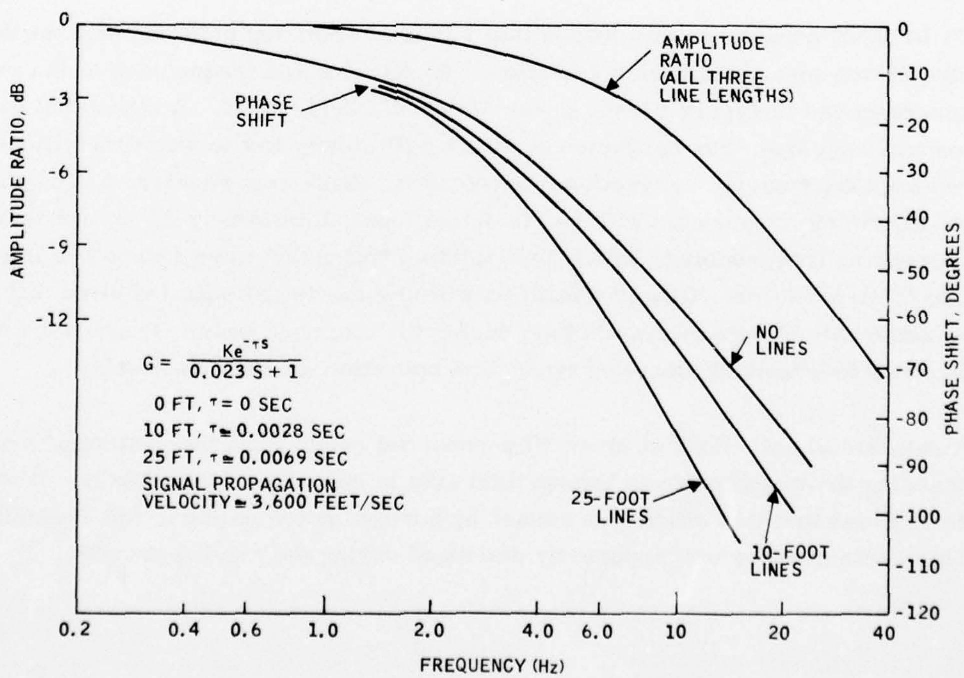


Figure 46. Transmission Line Response at 40°F (with a 100 PSID Transducer)

tabulated in Figure 46. Calculated signal propagation velocity is reduced to 3,600 feet per second due to the effects of fluid viscosity at this cold temperature.

8. SYSTEM FREQUENCY RESPONSE CHARACTERISTICS AT 180°F

Input transducer dynamics, as shown in Figure 47, are essentially the same as they were at 120°. Effects of the high frequency resonance with the long lines is somewhat more pronounced.

Transmission line response data shown in Figure 48 is also close to that obtained at 120°F. Calculated signal propagation velocity is slightly lower because the velocity of sound in liquids decreases with increasing temperature.

Response data with 10-foot lines was repeated using a 2,000 psid transducer at the output of the network in place of the 100 psid transducer. The results are shown in Figure 49. Note that peaking occurs with only 10 feet of line at the 180°F condition when this low capacitance transducer is used. The transfer function shown is only an approximation, and it assumes the undamped natural frequency remains constant with temperature.

9. VIBRATION

SN 01 input transducer was loaded into a pair of summing networks and the output of the circuit was measured during vibration. Amplitudes and frequencies of the vibration corresponded to Figure 514-1, curve M, of MIL-STD-810B. A sinusoidal cycling, per the test envelope, was conducted at a rate sufficiently low to allow identification of resonant frequencies or functional phenomena. Each axis received a 7.5 minute scan of increasing frequencies with no electrical input, followed by a 7.5 minute scan of decreasing frequencies in which an electrical triangular wave signal was introduced into the transducer. Circuit operation with the electrical signal showed that there was no detectable change in system gain during the vibration scan. There were no other observable effects of vibration on system operation during these tests.

A substantial null offset of about 10 percent did occur when the system was moved while changing the vibration from the vertical axis to one of the lateral axes. It was later determined that this offset was caused by contamination in one of the summing networks. This contamination was apparently dislodged during the moving process.

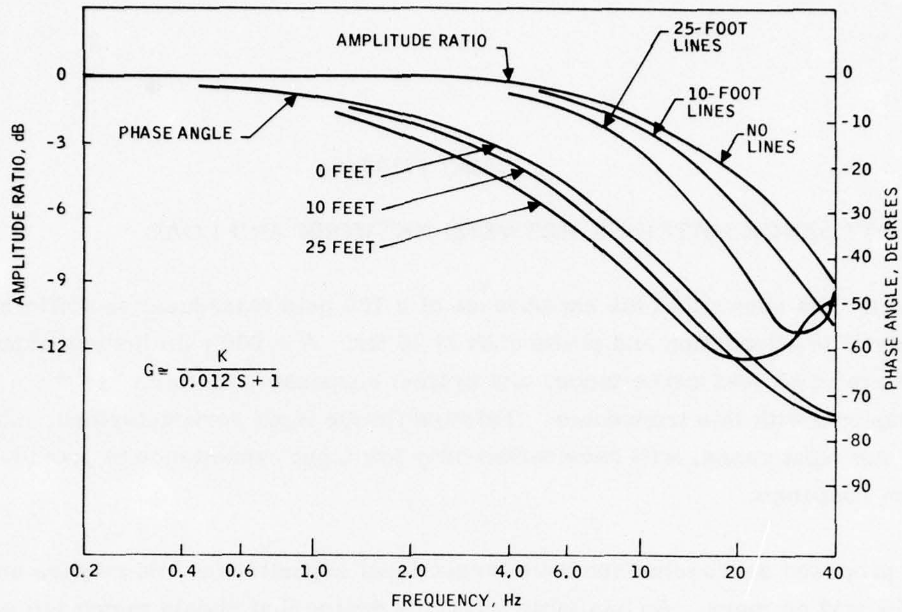


Figure 47. Input Transducer Response at 180°F

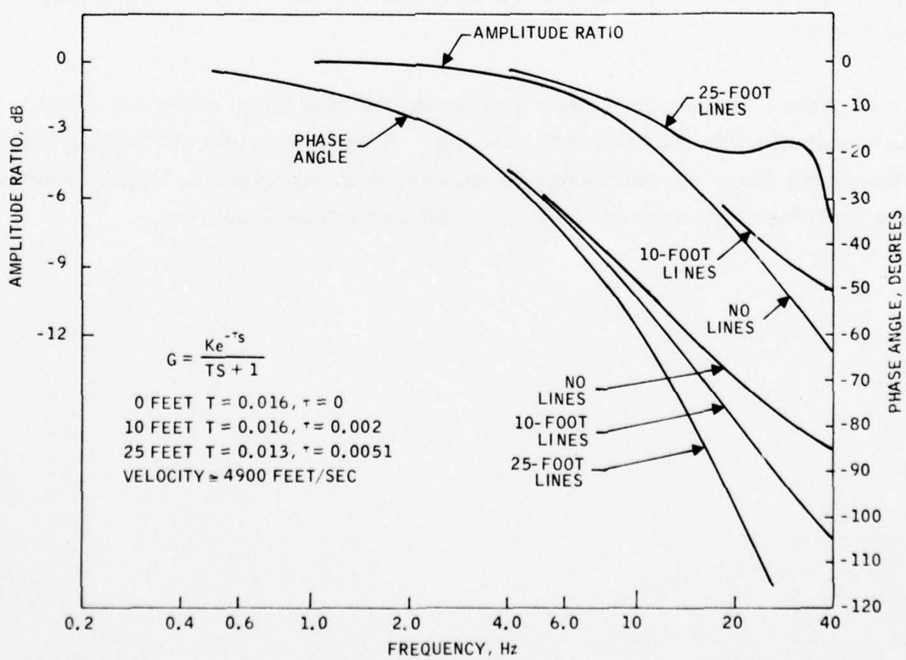


Figure 48. Transmission Line Response at 180°F
(with a 100 PSID Transducer)

10. IMPEDANCE MATCHING BETWEEN NETWORK AND LOAD

Previous data shows that the capacitance of a 100 psid transducer is sufficient to cause considerable attenuation and phase shift at 10 Hz. A 2,000 psid instrumentation transducer has much less capacitance, and system response is better when the network output is measured with this transducer. Existing fluidic input servoactuators, modified for a ±100 psid input range, will have sufficiently low input capacitance to provide reasonable system response.

Some proposed servoactuators have larger input capacitances and require an input signal of ±250 psid or more. An available interface device that should match the summing network to these proposed servoactuators is a simple pressure control spool valve described in Reference 3. This valve, shown schematically in Figure 50 has a pressure gain of about three. The steady state gain characteristics shown in Figure 51 are marginally acceptable for some systems. Hysterisis is high and the valve has considerable breakaway friction. Reduced friction would result in satisfactory steady state characteristics.

Figure 52 shows system frequency response with the spool valve attached. The valve is underdamped with considerable peaking. Response drops off sharply above 8 Hz when the valve stops operating due to excessive spool friction. This interface approach appears satisfactory, but requires some additional development.

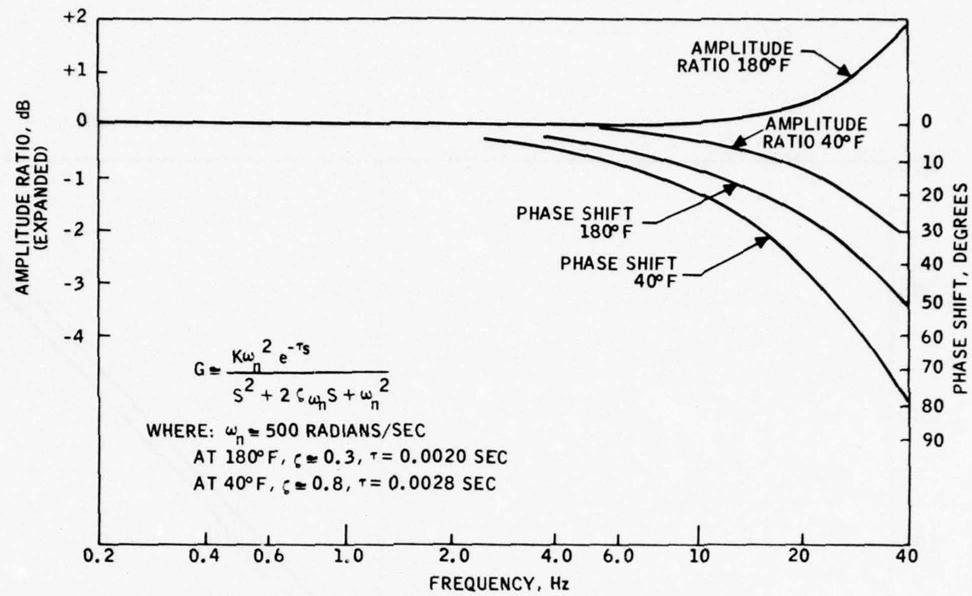


Figure 49. Transmission Line Response with a 2, 000 PSID Instrumentation on Transducer and 10 Foot Lines

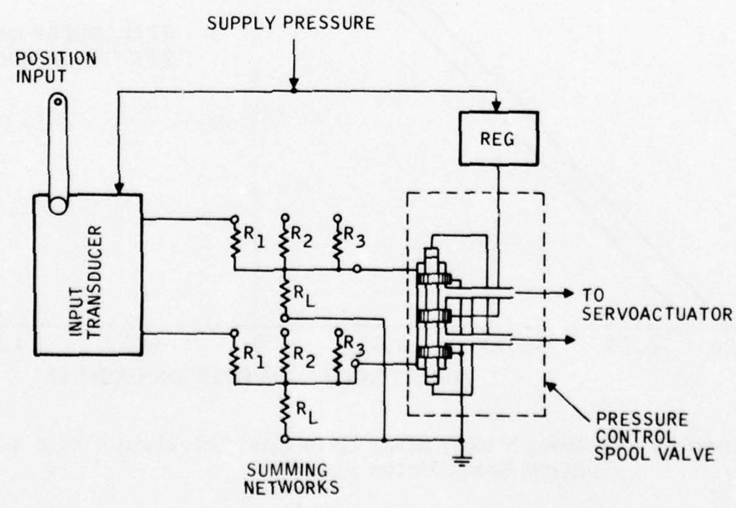


Figure 50. Pressure Control Spool Valve Schematic

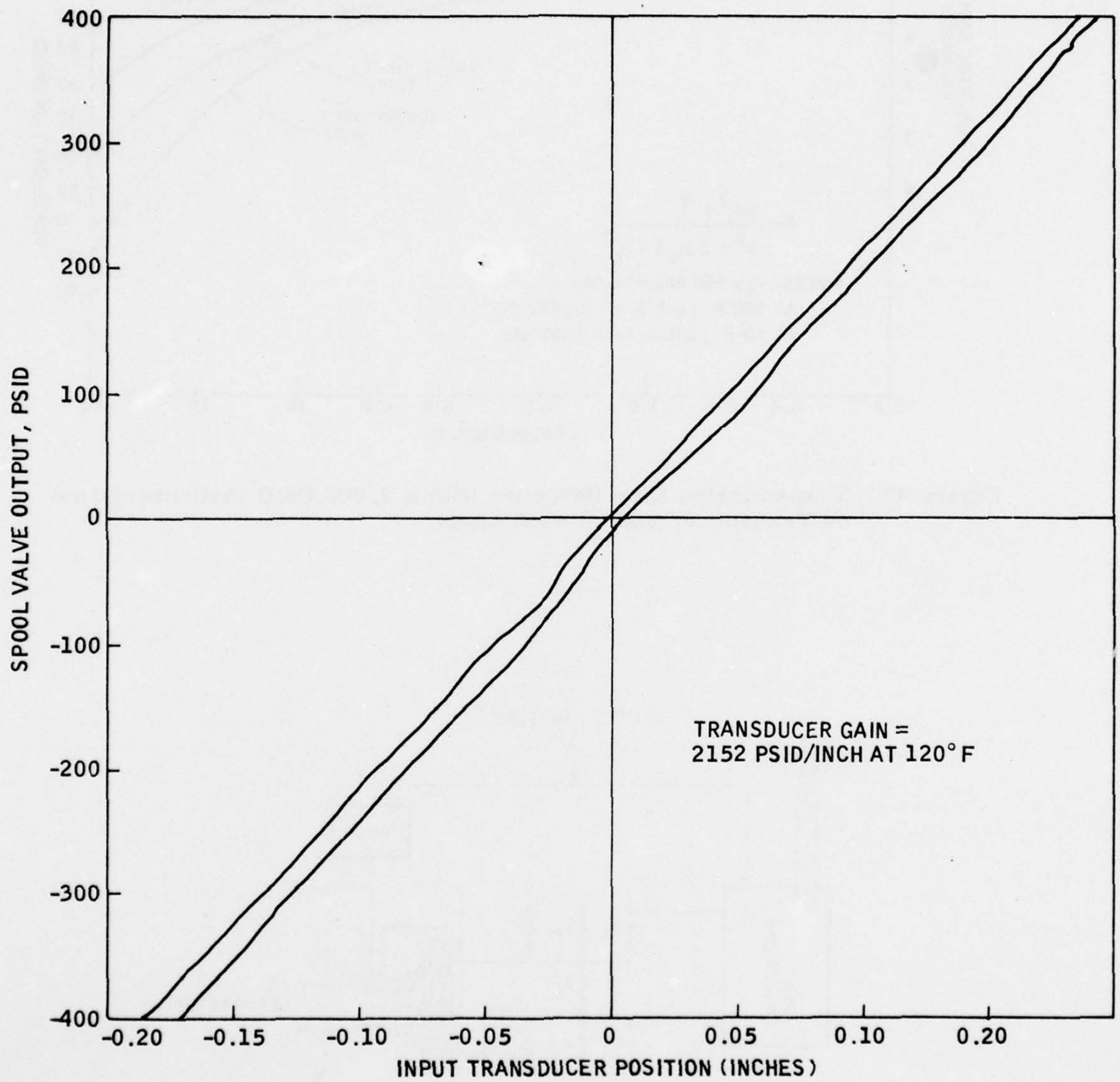


Figure 51. System Steady State Gain Characteristics with a Pressure Control Spool Valve Interface

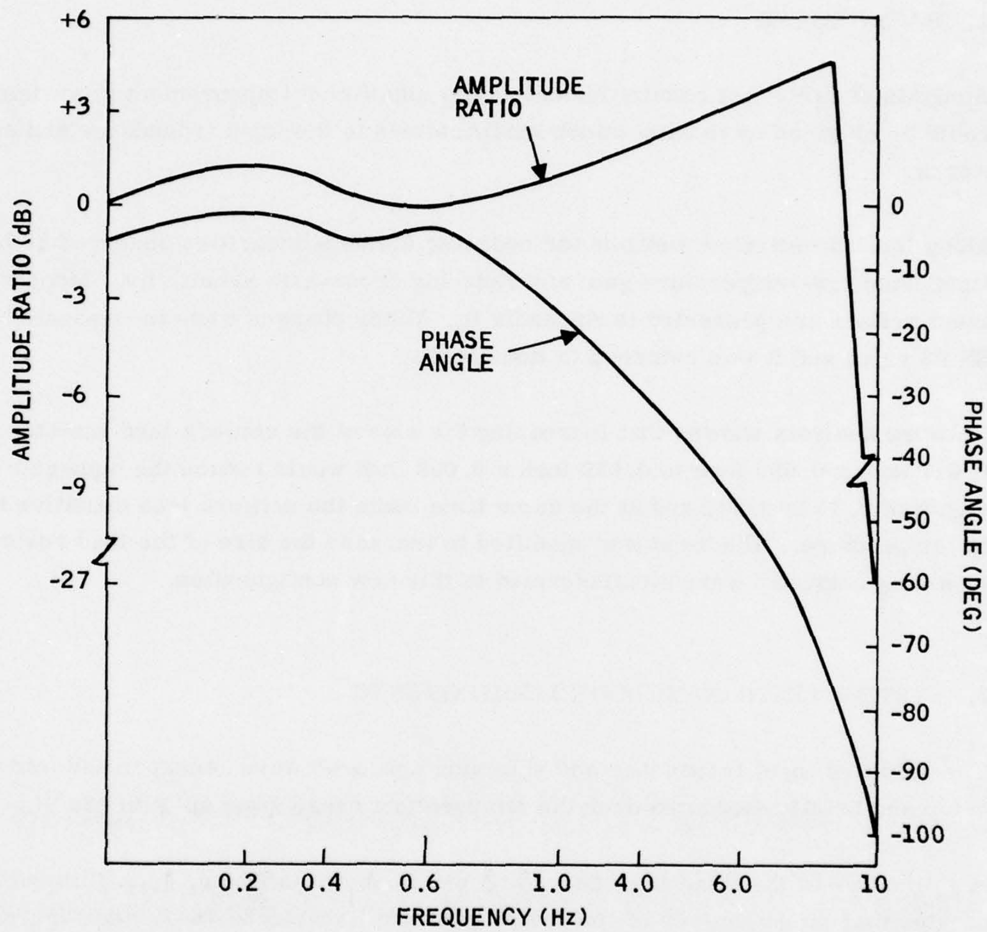


Figure 52. System Response with Pressure Control Spool Valve

SECTION VI
SYSTEM MODIFICATIONS

1. BACKGROUND

Analysis of early test results indicated that significant improvement in system performance could be obtained by making minor modifications to the input transducer and summing networks.

Moog Inc. investigated methods for reducing the non-linearities observed at 76°F, improving low-temperature gain and reducing cross-axis sensitivity. Moog's development results are presented in Appendix B. Minor changes were incorporated into the SN 02 valve and it was returned to Honeywell.

Network analysis showed that increasing the size of the network load resistor from 0.017 inch x 0.008 inch to 0.020 inch x 0.008 inch would reduce the high-gain input from a gain of 0.34 to 0.27, and at the same time make the network less sensitive to changes in temperature. The mold was modified to increase the size of the load resistor and two summing networks were electroformed to this new configuration.

2. SYSTEM TESTS ON MODIFIED COMPONENTS

The modified input transducer and summing networks were incorporated into the test setup and briefly evaluated over the temperature range from 40°F to 180°F.

A gain curve of the input transducer at 75°F is shown in Figure 53. This curve demonstrates that the objectives of improving gain and linearity at 76°F (see Figure 8) were fully met. Gain curves were obtained every 5°F, from 40°F to 100°F, to determine if the non-linear condition had shifted. All curves were nearly identical to that shown in Figure 53, including additional curves taken at 120°F and 180°F. Modifications to the input transducer demonstrated that the non-linearities and low-gain characteristics at cold temperature conditions could be improved to an acceptable level. This additional design iteration did not include any additional effort required to obtain the exact gain of 2,000 psid per inch or to improve the non-linearities at the ends of the curve.

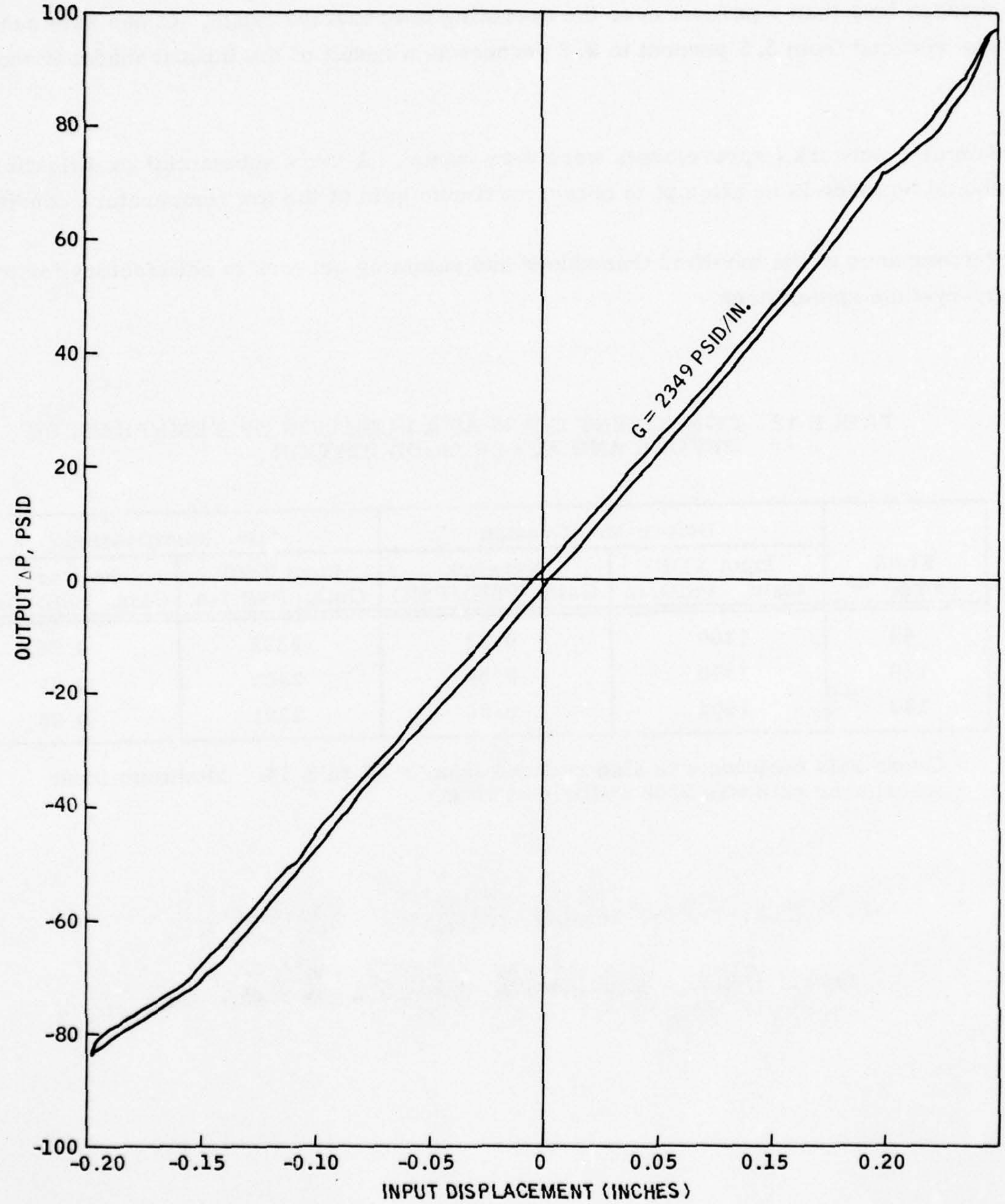


Figure 53. Modified SN 02 Input Transducer Gain Characteristics at 75°F

Table 12 gives the performance results of the input transducer and summing network. Gain of the input transducer, which previously decreased by 30 percent at 40°F, now changes less than 5 percent over the operating temperature range. Cross axis sensitivity was reduced from 3.5 percent to 2.7 percent as a result of the input transducer modifications.

Summing network improvements were very minor. A more substantial modification should be made in an attempt to obtain maximum gain at the low temperature condition.

Performance of the modified transducer and summing network is satisfactory for most fly-by-tube applications.

TABLE 12. COMPONENT GAINS AS A FUNCTION OF TEMPERATURE BEFORE AND AFTER MODIFICATION

Fluid Temp, °F	Before Modification		After Modification*	
	Input TDR Gain, PSID/in	Network Gain, PSID/PSID	Input TDR Gain, PSID/in	Network Gain, PSID/psid
40	1400	0.28	2382	0.26
120	1970	0.34	2409	0.31
180	1902	0.36	2391	0.33

* Cross axis coupling was also reduced from 3.5% to 2.7%. Minimum input transducer gain was 2308 PSID/in at 70°F.

SECTION VII

DEVELOPMENT STATUS OF CRITICAL COMPONENTS FOR FLUIDIC FLY-BY-TUBE SYSTEMS

This section describes the development status of the components shown in Figure 1 and discusses the status of the SAS interface and programmer/scheduler required in some fly-by-tube applications.

1. INPUT TRANSDUCER

Performance of the input transducer developed on this program is consistant with the requirements of a typical fly-by-tube system. Improved performance over the temperature range can be obtained by increasing supply pressure 20 percent and increasing flow by 50 percent or more.

2. SUMMING NETWORKS

Network development is complete. Design constraints can be releaxed somewhat from those used on this program since a linearity of better than 1 percent is not required in most applications.

Minor improvements in the electroforming process and cleaning process will be required for quantity production. Resistor networks as well as manifolds are made of electroformed nickel over a stainless steel baseplate. Substantial weight savings would be realized if a process were developed for electroforming aluminum over an aluminum baseplate.

3. SERVOACTUATOR

The most popular fluidic input servoactuator concept is one that uses force capsules (small bellows) in place of a torque motor to modulate a nozzle-flapper valve. Servoactuators using this concept have been flight tested for more than 25,000 hours in various types of helicopters. All of these servoactuators were designed to have a nominal input range of ±1 psid or ±2 psid. Reducing the effective area of the force capsules by a factor of 50 would make these servoactuators compatible with the output of the fluidic resistor summing networks. This modified servoactuator would be compatible with both flowing and sealed transmission lines. Very little development is required to build a fluidic fly-by-tube system using this type of servoactuator.

Several companies have developed a design concept that eliminates both the force capsules and first stage nozzle flapper valve in order to improve servovalve reliability and reduce costs. In this design the fluidic input signals drive the second stage spool valve directly. Because this concept has a relatively high input capacitance and usually requires an input signal greater than ±100 psid, some type of "amplification" will be required to interface between the fluidic resistor summing network and the direct drive servoactuator input. The direct drive servoactuator is only compatible with flowing transmission lines unless the spool is connected to dead-ended force capsules.

In order to realize the full reliability potential of the direct drive servoactuator, it will be necessary to develop a fluidic interface (rather than a mechanical state-of-the-art interface) between the summing network and servoactuator. Recent investigations indicate that suitable high-pressure, low-noise, fluidic amplifiers can be developed for this application. Development of a fluidic interface will require substantial amplifier development and will involve some design risk.

4. TRANSMISSION LINES

Reference 1 showed that most of the weight of a typical fly-by-tube primary flight control system is associated with the lines and fittings. Servoactuator input capacitance is one of the more important factors that determine the size of tranmission line required to obtain satisfactory system response under a given set of conditions. Sealed transmission lines filled with a low viscosity fluid will be significantly lighter in weight under conditions where the line is long and the required operating temperature is low.

Servoactuator input capacitance usually varies as a function of frequency; it is very low or zero for steady state inputs, and it reaches a maximum at high frequencies where the servoactuator response decreases. Transmission line response testing should be conducted with the system servoactuator connected and operating.

Data defining the performance of a simple transmission line between the input transducer and summing network was obtained over the temperature range from 40°F to 180°F on this program. Parametric data is also needed on transmission lines operating into several types of servoactuators over the temperature range from -65°F to 180°F. Test results can then be used to provide quantitative answers (usually in the form of a weight savings or a weight penalty) relative to the following type of questions for a specific system:

- What are the benefits of reducing servoactuator input capacitance?
- What weight savings would result from the use of sealed transmissions lines and a low viscosity fluid?
- Should the interface amplifier be located on the network end of the transmission line or the servoactuator end?
- What penalty is associated with requirements for a -65°F transmission line as compared with those for a -40°F line?

Parametric data from a comprehensive transmission line system study is necessary early in the development of a prototype fly-by-tube system so that the results can be incorporated into the design requirements for components such as servoactuators and interface amplifiers.

5. FLUID-TO-FLUID INTERFACE

A fluid-to-fluid interface is used only with sealed transmission lines. No development is needed since this approach is now widely used to protect pressure gages and pressure transducers from corrosive fluids.

6. SAS INTERFACE

State-of-the-art technology is capable of producing satisfactory interfaces using the force capsule/nozzle flapper technique. Improved high pressure amplifiers with suitable cascading techniques are required for a fluidic implementation of this interface. Most of the amplifier improvements required for the previously discussed servoactuator interface amplifier can be used directly in the SAS interface. The SAS interface development will be more difficult because it involves pressure level matching between the SAS and the summing network.

7. PROGRAMMER/SCHEDULER

This component, which is required on some V/STOL type aircraft, is a complex gain changer. Simple hydrofluidic gain changers with a gain ratio as high as 5 to 1 have been fabricated. A programmer/scheduler usually requires the gain of each channel to change over an infinite range from zero to a predetermined value. The most difficult task will be to change gain while maintaining system null.

AD-A070 387 HONEYWELL INC ST LOUIS PARK MN AVIONICS DIV F/G 1/3
PROGRAM FOR THE CRITICAL COMPONENTS OF A FLY-BY-TUBE BACKUP FLI--ETC(U)
JAN 79 W M POSINGIES N62269-78-C-0008
UNCLASSIFIED W0471-FR1-PT-1 NADC-77197-60-PT-1 NL

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A design study is required to define programmer requirements and to analytically evaluate the numerous mechanization approaches that have been proposed. This type of program usually also results in the generation of new concepts that have greater potential for providing the required function with a minimum of complexity.

SECTION VIII
CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

Dynamics of a transmission line between the input transducer and summing network is primarily a time delay determined by the effective signal propagation velocity. This velocity is somewhat less than the speed of sound in hydraulic oil but about three or four times as fast as the velocity of sound in air. At 10 Hz this 25-foot hydraulic transmission line will have a phase shift of only 27 degrees as compared to 81 degrees phase shift for an ideal pneumatic transmission line (using air at standard conditions). It is also highly unlikely that any practical pneumatic system can attain this ideal response.

Excellent response of the transmission line between the input transducer and summing network is due to the fact that the terminating impedances are almost purely resistive. These data are not directly applicable to a transmission line between the network and servoactuator where the terminating load is largely capacitive.

Signal lines used in this development (including the 25-foot transmission line) were only 0.125 inch in diameter. This results in a lightweight system. Increased impedance of the 25-foot lines at 40°F resulted in an attenuation of nearly 50 percent. This effect could be reduced somewhat by designing the network to compensate for this change in line impedance. Since line resistance is a function of the fourth power of line diameter, an increase in line diameter to 0.1875 would reduce its resistance by a factor of five.

The requirement for operation with MIL-H-83282 over the temperature range from 40°F to 180°F does not present any significant design problems. Some weight penalty would be associated with the 40°F requirement (equivalent to 10°F with MIL-H-5606) if long transmission lines are used because it will be necessary to increase their diameter from 0.125 to 0.1875 inch. Gain is nearly independent of fluid viscosity in a properly designed network, and null is very stable over the entire temperature operating range. Satisfactory operation could be obtained at colder temperatures, but system weight would increase greatly due to larger hydraulic lines and fittings.

Resistor networks are an ideal method for summing of fluidic signals if a gain as low as 0.25 can be tolerated. Gains as high as 0.50 can be obtained in some applications if a linearity of 5 percent is satisfactory.

The unique configuration of the resistor network orifices was designed to have low noise and a constant pressure recovery (zero). Electroforming is one of the few manufacturing techniques that can be used for fabricating this design. Differences in null offset between networks and changes in null offset with temperature were small, indicating the repeatability of the electroforming process. The uniquely designed resistor elements worked well and did not introduce any discernable additional noise. This good performance does not prove the resistor design to be superior to standard configurations, but it has eliminated problems that were previously encountered when operating several resistors in series.

The deflector jet valve input transducer is very compatible with this fly-by-tube concept. Alternate servovalve concepts could provide comparable performance, but their reliability would probably be lower.

A simple flightworthy fly-by-tube system (one without SAS or a programmer/mixer) can be produced using present state-of-the-art technology. Development work (with some development risk) is required in the areas of fluidic interfaces and a programmer/mixer. Parametric data is required on the performance of various transmission line/servo-actuator combinations.

2. RECOMMENDATIONS

The design approach developed on this program using resistor network summing with large signal levels throughout the system) should be used on all future fly-by-tube systems. In particular, the following actions are recommended:

- Incorporate fly-by-tube backup into future fly-by-wire aircraft. State-of-the-art of fly-by-tube is satisfactory for all applications except those requiring stability augmentation and/or a programmer/gain changer. Additional development will be required in these more complex applications.
- Develop a programmer/gain changer. Selecting the proper concept that provides good null stability and is capable of programming zero gain is an important phase of this development.
- Develop suitable high pressure fluid amplifiers and cascading techniques in order to reduce the weight and improve the reliability of state-of-the-art mechanical interface devices.

- Generate parametric data on transmission lines terminated into various types of servoactuators over the anticipated operating temperature range. This comprehensive study should include both sealed and flowing lines.
- Electroform resistor networks in order to obtain constant null over the operating temperature range. Use electroformed integrated circuits whenever practical in order to reduce the number of lines, fittings, and o-rings.

APPENDIX A
DESIGN CONTROL SPECIFICATION
INPUT TRANSDUCER, VG1005AA01
HONEYWELL INC. AVIONICS DIVISION
DECEMBER 6, 1978

RECORD OF CHANGE

Revision	Date	Description
1	12-06-78	Increase value ΔP to 1000 psig. Add 5 percent gain tolerance.

1.0 SCOPE

This specification describes the requirements for a mechanical input, pressure control servovalve. A secondary electrical input to this valve has an authority equivalent to 25 percent of the primary mechanical input. The valve will provide a differential pressure output signal to an orifice network. Flow through the device will remain nearly constant, and in some concepts all of the supply flow will be delivered to the orifice load.

This specification and Specification Control Drawing No. VG1005AA establish the performance, manufacture, and acceptance test requirements for the input transducer.

2.0 APPLICABLE DOCUMENTS

The following documents and drawings and the applicable specifications referenced therein shall apply to the extend specified herein.

2.1 VG1005AA, Specification Control Drawing

MIL-H-83282: Hydraulic fluid, fire resistant synthetic hydrocarbon base, aircraft

MIL-H-8775C: Hydraulic system components, aircraft and missiles, general specification for

MIL-H-5440F: Hydraulic system, aircraft Type I and II, design installation and data requirement for

MIL-F-8815B: Filter and filter elements, fluid pressure, hydraulic line, 15 micron absolute, Type II systems

MIL-STD-810B: Environmental test methods

3.0 REQUIREMENTS

3.1 Item Definition

The input transducer covered in this specification shall be a valve capable of providing a differential pressure output signal into a fixed orifice load as a function of either a mechanical displacement input or an electrical input signal or both. A typical concept for this valve is shown in Figure A-1.

3.1.1 Item Interface

3.1.1.1 Physical Interface - The valve installation and envelope requirements are defined in Honeywell drawing VG1005AA. (This drawing will be drawn to be compatible with the selected vendor's design approach.)

3.1.1.2 Functional Interface

3.1.1.2.1 System Interface Definition - The valve shall be designed to operate in a hydraulic system per MIL-H-5440, Type II, Class 3000.

3.1.1.2.2 System Pressure

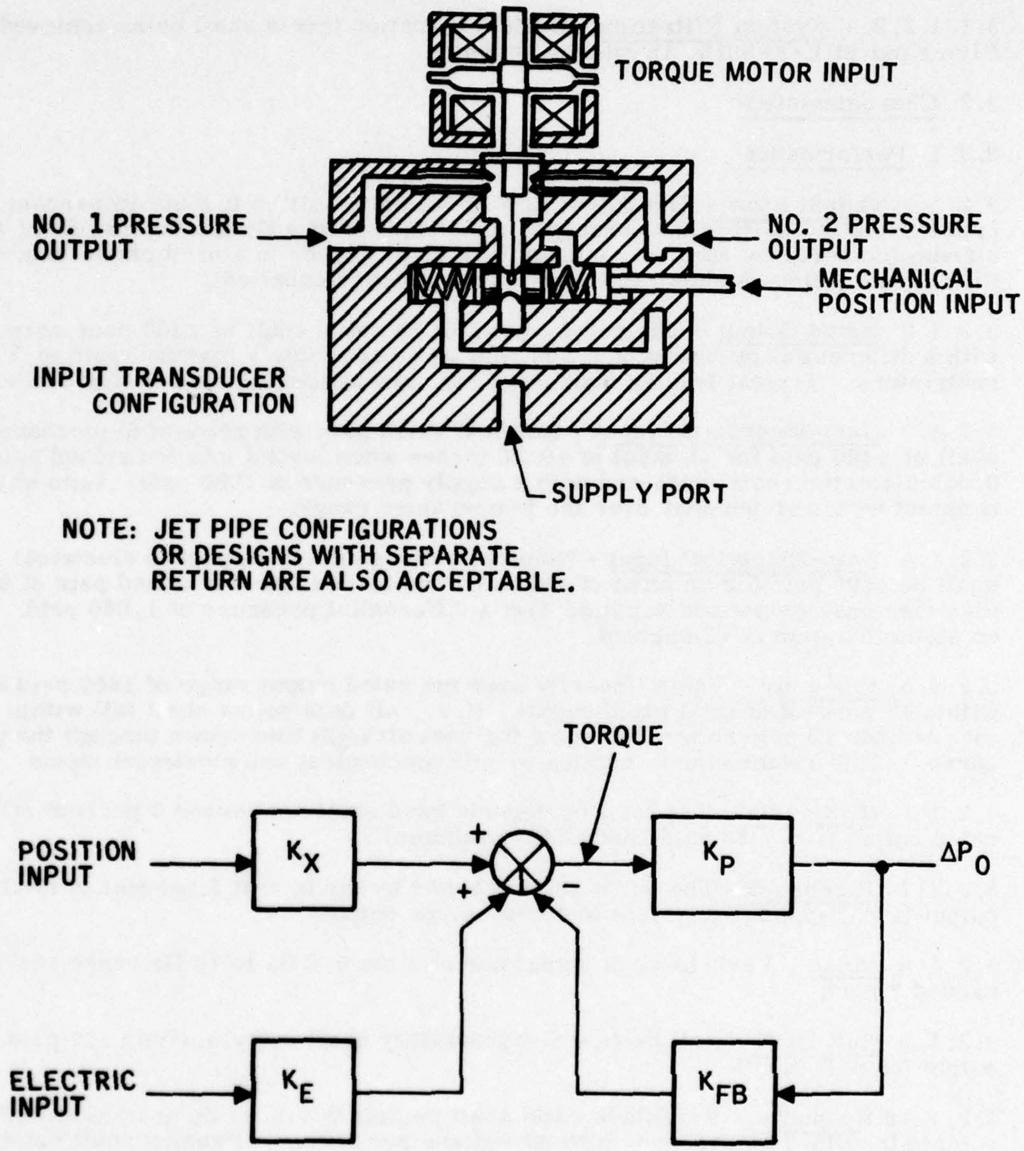


Figure A-1. A Typical Concept for the VG1005AA Input Transducer

3.1.1.2.2.1 Operating Pressure - The normal operating pressure of the unit shall be 2,500 psig at its inlet (supply) and the average of the two outputs (signals) shall be 1500 psig. Valve performance shall be independent of pressure level providing that it has a differential between its supply and outputs of 1000 psid.

3.1.1.2.2.3 Fluids - The unit shall be designed to operate with MIL-H-83282 hydraulic fluid. Maximum required supply flow shall not exceed 1.5 cis.

3.1.1.2.2.4 System Filtration - System filtration levels shall be as achieved by system filters per MIL-F-8815, 15 micron absolute.

3.2 Characteristics

3.2.1 Performance

3.2.1.1 Output Flow - The output flow of the unit shall be 0.8 cis ±5 percent when operating with a differential pressure of 1,000 psid at a fluid temperature of 120°F in a room temperature ambient. Output flow shall change in a predictable manner with fluid temperature as shown in Figure (TBD, vendor supplied).

3.2.1.2 Rated Output - The rated output of the valve shall be ±400 psid when supplied with a differential pressure of 1,000 psid and loaded into a matched pair of 0.015 restrictors. Typical loading conditions for normal operation are defined in Figure A-2.

3.2.1.3 Gain-Mechanical Input - Nominal valve gain with respect to mechanical inputs shall be ±400 psid for an input of ±0.20 inches when loaded into a matched pair of 0.015 diameter restrictors and with a supply pressure of 1000 psid. Gain shall remain constant within ±5 percent over the temperature range.

3.2.1.4 Gain-Electrical Input - Nominal valve gain with respect to electrical inputs shall be ±100 psid for an input of ±30 mA when loaded into a matched pair of 0.015 diameter restrictors and supplied with a differential pressure of 1,000 psid. Tolerance on electrical gain is ±5 percent.

3.2.1.5 Linearity - Valve linearity over the rated output range of ±400 psid shall be within ±2 percent of total rated output. (I.e., all data points shall fall within a band that extends 16 psid above and below the best straight line drawn through the gain curve.) This requirement applies to both mechanical and electrical inputs.

3.2.1.6 Hysterisis - The total hysteresis band shall not exceed 2 percent of total rated output (i.e., 16 psid bandwidth maximum).

3.2.1.7 Threshold - The valve shall respond to inputs of 0.5 percent of total rated output (i.e., inputs equivalent to 4 psid on the output).

3.2.1.8 Noise - Peak-to-peak output noise in the 0.1 Hz to 10 Hz range shall not exceed 8 psid.

3.2.1.9 Null Drift - Null drift and repeatability shall remain within ±32 psid at the output for null inputs.

3.2.1.10 Response - Amplitude ratio shall remain within ±1 db and phase shift shall remain less than 15 degrees up to 30 radians per second. Peaking shall not exceed 1.5 db below 50 radians or 3.0 db above 50 radians.

3.2.1.11 External Leakage - There shall be no evidence of external leakage, other than slight wetting at seals insufficient to form a drop, throughout all operation and environmental tests.

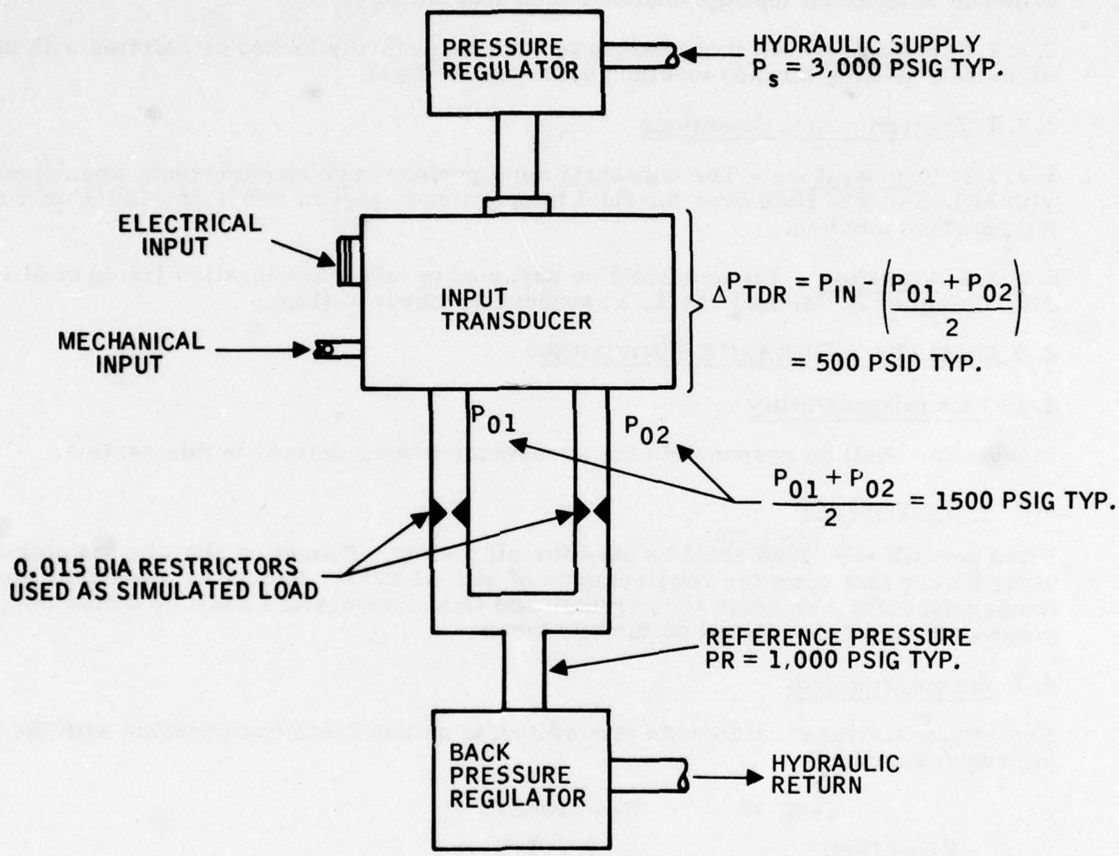


Figure A-2. Typical Loading Conditions for the VG1005AA Input Transducer

3.2.2 Physical Characteristics

3.2.2.1 Weight - The weight of the valve assembly shall not exceed 0.75 pounds.

3.2.2.2 Envelope - The physical envelope of the valve shall be held to a minimum but in no case shall it exceed the dimensions given in Honeywell drawing (TBD).

3.2.2.3 Proof Pressure - The unit shall withstand a proof pressure of 4,500 psid applied for 2 minutes at the inlet port with the output ports plugged. There shall be no evidence of external leakage and/or permanent damage.

3.2.2.4 Safetying - All threaded parts shall be securely locked or safetied with safety wire, self-locking threads or other approved methods.

3.2.3 Environmental Conditions

3.2.3.1 Temperature - The unit shall meet performance requirements when operating with MIL-H-83282 fluid over the fluid temperature range of +40°F to +180°F in a room temperature ambient.

3.2.3.2 Vibration - The unit shall be designed to meet the vibration levels of MIL-STD-810, Category A. Method 514.1, Procedure 1, Curve Z (10g).

4.0 QUALITY ASSURANCE PROVISIONS

4.1 Test Responsibility

The vendor shall be responsible for acceptance testing defined in this section.

4.2 Test Conditions

Fluid per MIL-H-83282 shall be used for all testing. Filtration shall be maintained using filters that meet the requirements of MIL-H-8775. Except as specified, ambient temperature shall be room temperature and fluid temperature shall be within temperature ranges normally maintained on the test bench.

4.3 Acceptance Test

Acceptance testing shall include procedures to demonstrate conformance with the following requirements:

Test	Requirement
Rated flow	3.2.1.1
Rated output	3.2.1.2
Gain-mechanical input	3.2.1.3
Gain-electrical input	3.2.1.4
Linearity	3.2.1.5
Hysterisis	3.2.1.6
Threshold	3.2.1.7
Noise	3.2.1.8
Null drift	3.2.1.9
Response	3.2.1.10
External leakage	3.2.1.11
Proof pressure	3.2.2.3

APPENDIX B

FINAL REPORT
INPUT TRANSDUCER, VG1005AA01
DEVELOPMENT FOR
HONEYWELL INC.
AVIONICS DIVISION
BY
MOOG INC.

December 7, 1978

DESCRIPTION

The Input Transducer (herein referred to as valve) developed for Honeywell Inc., Avionics Division, is basically a three port, single stage, single inlet Deflector Jet, pressure control valve. Two input modes are provided for, a mechanical input via a rotary lever having full authority, and an electrical input via the torque motor coils having one quarter authority. The valve flow is divided in greater or lesser proportion between the valve output ports C_1 and C_2. The only other port is the valve supply port P_S. In order to function, the valve must supply a nearly constant flow (the sum of C_1 and C_2) to two orifice-like load impedances which ultimately flow to return. A schematic showing the test circuit is attached and labeled Figure B-1.

OPERATION

With reference to the attached servovalve assembly labeled Figure B-2, the following is a description of the internal workings of the valve. Assuming lever A is displaced to the left or CCW, rocker arm B is also displaced CCW since it is rigidly fastened to A. This compresses the left input spring C and allows the right input spring C to extend. The resulting torque rotates the armature-flexure assembly through an angle sufficient to create torque balance with the input springs, retained flexure stiffness, and the feed-back wire E. The amplifier flowguide (not shown) rotates through the same angle as the armature about the effective center of rotation of the flexure and is displaced to the right in the D. J. amplifier F. This diverts the jet to the receiver connected to chamber G which supplies flow to port C_1, and away from the receiver which supplies port C_2 through chamber H. A differential back pressure is then developed as a result of the difference in flow through the load orifices. In response to the differential pressure across piston I, the piston seeks a new position for force balance against the centering springs by moving to the right. Since the feedback wire E is connected to the piston, the flowguide is moved toward null and a balance is created between output differential pressure and input torque; thus tending to make output differential pressure a linear function of input torque.

The operation of the valve is the same for an electrical input except that the armature torque is created magnetically via current in the torque motor drive coil.

The valve functions as a Type O servo because it contains no free integrators. A block diagram model of the valve is attached, and is labeled Figure B-3.

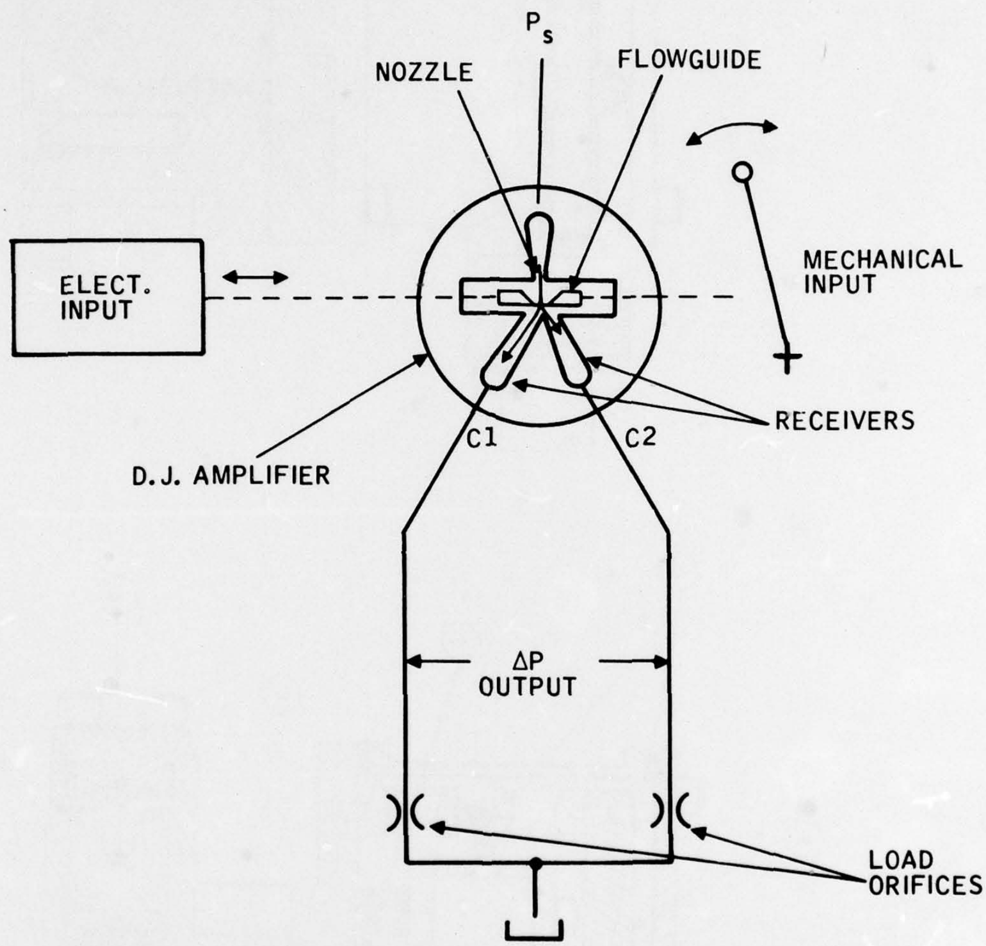


Figure B-1. Valve Test Schematic (Feedback not Shown)

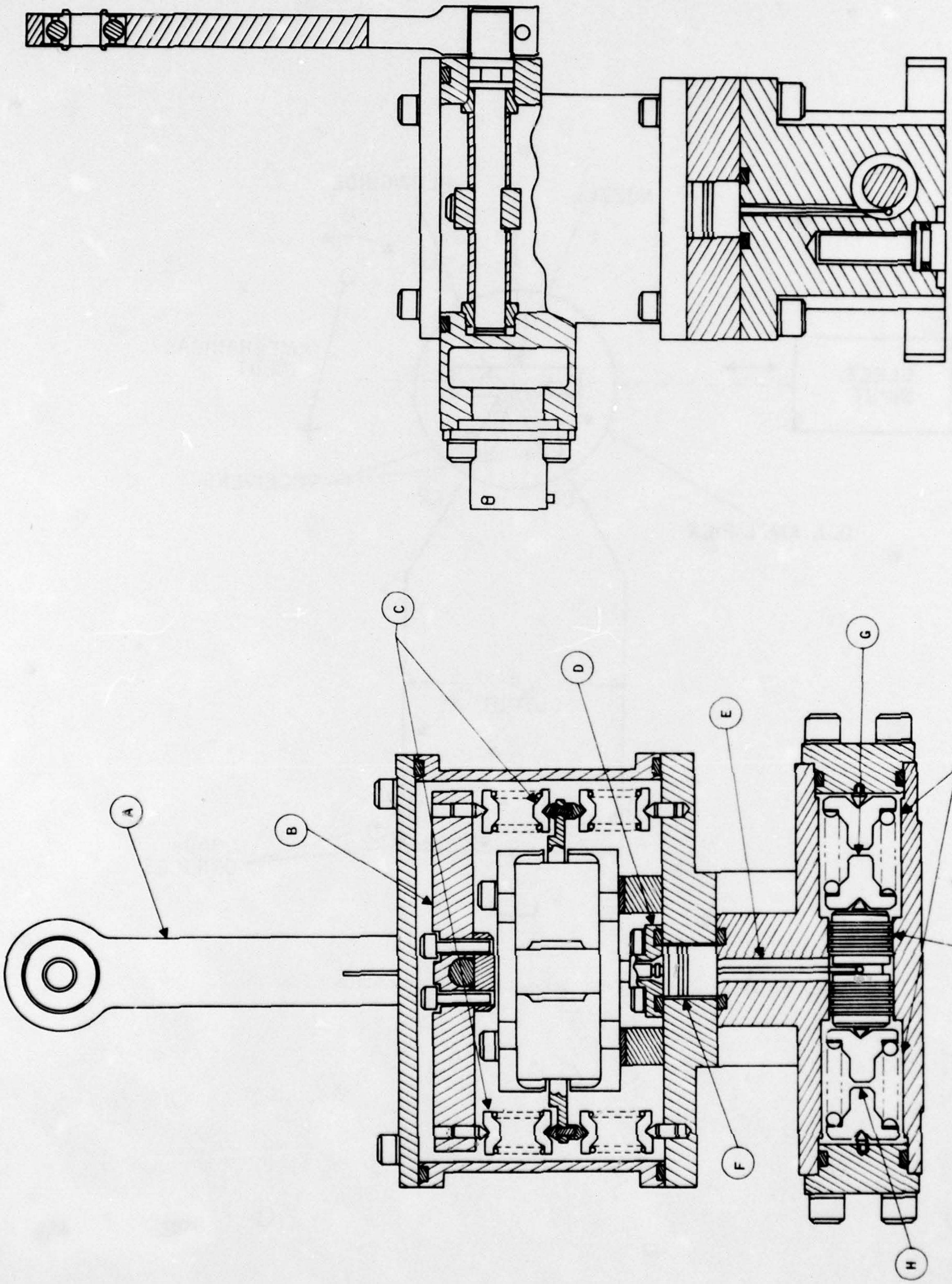
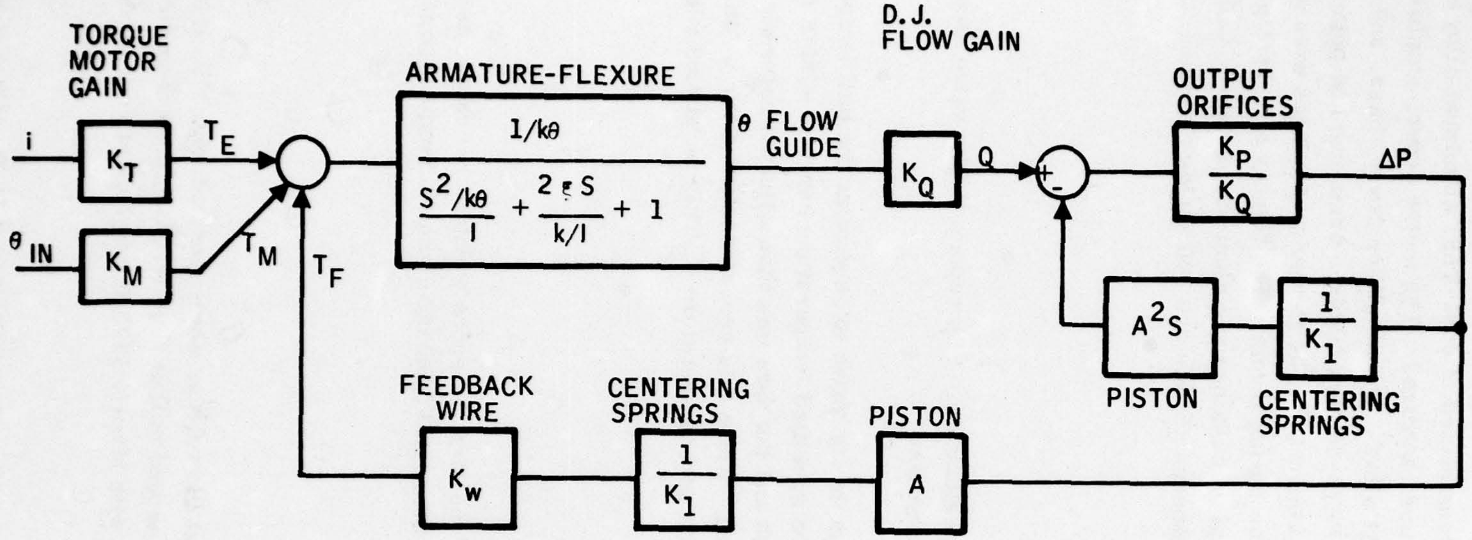


Figure B-2. Valve Assembly



SIMPLIFIED TRANSFER FUNCTIONS (NO ARMATURE FLEXURE DYNAMICS)

$$\frac{\Delta P(s)}{i(s)} = \frac{K_T \dfrac{K_Q}{k_\theta} \dfrac{K_P}{K_Q}}{\left(1 + K_w \dfrac{A}{K_1} \dfrac{K_Q}{k_\theta} \dfrac{K_P}{K_Q}\right) + \dfrac{K_P}{K_Q} \dfrac{A^2S}{K_1}} \qquad \text{ELECTRICAL INPUT}$$

$$\frac{\Delta P(s)}{\theta_{IN}(s)} = \frac{K_m \dfrac{K_Q}{k_\theta} \dfrac{K_P}{K_Q}}{\left(1 + K_w \dfrac{A}{K_1} \dfrac{K_Q}{k_\theta} \dfrac{K_P}{K_Q}\right) + \dfrac{K_P}{K_Q} \dfrac{A^2S}{K_1}} \qquad \text{MECHANICAL INPUT}$$

Figure B-3. Valve Block Diagram

MATERIALS

The valve body and feedback piston are constructed of 6061-T651 aluminum alloy with the piston and piston bore wearing surfaces hard anodized. The motor cover, amplifier body, and rocker arm are also 6061-T651 alloy. The amplifier cover, base, and segment are of stellite 6B. The flexure is PH13-8Mo stainless. Armature and polepieces are 4750 electrical alloy. Magnets are Alnico VI. The flowguide-feedback wire and spring seats are 440C stainless as are the spring pivots. The flapper and input pivot shaft are 17-4 PH stainless. The input pivot bushings are aluminum bronze. Coil springs are 17-7 PH stainless. Miscellaneous screws are 300 series stainless. All O-rings seals are Buna-N.

MOOG TEST RESULTS

The A. T. P. data sheet for valve S/N2 is attached to this report.* The valve tested within A. T. P. limits in all areas except weight.

In addition to the A. T. P., a test was run on one valve to determine the null temperature-flow characteristics of the valve over the specified temperature range of +180°F to +40°F. Testing was performed with MIL-H-5606 and the data was then adjusted using viscosity and density corrections for MIL-H-83282. From this corrected data a curve (attached) was plotted and is labeled "flow variation with temperature." This is labeled Figure B-4.

MOOG TEST CONCLUSIONS

The 56E187 valve concept is capable of meeting the specs which were tested, as set forth in Honeywell Design Control Specification VG1005AA01 and subsequent amendments agreed to by Moog and Honeywell.

HONEYWELL TESTS

Later testing at Honeywell revealed that the valves, when operated with MIL-H-83282 fluid, exhibit a marked gain reduction around null at fluid temperatures near 70°F. Development testing at Moog was done with MIL-H-5606 due to lack of an available

*Gain curves and frequency response plots supplied with this A. T. P. data are not included in this appendix. These curves are nearly identical to those included in the main body of this report.

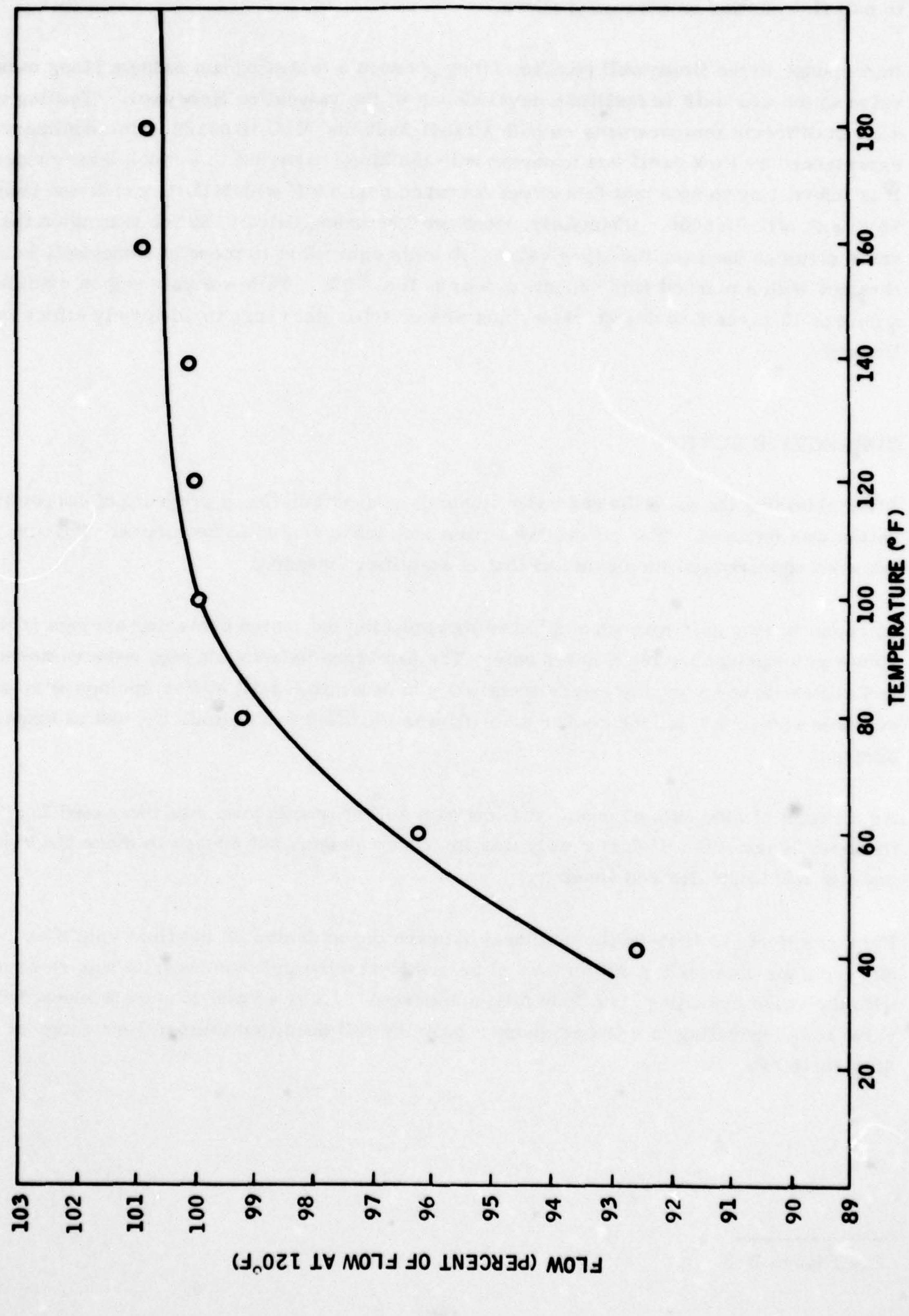


Figure B-4. Flow Variation with Temperature (56E187--Null Input)

MIL-H-83282 test facility at the time. Also reduced temperature testing was limited to null flow testing as discussed above.

In response to the Honeywell results, Moog pursued a test program using a Moog owned valve which was built to facilitate development of the valves for Honeywell. Testing was done at different temperatures on both MIL-H-5606 and MIL-H-83282. The nonlinearity experienced by Honeywell was apparent with the Moog valve but to a much lesser extent. It is interesting to note that this effect occurred near 65°F with MIL-H-83282 and near 35°F with MIL-H-5606. Ultimately, Honeywell returned valve S/N2 for testing on the same setup as used for the Moog valve. Results equivalent to those at Honeywell were obtained with a marked gain reduction near null at 70°F. This low gain region exhibited a gain of 15 percent of design value, and was of sufficient range to adversely effect valve linearity.

CORRECTIVE ACTION

After obtaining the as delivered valve linearity characteristic, a program of corrective action was initiated. The corrective action was concentrated in two areas. That is, the area of increased loop gain and that of amplifier linearity.

Increase in loop gain was accomplished by replacing the piston centering springs (J)* above with springs having a lower rate. The armature balance springs were removed and stiffer input springs (C) were installed. In order to install stiffer springs with acceptable stress levels, the rocker arm (B) was modified to facilitate the use of longer springs.

As a result of loop gain changes, the low gain null characteristic was increased in gain by about 90 percent. Unfortunately this improvement was not enough to make the valve operate within the desired linearity.

Further efforts to remove the nonlinearity were concentrated on the fluid amplifier. By adjusting the flowguide position toward the receivers the null nonlinearity was removed with the valve operating open loop (piston blocked). Later closed loop tests showed the valve to be operating in a linear manner over the full specified temperature range of 40°F to 180°F.

*See Figure B-2.

Some decrease in overall valve flow was observed as a result of moving the flowguide, but this could be remedied by using a slightly thicker amplifier segment if necessary. At this point, the valve was returned to Honeywell for further testing.

DISCUSSION

Some thought has been given to the source of the above nonlinearity with at least one hypothesis offered as to the reason for the phenomenon. Since the amplifier is operating near the laminar-turbulent transition flow region (Jet Reynolds number of approximately 2000), it is possible that the turbulent to laminar flow transition is occurring at approximately 70°F since the viscosity of 83282 increases with decreasing temperature. The velocity profile spreading rate of a free jet inturbulent flow decreases with decreasing Reynolds number while laminar jet velocity profile spreading rate increases with decreasing Reynolds number. This would result in minimum jet effective width at transition. If the slot in the flowguide were wider than the jet at this point, a sharply defined low gain region such as the one observed would occur and it would diminish for higher or lower temperatures as was observed.

With reference to the increased loop gain achieved, it should be noted that this is also desirable beyond the effect on linearity. Although not part of the valve spec, Honeywell has discovered that an increase in valve loop gain, and consequential improvement in load regulation, are beneficial in decreasing crosstalk among inputs in their systems. Further increases are possible here and this will be discussed under Recommendations.

Honeywell has also found that an increase in valve flow would be desirable for other system requirements. This is not considered to be difficult to achieve since it will generally cause the valve to operate at a higher Reynolds number due to an increase in area divided by wetted perimeter length. Recommendations on this subject will also be discussed below.

RECOMMENDATIONS

The two development units manufactured by Moog were intended to be used for non-flight development use only. Because of project time constraints, both units were shipped without input rocker arm stops and could possibly be operated at a deflection which would yield an inadequate fatigue life. Also the piston centering springs were not shot peened as was intended again possibly resulting in inadequate fatigue life. Honeywell was informed of this when the valves were shipped. Should extended testing life be anticipated, the valves should be returned in order to correct the above items.

With regard to the temperature induced nonlinearity, Moog is confident that this type of valve can be built to operate under specified conditions without problems. In order to achieve this, the valves would possibly be built with narrower flowguide slots. Also 100 percent linearity testing with MIL-H-83282 over the full temperature range of 40°F to 180°F would be implemented until sufficient confidence was developed that the problem was solved.

Should greater load regulation than that attained with S/N2 be required, redesign would be required. The design could consist of a proprietary Moog flowguide-feedback wire design to allow greater feedback authority. This approach would doubtless add cost to the valve manufacture. Another possible approach would be to add a return to the D. J. amplifier to allow the nozzle to operate at a higher Δp. This could be done with a minimum of added manufacturing cost.

Finally, should the valve application require higher flow, this could be accomplished with no additional cost by incorporating a thicker segment. However, the flow tolerance of ±5 percent for the valve is difficult and expensive to meet because normal manufacturing variations result in flow variations larger than ±5 percent. This requires selection of amplifier segments for the required flow characteristics. It is suggested that the flow tolerance be fixed at ±10 percent.

ACCEPTANCE TEST DATA

MOOG MODEL 56E187 S/N 2

Test Fluid	MIL-H-5606
Fluid Temperature	100 ±20°F
Supply Pressure	2500 psig
Centering Output Pressure	1500 psig
Back Pressure on Orifices (≈ 1000 psig)	1010

PROOF PRESSURE 3.2.2.3

(4500 psi for 2 minutes) verify no damage or leakage — OK

Polarity C1 high (Pin A(+) Pin D(-) Pins B and C common.) — OK

Polarity C1 high - input lever displaced CW (viewed from lever side of valve) — OK

GAIN

ELECTRICAL 3.2.1.4

Energize with -30 ma record ΔP output (-100 psi) — 89 psid

Energize with +30 ma record ΔP output (+100 psi) — 96 psid

GAIN MECHANICAL 3.2.1.3

Displace input lever .2 inches CCW note ΔP output (-400 psi) — 390 psid

Displace input lever .2 inches CW note ΔP output (+400 psi) — 395 psid

OUTPUT FLOW 3.2.1.1

With electrical input 0 and mechanical input centered note total flow through valve with ΔP across the valve at 1000 psi (.8 cis ±.04 cis) — .79 cis

RATED OUTPUT 3.2.1.2

Verify max. output > ±400 psi — OK

LINEARITY 3.2.1.5

Plot input vs ΔP for mechanical input range +.2 to -.2 inches output plot must fall in linear band 32 psid wide. Attach Plot — OK

Same for electrical input ±30 ma. Attach Plot — OK

HYSTERESIS 3.2.1.6

Hysteresis must be < 16 psi at any point. From Linearity Plots — Mech. 5.0 psi; Elect. 1.5 psi

THRESHOLD 3.2.1.7	
With valve at null apply D.C. input of +1.2 ma verifying that change in output can be observed	OK
With valve at null apply mechanical input of .002 inches verify observable change in output	OK
NOISE 3.2.1.8	
With valve at null observe Kronhite filtered ΔP output <8 psi peak to peak .1 Hz <W <10 Hz	OK
NULL DRIFT 3.2.1.9	
Run null bias loop with mechanical input.	+.6 psi
Allow valve to function with 0 input for 15 minutes. Run null bias loop. Note null bias (< ±32 psid)	+.9 psi
Lower P_S to 1500 psig. Run null bias loop. Note null bias (< ±32 psid)	+5.2 psi
RESPONSE 3.2.1.10	
Electrical	
Bafco plot of input current and output ΔP A.R., phase shift .1 Hz to 50 Hz (current 40 ma p-p)	
peak below 8 Hz <1.5 db	None
peak above 8 Hz <3.0 db	None
A.R. below 4.77 Hz < ±1 db	0 to -.9 db
phase below 4.77 Hz < 15° lag	14.0°
ATTACH PLOT	
Mechanical	
Same as above for (.100 inch p-p)	
peak below 8 Hz <1.5 db	+.1 db
peak above 8 Hz <3.0 db	None
A.R. below 4.77 Hz < ±1 db	+.1 db to -.3 db
phase below 4.77 Hz < 15° lag	13.5°
ATTACH PLOT	
EXTERNAL LEAKAGE 3.2.1.11	
Observe for external leakage, none visible	OK
COIL RESISTANCE	Pins A to C 104.4 Ω
INSULATION RESISTANCE	Pins B to D 103.1 Ω
At 500 VDC pins to case > 50 megohms	70,000 meg Ω
WEIGHT (lbs)	.926 lbs
421 grams	

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