m

NASA CR-54005
GE No. 63GL134

FEASIBILITY STUDY - APPLICATION OF FLUID AMPLIFIERS TO REACTOR ROD CONTROL

by W. A. Boothe

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-2567

Advanced Technology Laboratories
GENERAL ELECTRIC

RQ1-45848

Requests for copies of this report should be referred to

National Aeronautics and Space Administration
Office of Scientific and Technical Information
Attention: AFSS-A
Washington, D.C. 20546

NASA CR-54005
GE No. 63GL134

FINAL REPORT

FEASIBILITY STUDY - APPLICATION OF FLUID AMPLIFIERS TO REACTOR ROD CONTROL

by W. A. Boothe

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-2567

Reprinted from GE Report 63GL134, October 24, 1963
(Revised November 25, 1963)

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
Nuclear Rocket Technology Office
Vernon D. Gebben

Advanced Technology Laboratories
GENERAL ELECTRIC

Feasibility Study - Application of Fluid Amplifiers to Reactor Rod Control

by W. A. Boothe

Abstract

The study shows that it is feasible to use fluid amplifiers to replace the electronic portions of electropneumatic drives for reactor rod control systems under development. The fluid amplifiers and associated circuit elements are reasonable in size and gas consumption.

Several methods of controlling power flow to the actuator were considered, including one vortex valve circuit with no moving parts. Indications are that this will have low efficiency. A simplified version of the present single stage electropneumatic valve is recommended for adaptation to fluid amplifier operation.

PRECEDING PAGE BLANK NOT FILMED.

TABLE OF CONTENTS

1.0 INTRODUCTION

Fluid amplifiers with no moving parts present a real opportunity for increasing reliability of control systems that must operate in high temperature, high radiation environments. Rod controls for nuclear reactors must operate in such environments and must have extreme reliability. This report consists of a study of the feasibility of applying fluid amplifiers (or Fluid Transistors) to a gas cooled reactor rod control.

The system under study is defined in Exhibit 1.1. It is assumed that a pneumatic position command signal is available as the input. This may be generated by an electrical signal driving an electropneumatic valve (as shown) or by other means. The output is gas flow to the rod actuator. The objective of this study is to devise feasible fluid circuitry to perform the control functions required to complete a stable rod position servo loop. The circuitry must contain a minimum number of moving parts, if any.

This study was sponsored by the Lewis Laboratories of NASA under Contract NAS 3-2567, and was performed by the Advanced Technology Laboratories and the Aircraft Accessory Turbine Department of the General Electric Company.

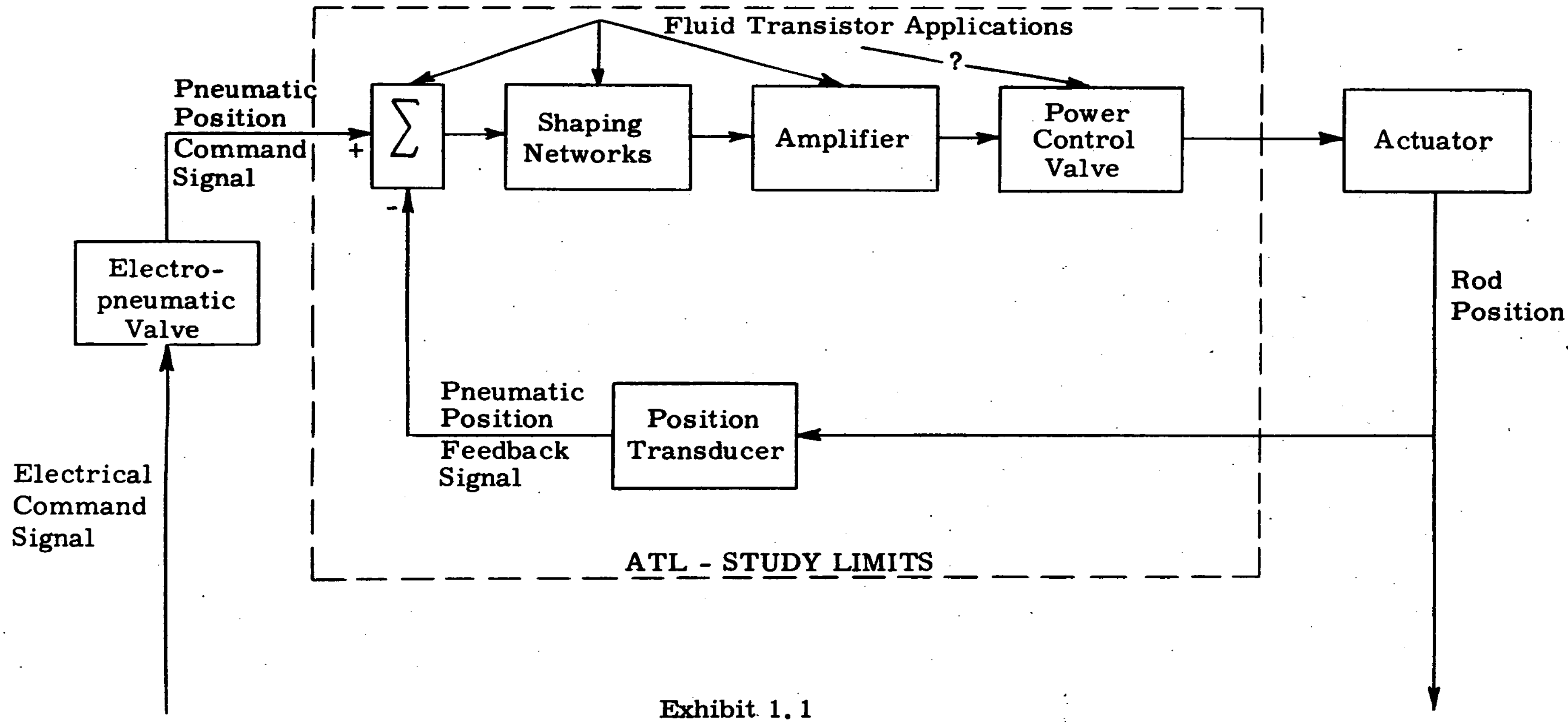


Exhibit 1.1

Gas Cooled Reactor Rod Control
NASA - Lewis Labs

2.0 SUMMARY AND CONCLUSIONS

The study showed that it is feasible to use fluid amplifier circuits to replace the electronic portions of electropneumatic drives for reactor rod control systems under development. The amplifiers and associated circuit elements are reasonable in size and gas consumption.

Several methods for controlling the power flow to the actuator were considered. The most practical one for reliability potential with efficiency involves a simplified version of the present single stage electropneumatic valve. The torque motors would be replaced by low pressure driving bellows controlled by fluid amplifiers. The high pressure feedback bellows would be eliminated. This system is described in detail in Sections 2.4 and 6.0.

It is possible to build a system entirely without moving parts (except for the actuator) using vortex amplifiers. Preliminary analysis indicates, however, that efficiency will be very poor and the size of the actuator would have to be increased appreciably. Much more information on the characteristics of vortex amplifiers operated on high pressure gas is needed, however, before a final conclusion can be definitely drawn. This approach is discussed in Sections 2.3 and 8.0. Sections 2.5 and 7.0 discuss the use of a two stage power valve which does not appear to be a good approach for reliability, but would reduce gas consumption.

The following paragraphs of this Section summarize the detailed findings of each portion of the study and point out areas where additional investigations appear necessary. The Appendices include circuit approaches which were considered and rejected. Appendix C defines the symbols used in this report.

2.1 Shaping Networks

Fluid amplifier techniques can replace present electronic methods both for generating the position error signal and providing the necessary signal shaping for loop stability. Techniques for generating the position error signal are straightforward, as shown in Exhibit 2.1. The necessary shaping networks are a lag-lead and a lead (or lead-lag). Exhibit 2.2 shows the recommended lag-lead network for providing a high d.c loop gain. For the recommended amplifier sizes and pressures, the pneumatic capacitances C_1, will consist of 44.9 in^3 volumes. Exhibit 2.3 shows the recommended lead-lag network for providing the necessary stability of the closed loop. C_2 here is a 0.692 in^3 volume.

Both of these shaping circuits are push-pull in nature and incorporate no orifices or restrictions other than the nozzles of the fluid amplifiers. It is felt that this provides greater linearity and will result in less sensitivity to compressibility effects. The pressure levels to be used in the shaping networks will be governed by the type of power control valve and will be discussed in the ensuing sections. It is recommended that .010" x .010" power nozzles be used in final design amplifiers in order to minimize flow requirements to the fluid amplifiers.

2.2 Combined Circuit Using Present Single Stage Power Valve

The present single stage power valve is a flapper-nozzle type with built-in bellows feedback for providing the lag-lead characteristic.. As a result, the required stabilizing network is simply the lead-lag. The stabilizing network and power valve configuration are shown in Exhibit 2.4. Assuming a return pressure of 50 psia, the supply pressure to the lead-lag stages will be 60 psia. Supply to the final fluid amplifier stage will be 70 psia. The estimated total flow demand of the fluid amplifiers is .0013 lbs/sec compared to the .0055 lbs/sec maximum continuous flow demand of the power valve itself.

2.3 Combined Circuit Using Vortex Type Power Valves

It is possible to combine vortex valves into a bridge circuit to obtain push-pull operation. Exhibit 2.5 shows the preferred arrangement of such a circuit, as well as the necessary stabilizing networks. In this case, both the lag-lead and the lead-lag are used. At the time of writing, analytical techniques are not satisfactory for predicting high pressure gas operation of vortex valves. As a result, flow and pressure requirements cannot be specified. However, to obtain at least a rough figure of merit for such a system, an analysis was conducted on an incompressible flow basis. This showed that control pressures to the vortex valve should be considerably higher than the output load pressures. One method of meeting this requirement would be to provide a small, separate high-pressure supply for the control and a larger, low pressure supply for the power valves. The alternative is to use the same supply for both, and to accept the lower efficiencies in the vortex valves that will result. The incompressible flow analysis shows that the latter case would call for an actuator having 6.7 times the effective area presently used if the same force levels are to be produced. This is because the output pressure swing of the vortex valve bridge will not exceed 35 to 40% of the bridge supply pressure. Quiescent leakage flow of the power valves was not predicted but will undoubtedly be high due to the open center nature of the valving. Since the shaping networks must operate at high pressure (assumed to be 215 psia), a flow of at least .0026 lbs/sec will be needed in the control stages alone. The reliability of such a circuit is high, since there are no moving parts. As a result, the expected flow penalties may be offset by the added reliability. Further work is needed to more accurately evaluate these trade-offs.

2.4 Combined Circuit Using Simplified Single Stage Power Valve

The single-stage power valve currently being developed for reactor rod control can be simplified by removing the built-in lag-lead. This results in fewer moving parts due to removal of the bellows and restrictors used for obtaining this function. Exhibit 2.6 shows the simplified power valve configuration. The fluid amplifier logic must provide both a lag-lead and lead-lag function. The system will be of the configuration shown in Exhibit 2.7. The supply pressure level of this logic will be 60 psia for the shaping networks and 70 psia for the driver stage. The resulting fluid amplifier flow is estimated to be .00147 lbs/sec compared to the .0055 lbs/sec leakage flow of the power valve. It is felt that this system offers reliability second only to that of the vortex system, and will be considerably more efficient.

2.5 Combined Circuit Using Two-Stage Power Valve

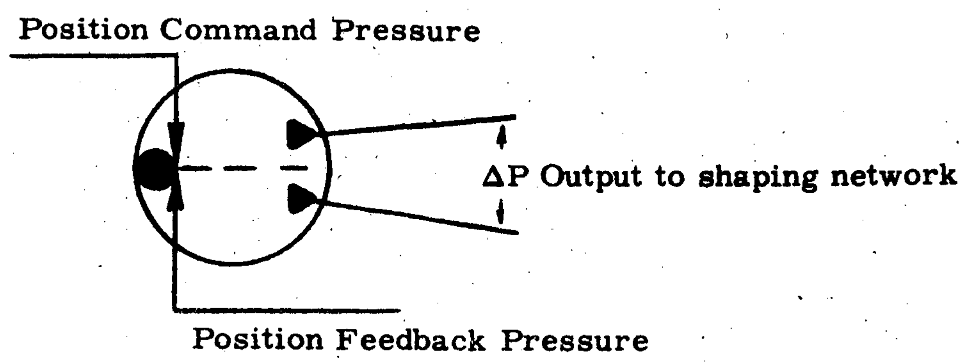
The system of Exhibit 2.8 is of interest due to the low leakage of the two-stage power valve. The fluid logic will again be of the type in Exhibit 2.7 which provides both the lag-lead and lead-lag compensation. In this case, the logic must operate at full system pressure and is estimated to require .0056 lbs/sec flow. The net decrease in system leakage flow is small, as a result, and does not seem to merit the added complexity of a two-stage valve.

2.6 Areas Requiring Additional Investigation

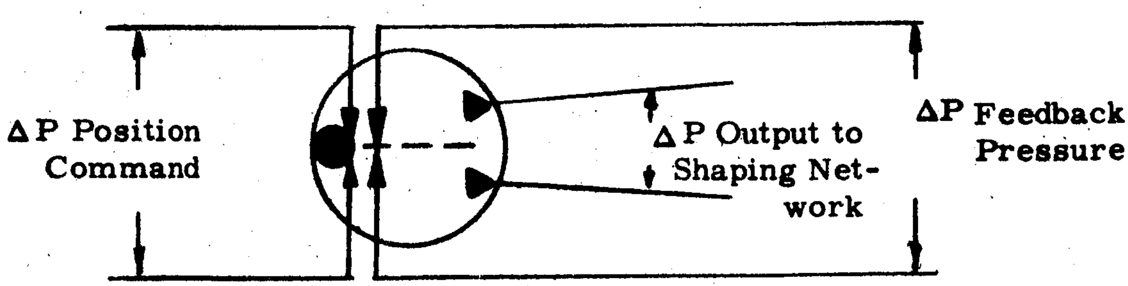
The study covered in this report was limited in scope and additional work is obviously needed in several areas. A particular need exists for a detailed design of the stabilizing circuits. This will involve a detailed analytical and experimental look at signal levels throughout the circuit in order to strike a happy balance between the minimum signal level set by noise considerations and the maximum signal level set by saturation of the amplifier. This is primarily a design problem that is not believed to present fundamental limitations.

It will also be necessary to further define the characteristics of the four-input analog amplifier to determine agreement with the assumptions of the analysis.

The final area of need is in the understanding of the vortex amplifier itself. Additional work must be done to determine its operation on high pressure air and ultimately on high pressure hydrogen. Design refinements are necessary, not only to reduce control pressure requirements, but also to increase the flow modulation range. Until these steps are taken, the feasibility of the vortex control approach will not be firmly established.



Single Sided System



Push-Pull System

Exhibit 2.1 Position Error Sensing Networks

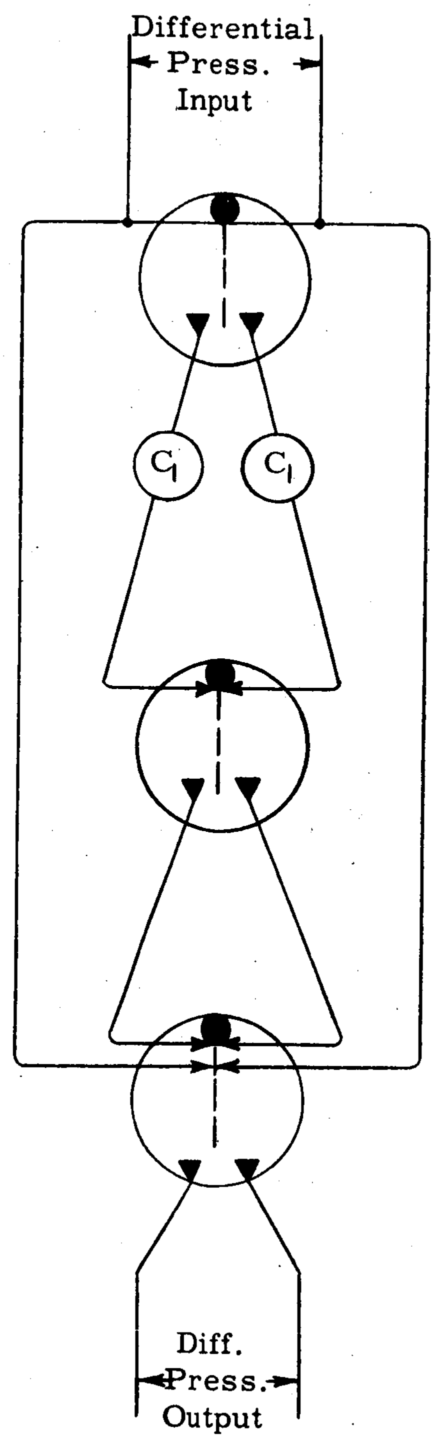


Exhibit 2.2 Recommended Lag-Lead Circuit

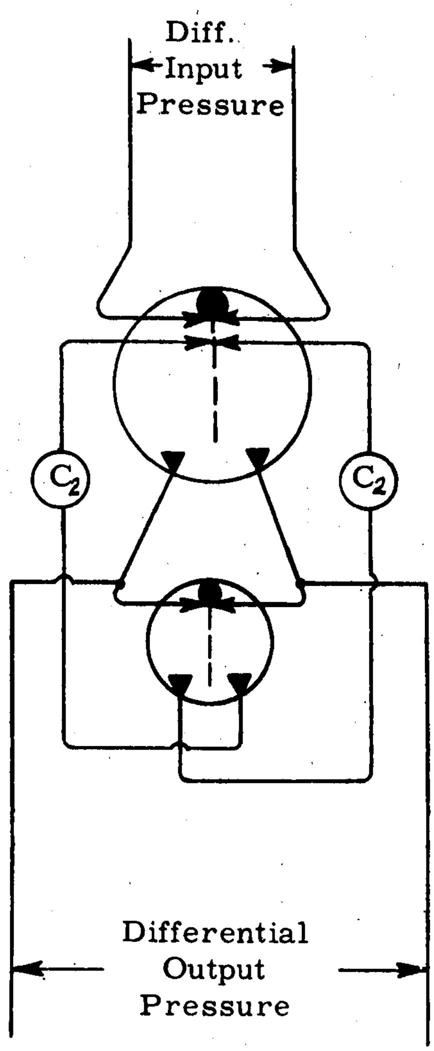


Exhibit 2.3 Recommended Lead-Lag Circuit

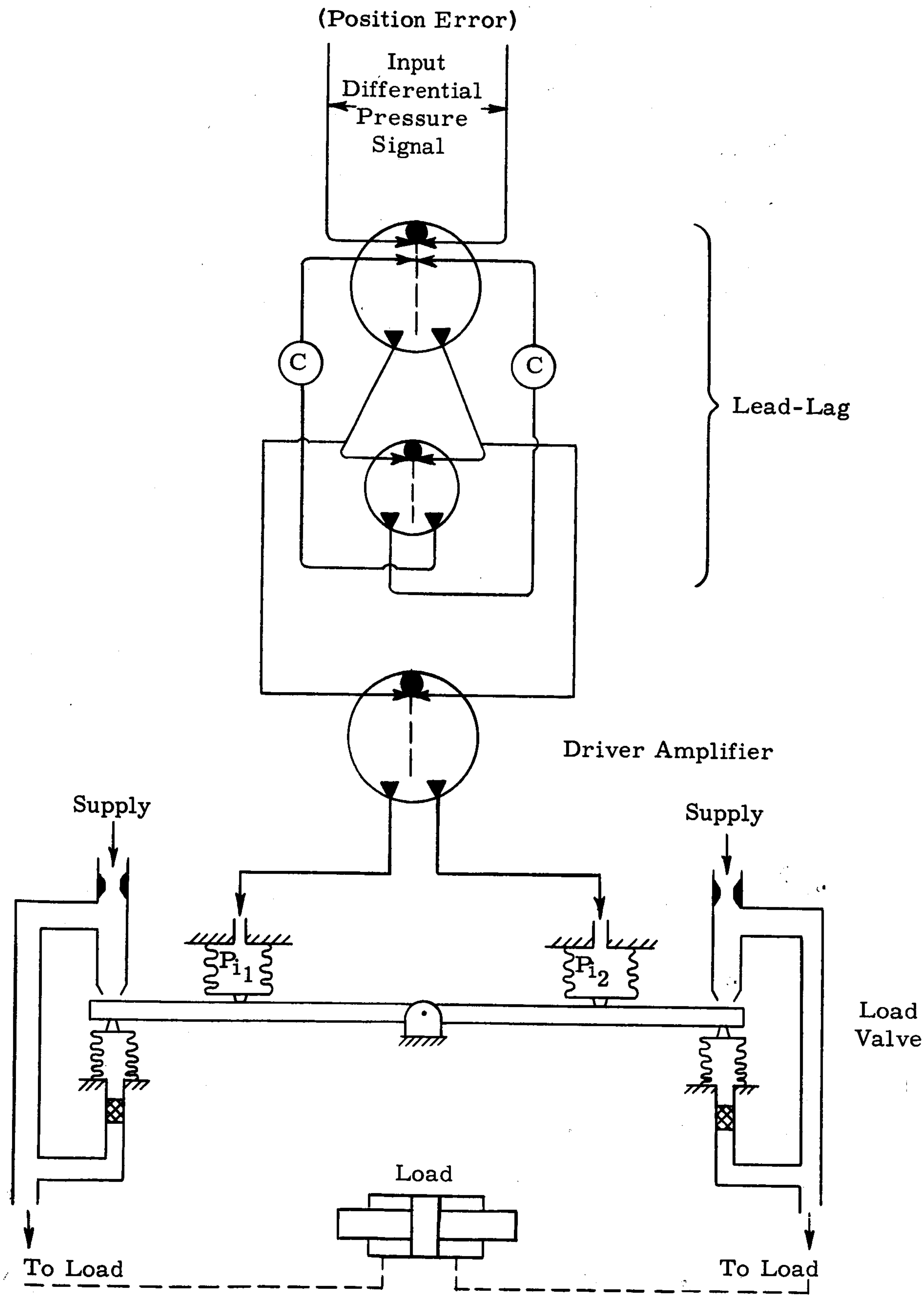


Exhibit 2.4 Combined System Using Present Single-Stage Power Valve

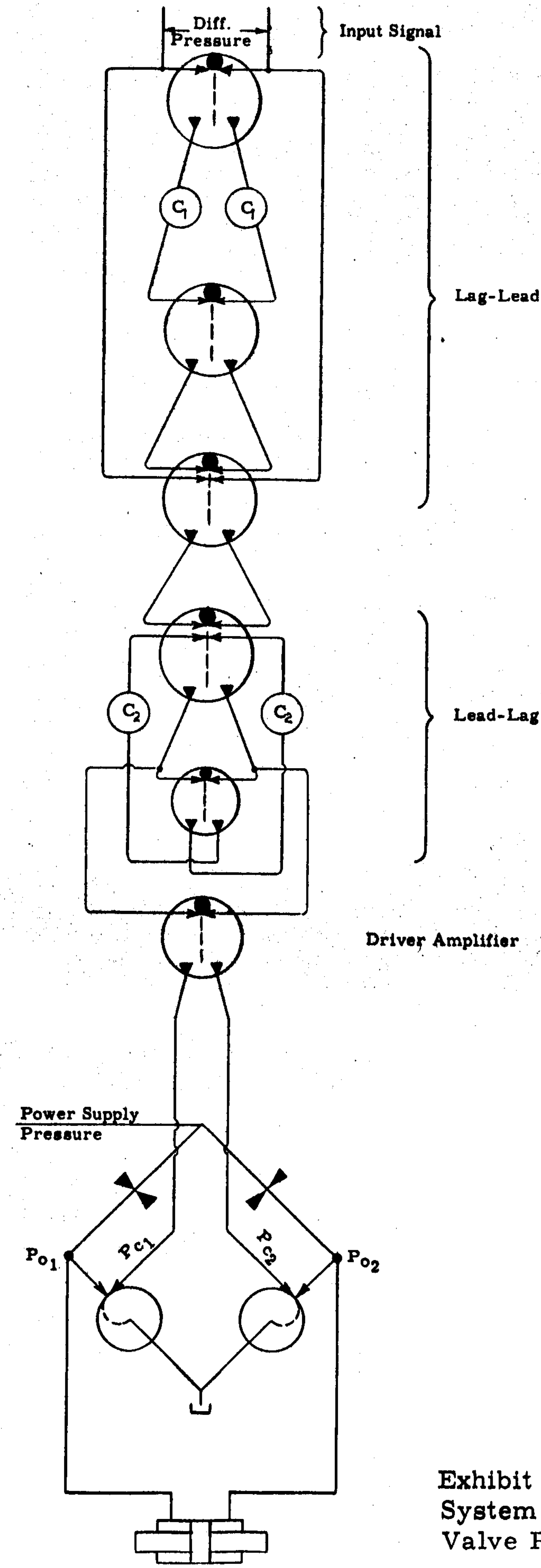


Exhibit 2.5 Combined System Using Vortex Valve Power Amplifiers

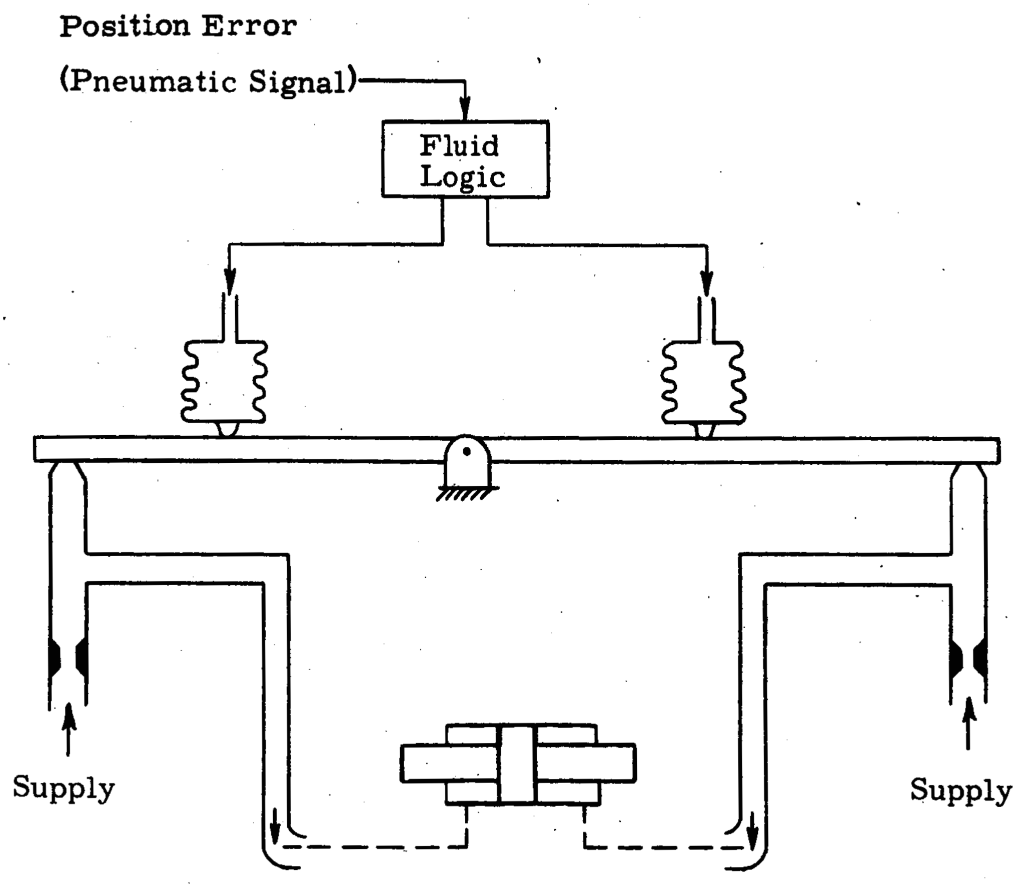


Exhibit 2.6 Simplified Single Stage Power Control Valve

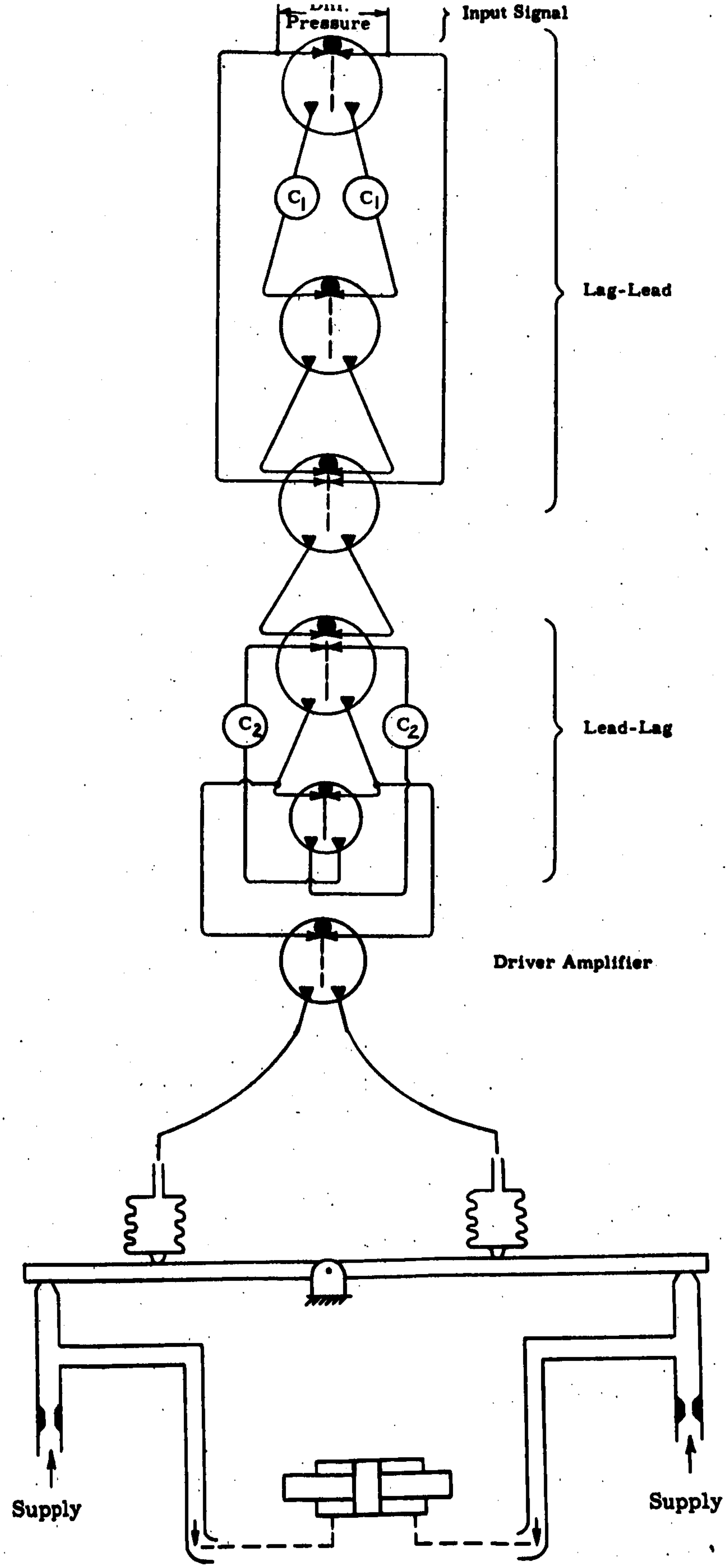


Exhibit 2.7 Combined System Using Simplified Single Stage Power Control Valve

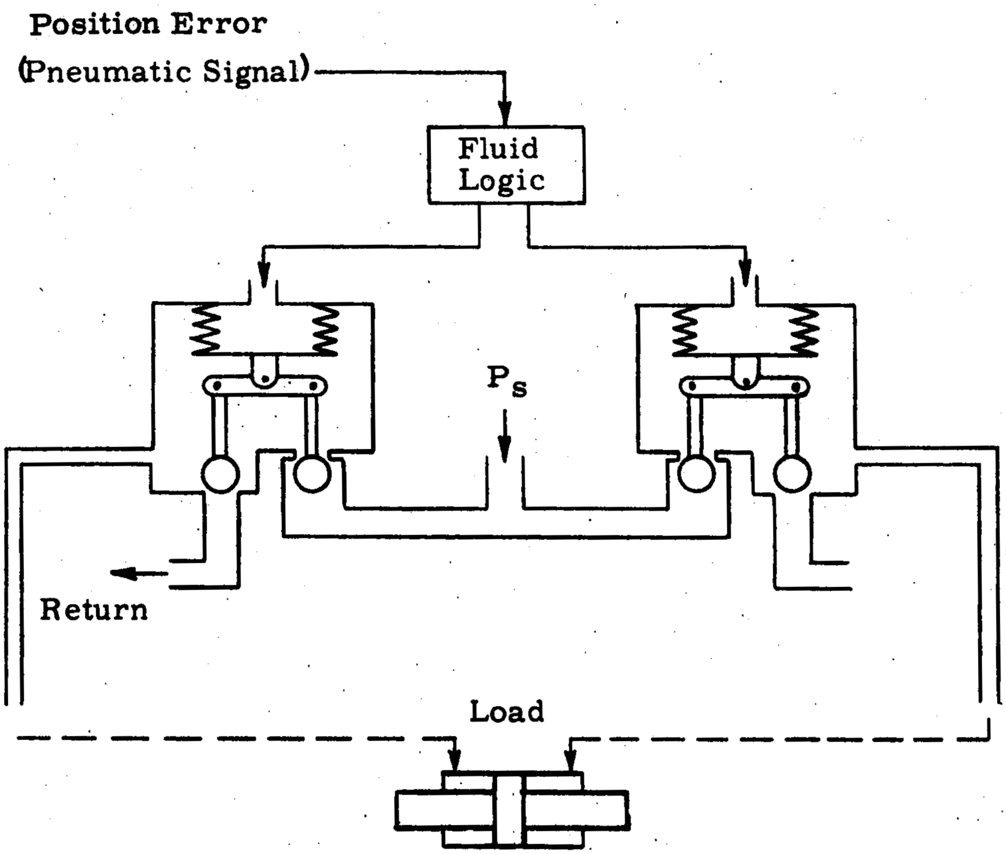


Exhibit 2.8 Two-Stage Power Control Valve

3.0 SYSTEM REQUIREMENTS

The rod control function is currently performed by an electropneumatic servo valve and amplifier. A typical open loop frequency response is shown in Exhibit 3.1. The loop crossover frequency is approximately 100 rad/sec, and phase margin at crossover is on the order of 32 degrees. The block diagram of such a loop is as shown in Exhibit 3.2. Since the load is a pure inertia load, the response of the summing network, amplifier, electropneumatic valve, and feedback networks must be as shown in Exhibit 3.3. This is the transfer function of the control elements. To be equivalent to the electropneumatic system, a fluid transistor control must exhibit the same transfer function as the electropneumatic control up to the crossover frequency. Beyond the crossover frequency, the transfer functions need not be identical, but the resulting phase lag at crossover frequency should be the same if comparable performance is to be obtained.

Considering Exhibit 3.3, there is a lag at 2 rad/sec and a lead at 20 rad/sec. This lag-lead is necessary to obtain high d.c. gain and is obtained by time constants τ_2 and τ_3 in the electropneumatic valve. A lead time constant at 50 rad/sec is necessary for stability. This is generated by lead time constant τ_1 in the electronic amplifier. The resonance at 36 rad/sec is the crossover frequency of an inner loop of the valve-torquemotor-load combination of the electropneumatic system. The lag break at 1200 rad/sec is the torquemotor electrical break. It is assumed that the feedback loop has no inherent lags in the electric-pneumatic system.

In view of the above considerations, it is seen that the fluid amplifier control must produce a lag at 2 rad/sec, a lead at 20 rad/sec, a lead at 50 rad/sec, and must exhibit an overall phase lead of 32 degrees at a 100 rad/sec frequency.

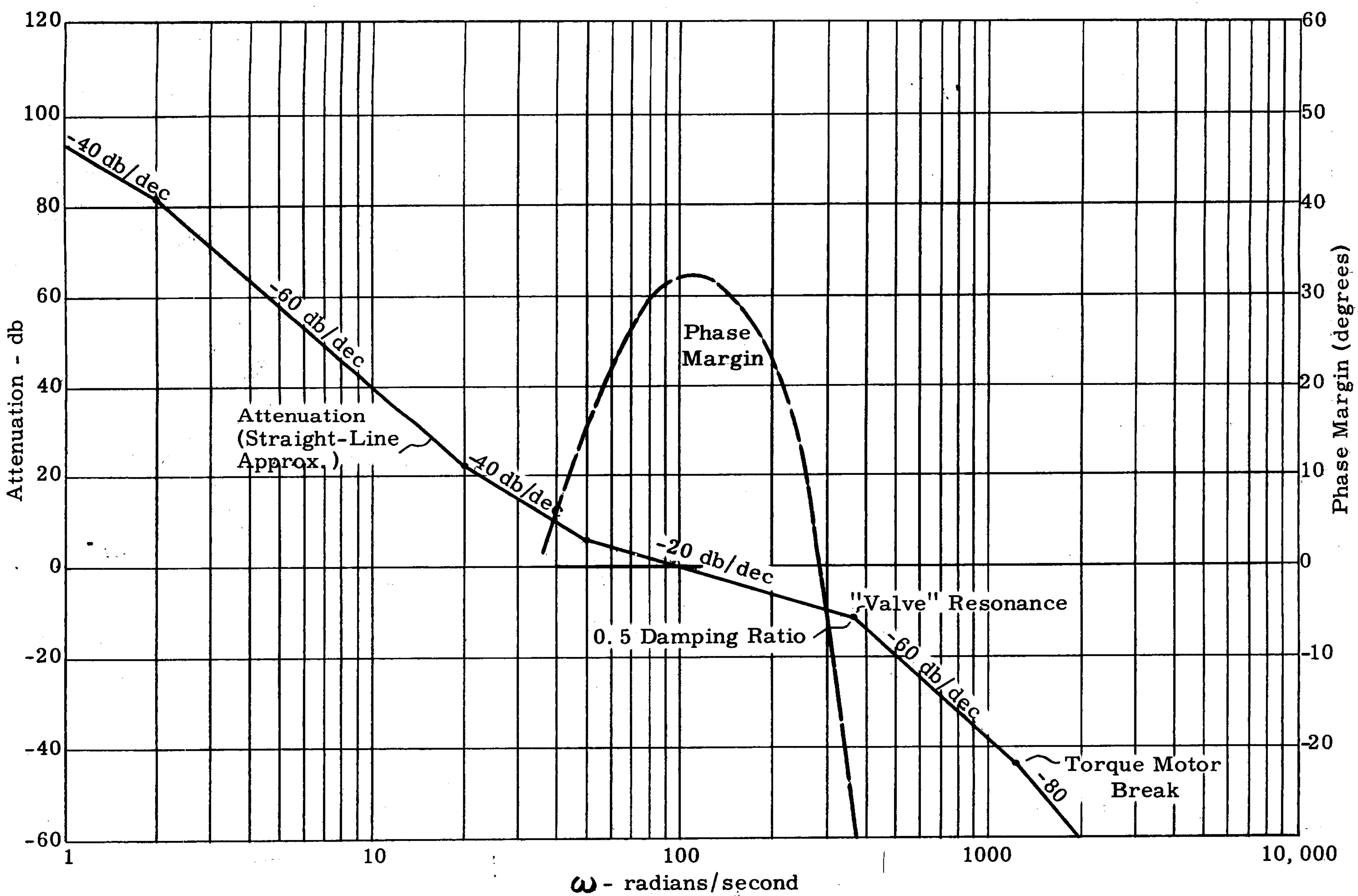


Exhibit 3. 1 Open Loop Bode Diagram of Typical Electropneumatic Rod Position Servo

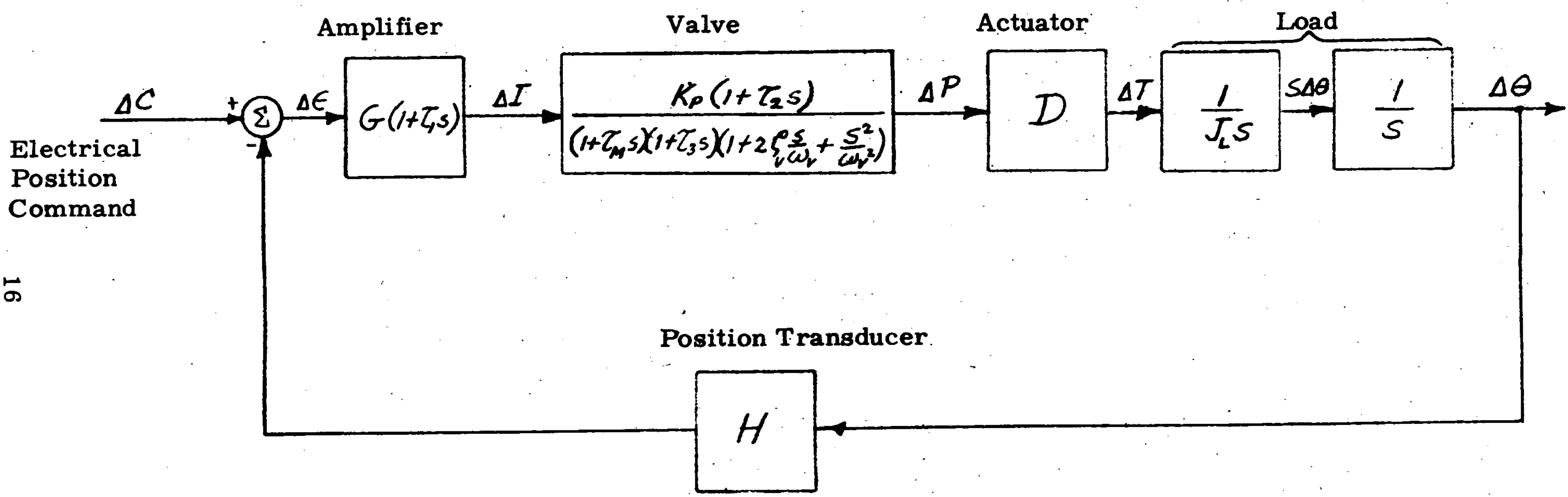


Exhibit 3.2 - Block Diagram of Present Electropneumatic
Position Servo Loop

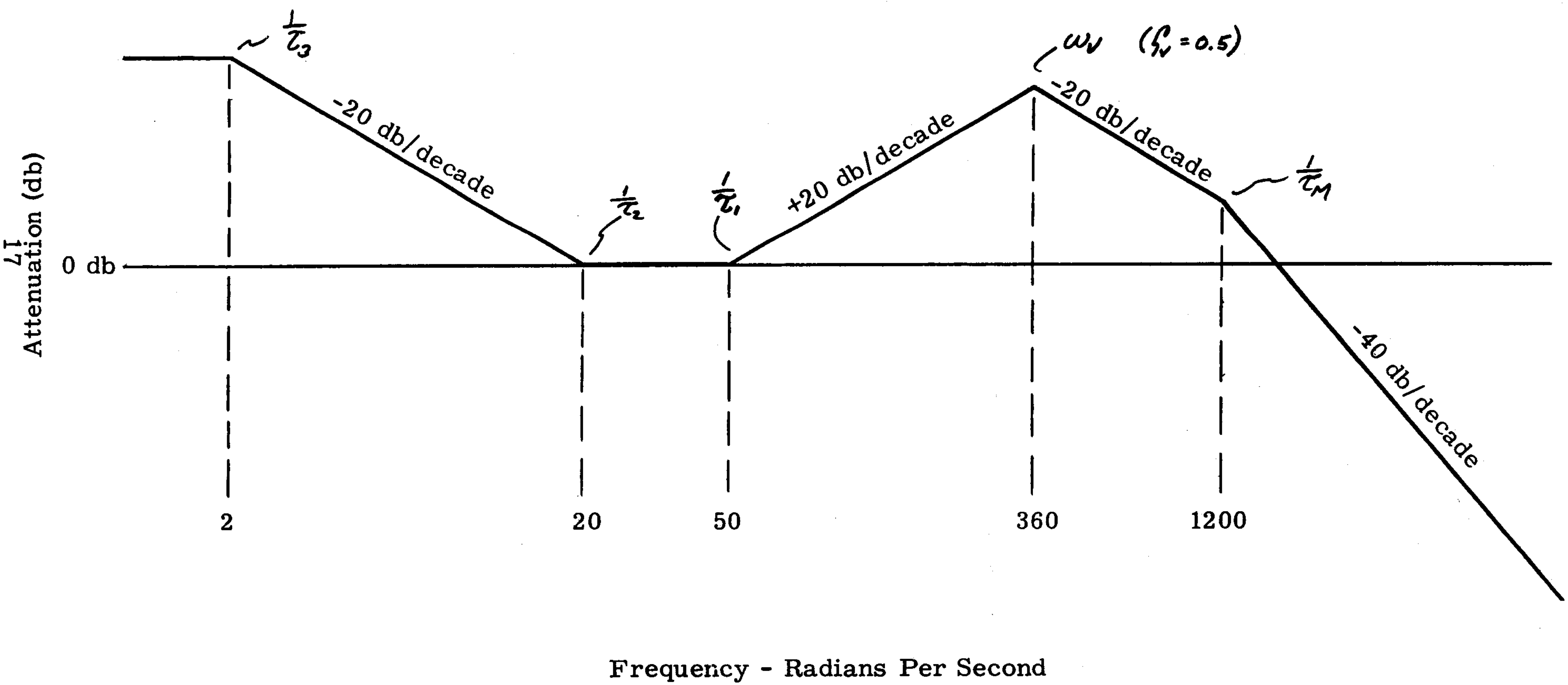


Exhibit 3.3 Straight Line Attenuation Diagram of Response of Control Elements in Electropneumatic System

4.0 STABILIZING CIRCUIT DESIGNS

4.1 Characteristics of Beam Deflector Analog Amplifiers

Before deriving specific circuits to perform the stabilizing functions, it is necessary to understand the characteristics of the elements to be used. In this case, analog beam deflector type amplifiers are the elements best suited for these applications. The basic schematic diagrams for such elements are given in Exhibits C.1 and C.4 of Appendix C.

The elements used by General Electric are "pressure control" elements which exhibit a higher flow gain than the more common "momentum control" elements. A typical input-output curve for blocked load conditions is given in Exhibit 4.1. At blocked flow, the differential pressure gain is 8. When driving another identical element operating at the same supply pressure, the differential pressure gain is approximately 4.5. In the curve of Exhibit 4.1, the differential input and output pressures are normalized to P_S the supply pressure. Pressures are expressed in gage units, the gage datum being the pressure of the vents.

4.1.1 Steady State Characteristics

The input characteristics of the "pressure control" analog amplifier are given in Exhibit 4.2. It can be seen that the two opposing control ports characteristics are interdependent. However, when operating in push-pull fashion, if control pressure P_{CA} is raised by a given amount ΔP_{CA}, control pressure P_{CB} will be dropped by an equal amount. As a result, the sum of the pressures will remain equal. Lines are plotted in Exhibit 4.2 for varying values of control pressure level. Assuming operation will be in the region of $\dfrac{P_{CA} + P_{CB}}{P_S}$ from 0.44 to 0.64, the slope of the normalized curve at P_{CA} $= P_{CB}$ can be seen to be 0.50. Thus the actual slope will be

$$K_C = \left.\frac{\partial P_{CA}}{\partial W_{CA}}\right|_{P_{CA} + P_{CB} = \text{const}} = 0.50 \frac{P_S}{W_S} \qquad (4-1)$$

where P_S = supply pressure (psia) minus vent pressure (psia)

and W_S = supply flow (#/sec)

On the basis of small changes, control flow can be related to control pressure as

$$\Delta P_{CA} = K_C \, \Delta W_{CA}. \qquad (4-2)$$

The relationship will actually be true for relatively large changes due to the linearity of the characteristic.

Next, it can be observed that the deflection of the power jet is a direct function of the difference in supply pressures, or

$$\theta = K_D \left| P_{CA} - P_{CB} \right| \tag{4-3}$$

In terms of small changes,

$$\Delta \theta = K_D \left| \Delta P_{CA} - \Delta P_{CB} \right| \tag{4-4}$$

The output characteristics of the pressure control analog valve are presented in normalized form in Exhibit 4.3. These curves are less linear than the input curves but still permit linearization over a fairly wide range before accuracy becomes compromised. Shown as dotted lines are the load-lines presented by the control ports of an identical valve operating at the same supply pressure. The linearized output relationship for one side can be expressed as

$$\Delta P_{OA} = -K_E \Delta\theta - K_F \Delta W_{OA} \tag{4-5}$$

and, for the other side,

$$\Delta P_{OB} = + K_E \Delta \theta - K_F \Delta W_{OB} \tag{4-6}$$

At the load point presented by the control ports of one identical valve at the same supply pressure, the normalized curve slope is -0.552 so that

$$K_F = \left. \frac{\partial P_{OB}}{\partial W_{OB}} \right|_{\theta = 0} = 0.552 \frac{P_S}{W_S} \tag{4-7}$$

Now, combining eqs (4-2), (4-4), (4-5), and (4-6)

$$\Delta P_{OA} - \Delta P_{OB} = 2K_E K_D \left| \Delta P_{CA} - \Delta P_{CB} \right| - K_F \left| \Delta W_{OA} - \Delta W_{OB} \right| \tag{4-8}$$

where $2 K_E K_D$ = element pressure gain (4-9)

Next, if we assume symmetry of operation, it can be concluded that

$$\Delta P_{OA} = -2 K_E K_D \Delta P_{CA} - K_F \Delta W_{OA} \tag{4-10}$$

In other words, the output signal is affected by control pressure and output flow.

4.1.2 Dynamic Characteristics

The linearized steady state characteristics defined above may be combined with lumped parameter values of pneumatic inductance and capacitance in the element and its load. The inductance relationship is defined as

$$\Delta \left(P_1 - P_2\right) = L \frac{dW}{dt} \tag{4-11}$$

where L = pneumatic inductance

$$= \frac{\ell}{ga} \text{ for a constant area passage}$$

$$= \frac{\ell}{g\,(a_1 - a_2)} \left(\log_e \frac{a_1}{a_2}\right) \text{ for a linearly tapered passage}$$

and ℓ = length of passage

a_1 = cross sectional area at one end

a_2 = cross sectional area at other end

g = accel. due to gravity

$P_1 - P_2$ = pressure drop across inductance

W = weight flow through inductance

The capacitance relationship (if confined to an adiabatic process) will be

$$\Delta P = \frac{1}{CS} \left(\Delta W_1 - \Delta W_2\right) \tag{4-12}$$

where C = capacitance = $\frac{V}{\alpha RT}$ (4-13)

V = volume

R = gas constant (Assume 9300 in/°R for H_2)

α = specific ht. ratio (Assume 1.5 for H_2)

T = absolute temp.

W_1 = weight flow in

W_2 = weight flow out

Using the steady state characteristics of section 4.1 in conjunction with the lumped inductances and capacitances of this section, it is possible to represent any form of circuit. It would be expected that the assumption of lumped inductances and capacitances would break down at the higher frequencies where distributed effects must be considered. A series of frequency response tests have been performed on a General Electric funded program. Tests were performed with a sinusoidal pressure input on an analog element with various volume loads on the output. It would be expected that, as the load volume decreases, the assumption of lumped parameters becomes less accurate. Exhibit 4.4 shows the worst case where the receiver outputs are blocked. Thus, the load seen by the amplifier is considered to be the lumped inductance of the receiver passage plus the lumped capacitance of the passage volume. This is obviously not exact, yet reasonable agreement is shown between the test results and the analysis. As the load volume is increased, better agreement was experienced. As a result, it is felt that this approach to the analysis is realistic.

4.2 Position Error Sensing

Position feedback from the actuator output could be generated by a variety of means. In general, they all rely on a form of flapper-nozzle circuit. The flapper can be a cam surface which backs away from a nozzle as a function of actuator displacement. A single flapper will provide a one-sided signal. Two cam "flappers" working into a bridge circuit can produce a push-pull or differential pressure feedback signal. Exhibit 4.5 shows arrangements for comparing the position command to position feedback signals. At the top is shown the single sided approach and the bottom is shown the push-pull approach. In the following circuits, the push-pull approach is preferred due to its greater linearity.

4.3 Lag - Lead Circuits

A variety of lag-lead circuits were considered (Appendix A) and discarded in favor of the one given in Exhibit 4.6. This circuit requires no dropping orifices and will exhibit more linear characteristics than those of Appendix A. Basically it is a proportional plus reset circuit having a block diagram as shown in Exhibit 4.7. This can be verified by a closer look at the equations. Since operation is push-pull, symmetry will prevail and we can look at the right side of the circuit only. The subscript A will be implied throughout but will not be used for brevity. Also, since this circuit is primarily a low frequency circuit, inductive effects will be neglected. As a result, the equations will be

$$\Delta\Theta_1 = 2K_{D1}\,\Delta P_{C1} \tag{4-14}$$

$$\Delta P_{O1} = -K_{E1}\,\Delta\Theta_1 - K_{F1}\,\Delta W_{O1} \tag{4-15}$$

$$\Delta P_{O1} = \frac{1}{C_1 S}\left[\Delta W_{O1} - \Delta W_{C2}\right] \tag{4-16}$$

$$\Delta P_{C2} = \Delta P_{O1} = K_{C2}\,\Delta W_{C2} \tag{4-17}$$

$$\Delta\Theta_2 = 2\,K_{D2}\,\Delta P_{C2} \tag{4-18}$$

$$\Delta P_{O2} = -\,K_{E2}\,\Delta\Theta_2 - K_{F2}\,\Delta W_{O2} \tag{4-19}$$

$$\Delta P_{O2} = K_{C3}\,\Delta W_{O2} \tag{4-20}$$

These terms combine to give the block diagram of Exhibit 4.8 which can then be simplified as shown in Exhibit 4.9. The diagram of Exhibit 4.9 is of the same form as that of Exhibit 4.7

where $$K_1 = \frac{2\,K_{D1}\,K_{E1} \cdot 2\,K_{D2}\,K_{E2}}{\left(1 + \frac{K_{F1}}{K_{C2}}\right)\left(1 + \frac{K_{F2}}{K_{C3}}\right)} \tag{4-21}$$

and $$\tau_3 = \frac{K_{C2}\,C_1}{1 + \frac{K_{F1}}{K_{C2}}} \tag{4-22}$$

The output will then be

$$\Delta P_{C1} + \Delta P_{O2} = \left[1 + \frac{K_1}{1 + \tau_3 S}\right] \Delta P_{C1}$$

$$= (1 + K_1)\left[\frac{1 + \tau_2\,S}{1 + \tau_3\,S}\right] \Delta P_{C1} \tag{4-23}$$

where

$$\tau_2 = \left(\frac{1}{1 + K_1}\right) \tau_3 \tag{4-24}$$

Now, to meet the specifications, it is desired that

$$\tau_2 = .05 \text{ sec}$$

and that $$(1 + K_1) \geqq 10$$

Here K_1 is recognized as the pressure gain of two amplifiers in series, the last amplifier being loaded by a third. Assume all three amplifiers are of the same size and operate at the same pressure. Then the individual pressure gain per stage will be 4.5 and

$$K_1 = 4.5 \times 4.5 = 22.5$$

or $1 + K_1 = 23.5$

which more than meets the specification.

Combining eqs (4-22), and (4-24), to meet the τ_2 specification:

$$.05 \text{ sec} = \frac{1}{23.5} \cdot \frac{K_{C2}\, C_1}{\left(1 + \frac{K_{F1}}{K_{C2}}\right)} \tag{4-25}$$

Assume that a .010" nozzle width is used and that hydrogen supply pressure is 60 psia, 100°R exhausting to 50 psia. Then, from Exhibit 9.1,

$$W_S = 6.5 \times 10^{-5} \text{ \#/sec}$$

$$P_S = 10 \text{ psig}$$

and

$$K_{C2} = 0.50 \times \frac{P_S}{W_S} = .50 \times \frac{10 \text{ \#/in}^2}{6.5 \times 10^{-5} \text{ \#/sec}}$$

$$= 1.769 \times 10^5 \frac{\text{sec}}{\text{in}^2}$$

$$K_{F1} = 0.552 \frac{P_S}{W_S}$$

$$\frac{K_{F1}}{K_{C2}} = \frac{0.552}{0.50} = 1.104$$

$$C_1 = \frac{V_1}{\alpha RT} = \frac{V_1}{1.5 \times 9300 \text{ in/}^\circ\text{R} \times 100^\circ\text{R}}$$

$$= \frac{V_1}{1.395 \times 10^6 \text{ in}}$$

Substituting these numbers into eq (4-25),

$$.05 \text{ sec} = \frac{1}{23.5} \times \frac{1.769 \times 10^5 \frac{\text{sec}}{\text{in}^2} \times \frac{V_1}{1.395 \times 10^6 \text{ in}}}{(1 + 1.104)}$$

which solves to $V_1 = 44.88 \text{ in}^3$

This is a reasonable volume to work with. Summarizing, using .010" elements with capacitance volume of 44.88 in^3,

$$\tau_3 = 1.175 \text{ sec}$$

$$\tau_2 = .05 \text{ sec}$$

4.4 Lead-Lag Circuits

A variety of lead-lag circuits were also considered. Of these, the most attractive is given in Exhibit 4.10. Alternates are listed in Appendix B. The circuit of Exhibit 4.10 is push-pull, uses no flow restrictions other than the nozzle and, as a result, offers greater potential for linear operation over a wider range of conditions.

The desired frequency characteristic is achieved by using a feedback path having series capacitance. When operating at low frequencies, the negative feedback is large, resulting in a small output signal $\Delta P_{O4A} - \Delta P_{O4B}$. As the frequency increases, the negative feedback is attenuated by the fluid capacitors C_2 and output will increase. Finally, at the frequency where the negative feedback is highly attenuated, the output amplitude will level off at some higher value.

To develop equations describing the operation it is assumed that the input relationships for the four input first stage are the same as for a two input amplifier. Symmetry is also assumed, so we will again look at one side of the circuit only. The subscript A will again be implied but omitted for brevity. Although the lead-lag circuit is not a low frequency circuit, inductive effects will still be small enough to ignore at frequencies of interest. As a result, the equations will be

$$\Delta\Theta_4 = 2K_{D4}\left(\Delta P_{O3} + \Delta P_{F4}\right) \qquad (4\text{-}26)$$

$$\Delta P_{O4} = -K_{E4}\,\Delta\Theta_4 - K_{F4}\left(\Delta W_{O4} + \Delta W_{C5}\right) \qquad (4\text{-}27)$$

$$\Delta P_{O4} = K_{C5}^{*}\left(\Delta W_{O4} + \Delta W_{C5}\right) \qquad (4\text{-}28)$$

$$\Delta\Theta_5 = 2K_{D5}\,\Delta P_{O4} \qquad (4\text{-}29)$$

$$\Delta P_{F4} = K_{E5}\,\Delta\Theta_5 - K_{F5}\,\Delta W_{O5} \qquad (4\text{-}30)$$

$$\Delta P_{F4} = \frac{1}{C_2 S}\left(\Delta W_{O5} - \Delta W_{C4}\right) \tag{4-31}$$

$$\Delta P_{C4} = K_{C4}\ \Delta W_{C4}$$

The block diagram is shown in Exhibit 4.11. This may be simplified to the diagram of Exhibit 4.12.

In Exhibit 4.12

$$\tau_1 = \frac{K_{F5}\, C_2}{1 + \dfrac{K_{F5}}{K_{C4}}} \tag{4-32}$$

With a forward loop gain of

$$G = \frac{2K_{D4}\, K_{E4}}{1 + \dfrac{K_{F4}}{K'_{C5}}}$$

and a feedback gain of

$$H = \frac{2K_{D5}\, K_{E5}}{\left(1+\dfrac{K_{F5}}{K_{C4}}\right)\left(1 + \tau_1 S\right)}$$

the closed loop transfer function will be

$$\frac{\Delta P_{O4}}{\Delta P_{O3}} = \frac{-G}{1 + GH} = \frac{-1/H}{\dfrac{1}{GH} + 1}$$

$$= \frac{\left(1 + \dfrac{K_{F5}}{K_{C4}}\right)\left(1 + \tau_1 S\right)}{2K_{D5}\, K_{E5}\left[1 + \dfrac{\left(1 + \dfrac{K_{F4}}{K'_{C5}}\right)\left(1 + \dfrac{K_{F5}}{K_{C4}}\right)\left(1 + \tau_1 S\right)}{4\, K_{D4}\, K_{E4}\, K_{D5}\, K_{E5}}\right]} \tag{4-33}$$

or

$$\frac{\Delta P_{O4}}{\Delta P_{O3}} = \frac{-K_2\left(1 + \tau_1 S\right)}{\left(1 + \tau_4 S\right)} \tag{4-34}$$

$$\text{where } K_2 = \frac{1}{\left[\dfrac{2K_{D5}\,K_{E5}}{\left(1 + \dfrac{K_{F5}}{K_{C4}}\right)} + \dfrac{\left(1 + \dfrac{K_{F4}}{K'_{C5}}\right)}{2K_{D4}\,K_{E4}}\right]} \tag{4-35}$$

$$\text{and } \tau_4 = \frac{1}{1 + \dfrac{(2K_{D4}\,K_{E4})\,(2K_{D5}\,K_{E5})}{\left(1 + \dfrac{K_{F4}}{K'_{C5}}\right)\left(1 + \dfrac{K_{F5}}{K_{C4}}\right)}}\;\tau_1 \tag{4-36}$$

The term $\dfrac{2K_{D4}\,K_{E4}}{1 + \dfrac{K_{F4}}{K'_{C5}}}$ is the pressure gain of amplifier #4. This feeds two like amplifiers, its value is approximately 3.0.

Similarly $\dfrac{2K_{D5}\,K_{E5}}{1 + \dfrac{K_{F5}}{K_{C4}}}$ is the pressure gain of amplifier #5. Since it feeds only one amplifier, its gain is approximately 4.5.

Therefore, eqs (4-35) and (4-36) simplify to

$$K_2 = \frac{1}{4.5 + \dfrac{1}{3}} = \frac{3}{13.5 + 1} = 0.207 \tag{4-35a}$$

$$\tau_4 = \frac{1}{14.5}\;\tau_1 \tag{4-36a}$$

Now it is necessary that

$$\tau_1 = .02 \text{ sec}$$

but, by eq (4-32)

$$\tau_1 = .02 \text{ sec} = \frac{K_{F5}\,C_2}{1 + \dfrac{K_{F5}}{K_{C4}}} \tag{4-37}$$

Assume amplifiers #4 & 5 are of .010" nozzle width, operating on 60 psia hydrogen and exhausting to 50 psia vent. Then, again

$$W_S = 6.5 \times 10^{-5} \ \#/\text{sec}$$

$$P_S = 10 \text{ psig}$$

$$K_{C4} = .50 \frac{P_S}{W_S} = .769 \times 10^5 \frac{\text{sec}}{\text{in}^2}$$

$$K_{F5} = .552 \frac{P_S}{W_S} = 0.848 \times 10^5 \frac{\text{sec}}{\text{in}^2}$$

$$\frac{K_{F5}}{K_{C4}} = \frac{.848}{.769} = 1.104$$

$$C_2 = \frac{V_2}{\alpha RT} = \frac{V_2}{1.395 \times 10^6 \text{ in}}$$

Substitute these numbers in eq (4-37):

$$\tau_1 = .02 \text{ sec} = \frac{0.848 \times 10^5 \frac{\text{sec}}{\text{in}^2} \times V_2}{(2.104) \times 1.395 \times 10^6 \text{ in}}$$

which solves to $V_2 = 0.692 \text{ in}^3$

This, too is a reasonable volume.

Summarizing, using .010" elements with a capacitance volume of 0.692 in^3,

$$\frac{\Delta P_{O4}}{\Delta P_{O3}} = \frac{-K_2 \left(1 + \tau_1 S\right)}{1 + \tau_4 S}$$

where $K_2 = 0.207$

$\tau_1 = .02$ sec

$\tau_2 = .00138$ sec

4.5 Driver Amplifier

The output of the stabilizing circuits must be amplified sufficiently to drive a power valve. This is done with the driver amplifier which must have a large enough output to drive the valve, while still having sufficient response to maintain servo performance. In the case of the mechanical power valve, the driver amplifier will supply driving bellows on the valve arm as in Exhibit 4.13. The bellows move the arm in the same way that a torque motor drives the present electropneumatic valve. If vortex valves are used, the output of the driver stage will go directly to the control ports of the vortex valves. The mechanical case will be discussed here in order to bring out a few factors ~~not~~ obvious at first glance.

The fluid amplifier itself will have the familiar equations for one side

$$\Delta\Theta_6 = 2K_{D6} \quad \Delta P_{C6} \tag{4-38}$$

$$\Delta P_{O6} = -K_{E6} \quad \Delta\Theta_6 - K_{F6} \quad \Delta W_{O6} \tag{4-39}$$

Now, since the bellows can move, it is a combined capacitance and spring. Assume adiabatic changes:

$$\Delta P_{O6} = \frac{\Delta W_{O6}}{C_3 S} - \frac{\alpha P_{C60} A_b \, \Delta X}{V_b} \tag{4-40}$$

where A_b = bellows effective area

V_b = bellows volume

P_{C60} = quiescent value of P_{C6}

α = specific heat ratio for Hydrogen

The bellows force is $\Delta F_b = A_b \ \Delta P_{O6}$ (4-41)

The mechanical valve's pressure feedback force is $A_N \ \Delta P_{L1}$

where $$\Delta P_{L1} = \frac{\alpha R T K_{N1}}{V_A S} \Delta X \tag{4-42}$$

with a bellows spring constant k,

$$k \, \Delta X = A_b \quad \Delta P_{O6} - A_N \quad \Delta P_{L1} \tag{4-43}$$

This results in the block diagram shown in Exhibit 4.14. The term ΔW_{P6} is the "pressurizing flow" to the driver bellows and ΔW_{V6} is the "velocity flow" to the bellows. It can be shown that the greatest value of $\frac{W_{V6}}{W_{P6}}$ is

$$\left.\frac{\Delta W_{V6}}{\Delta W_{P6}}\right|_{max} = \frac{\alpha P_{C60} A_b^2}{k V_b}$$

As long as $$\frac{\alpha P_{C60} A_b^2}{k V_b} << 1,$$

the feedback from X can be eliminated and the block diagram simplifies to that of Exhibit 4.15, and it is now possible to say

$$\frac{\Delta P_{O6}}{\Delta P_{C6}} = \frac{-2K_{D6}K_{E6}}{1 + K_{F6}C_3S} \tag{4-44}$$

The above analysis neglected inductance in the amplifier receivers. In this case, this inductance should be considered and, if factored in, the relationship of eq (4-44) becomes

$$\frac{\Delta P_{O6}}{\Delta P_{C6}} = \frac{-2K_{D6}K_{E6}}{1 + 2\zeta_D \frac{S}{\omega_D} + \frac{S^2}{\omega_D^{\;2}}} \tag{4-45}$$

where $\omega_D = \sqrt{\frac{1}{L_6 \; C_3}}$

$$\zeta_D = \frac{\omega_D}{2}\left(K_{F6} \; C_3\right)$$

$$= \frac{K_{F6}}{2}\sqrt{\frac{C_3}{L_6}}$$

L_6 = inductance of amplifier receiver

The bellows is essentially a dead end load so that

$$2K_{D6} \, K_{E6} = 8$$

Now it will be shown that, for a given set of pressures, and a fixed bellows volume, the values of ω_D and ζ_D will depend on the size of the driver amplifier. The index of amplifier size is the nozzle width, d. Now, assume

$$A_b = 0.25 \text{ in}^2$$

$$V_b = 0.1 \text{ in}^2$$

$$P_S = 70 \text{ psia}$$

$$P_D = 50 \text{ psia}$$

Then $W_S = .905 \; d^2$

and $K_{F6} = 0.552 \frac{P_S}{W_S} = \frac{12.2}{d^2}$

$$C_3 = \frac{V_3}{\alpha RT} = \frac{0.1}{1.5 \text{x} 9300 \text{x} 100} = .7166 \text{x} 10^{-8} \text{in}^2$$

We know that $L_6 = \frac{.03964}{d}$

As a result,

$$\omega_D = \sqrt{\frac{1}{L_6 \; C_3}} = \sqrt{\frac{d}{.03964 \times .7166 \times 10^{-8}}}$$

$$= 18,750 \sqrt{d} \quad \text{rad/sec}$$

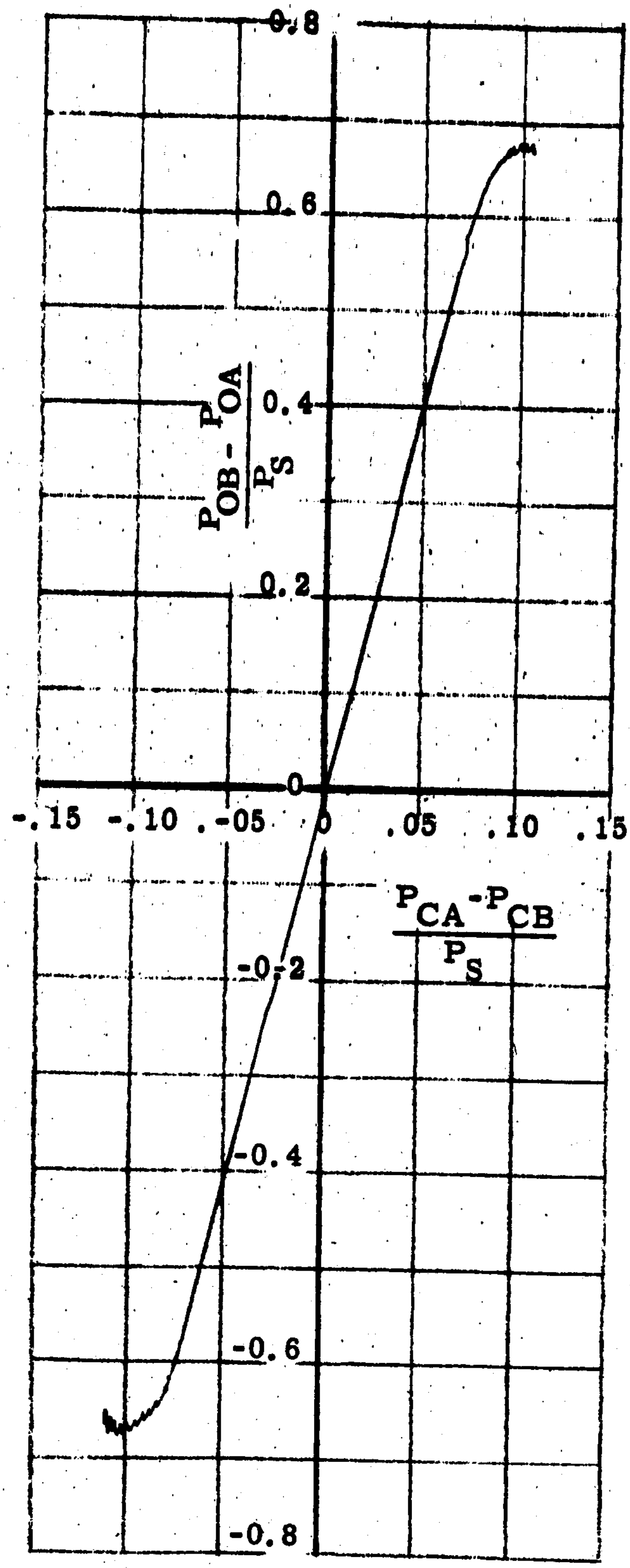
and

$$\zeta_D = \frac{18,750 \sqrt{d}}{2} \left(\frac{12.2}{d^2} \times 7.166 \times 10^{-8} \right)$$

$$= \frac{.0082}{d^{3/2}}$$

This shows that, for small driver amplifiers, the response will be slow and overdamped. As d is increased, ω_D will increase and damping will decrease. What is not obvious is that the term K_{F6} will not be particularly affected by further supply pressure increases since the term $\frac{P_S}{W_S}$ will decrease not more than 10% with further supply pressure changes. As a result, the response is primarily governed by amplifier size as represented by throat width, d. Exhibit 4.16 shows how response varies with d. For nozzle widths below .0406'', the response is overdamped and can be represented by two first order breaks at ω_5 and ω_6. Also shown in Exhibit 4.16 is the phase lag at 100 rad/sec introduced by the driver amplifier response.

The necessary response will be a function of the power valve that is used. Therefore, specific values of d must be computed separately for the particular power valves used.



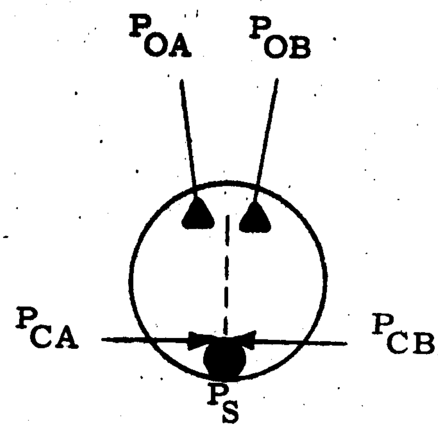


Exhibit 4.1 - Input - Output Curve for Analog Amplifier (Blocked Load)

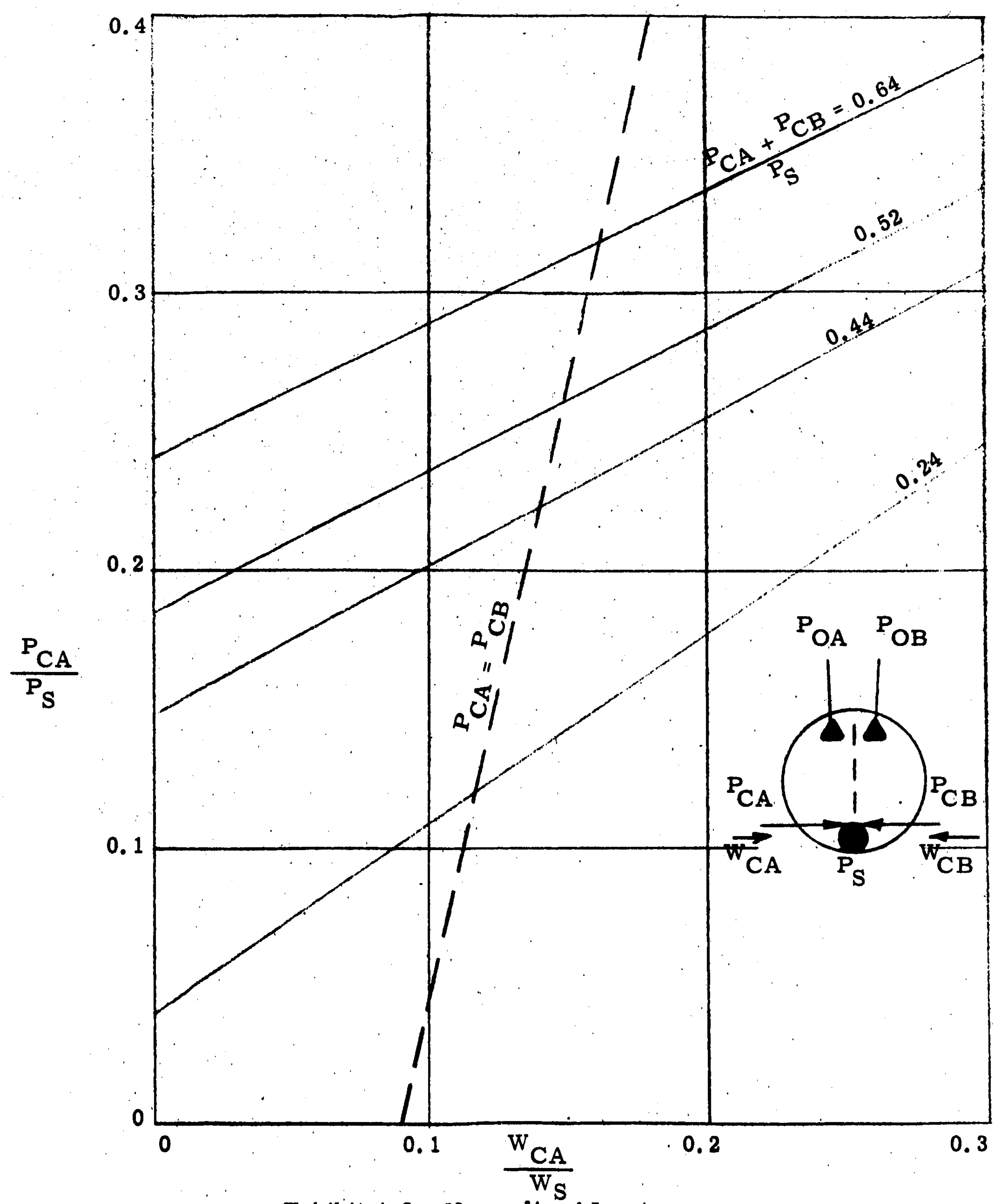


Exhibit 4.2 - Normalized Input Characteristics for Analog Amplifier

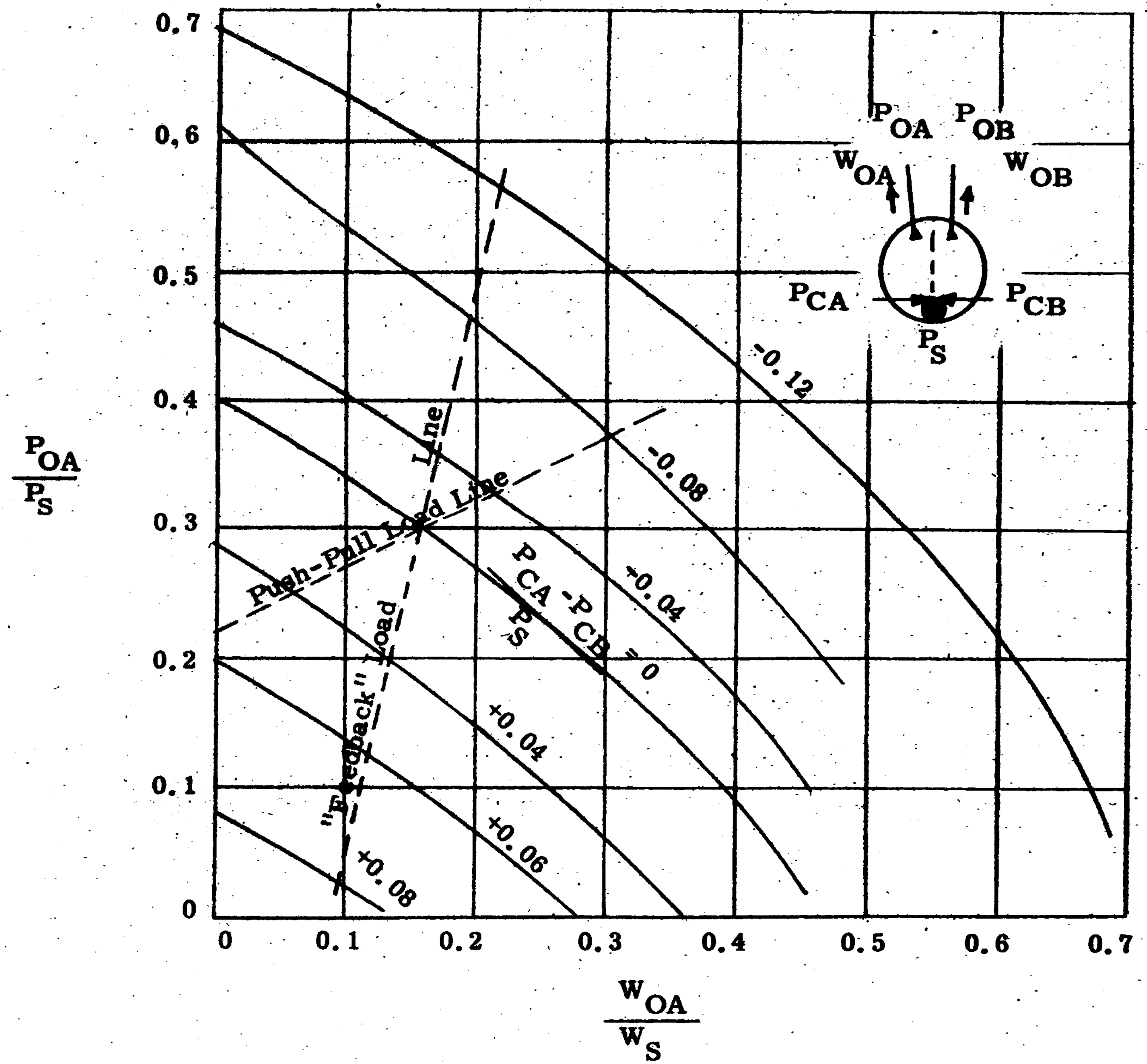


Exhibit 4.3. Normalized Output Characteristics for Analog Amplifier.

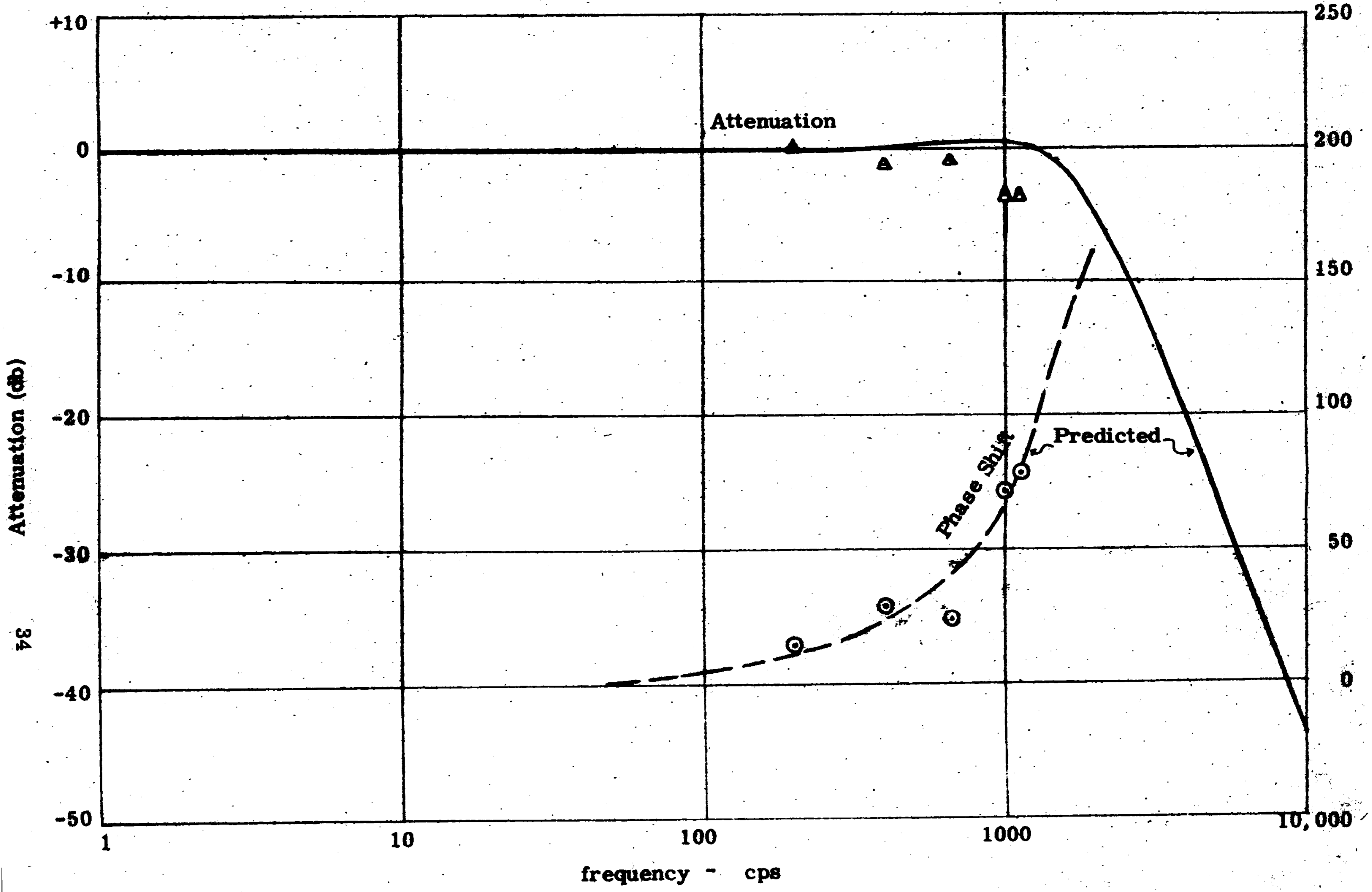
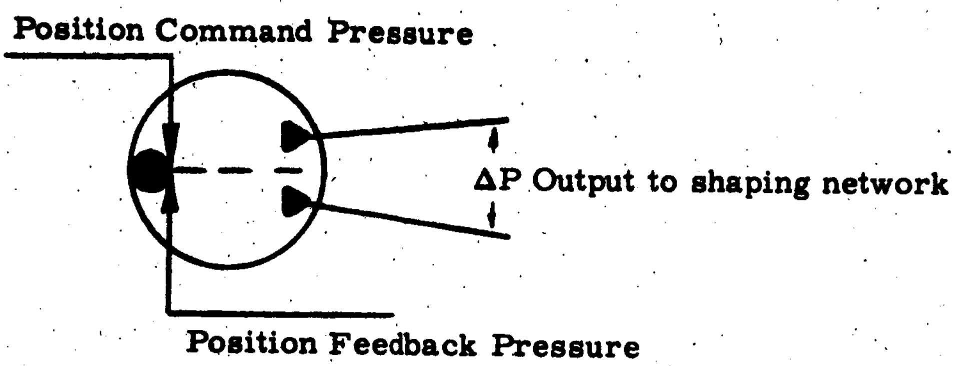
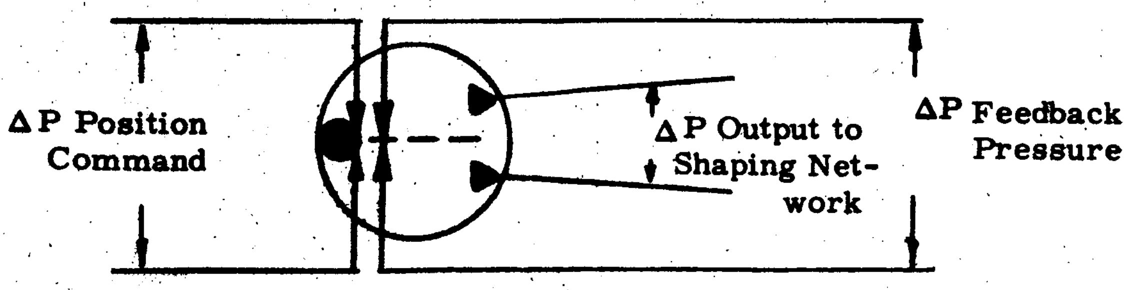


Exhibit 4.4 Comparison of Test Results to Predicted Frequency Response for Analog Amplifier



Single Sided System



Push-Pull System

Exhibit 4.5 Position Error Sensing Networks

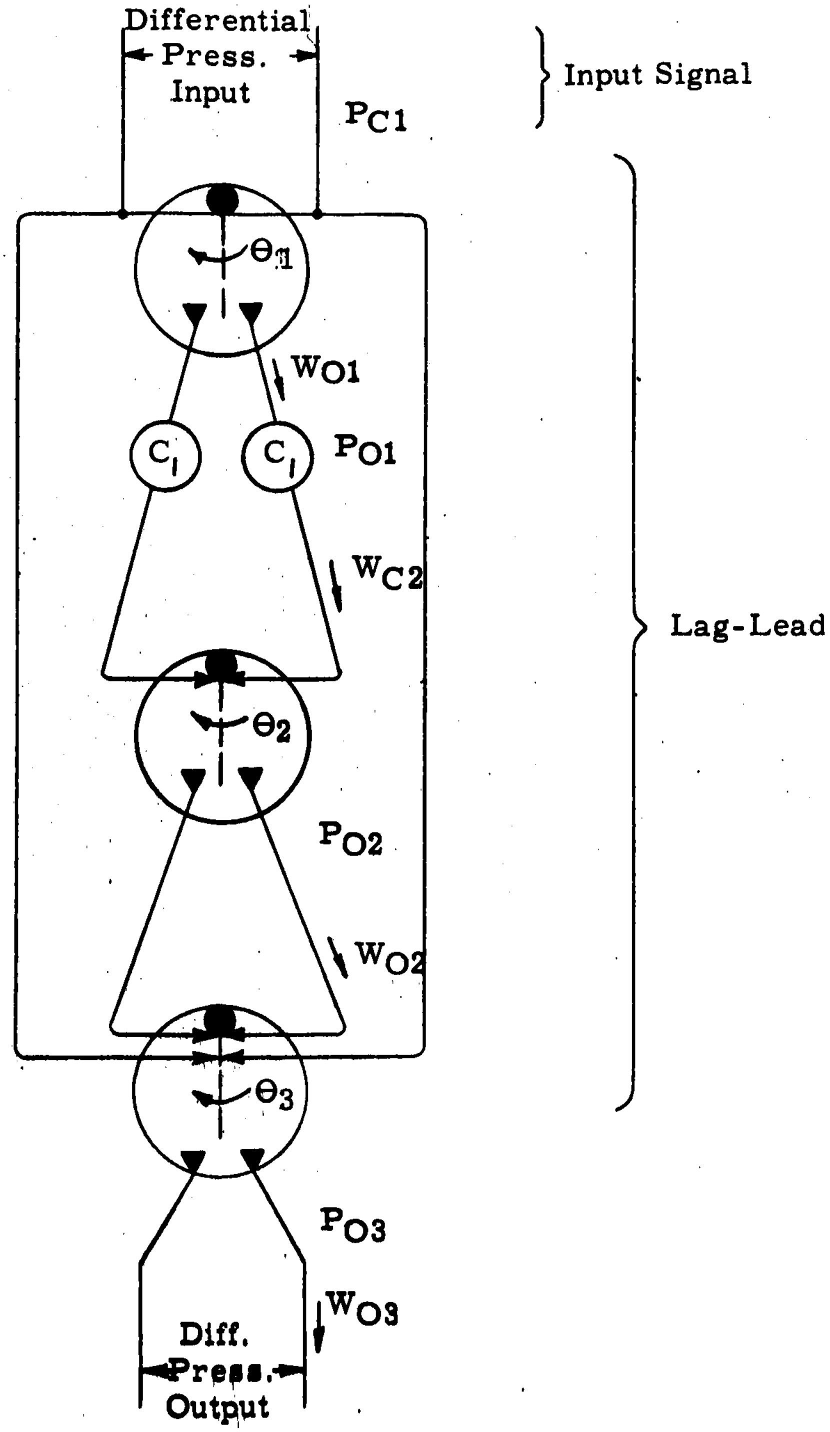


Exhibit 4.6 Recommended Lag-Lead Circuit

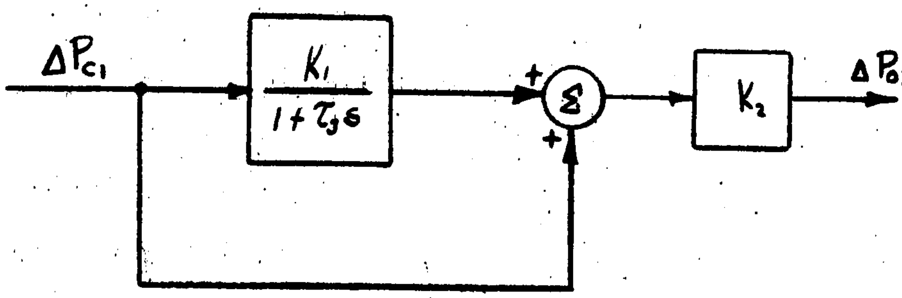


Exhibit 4.7 Basic Principle of Lag-Lead

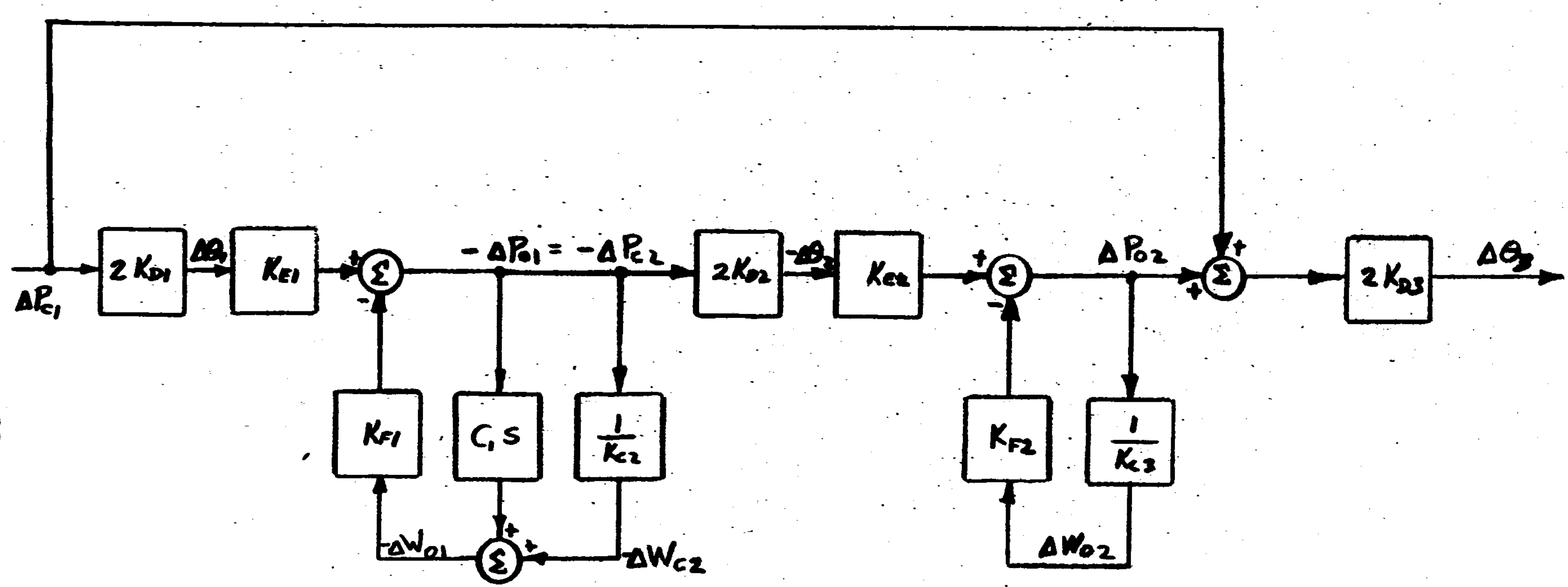


Exhibit 4.8 Initial Block Diagram of Lag-Lead

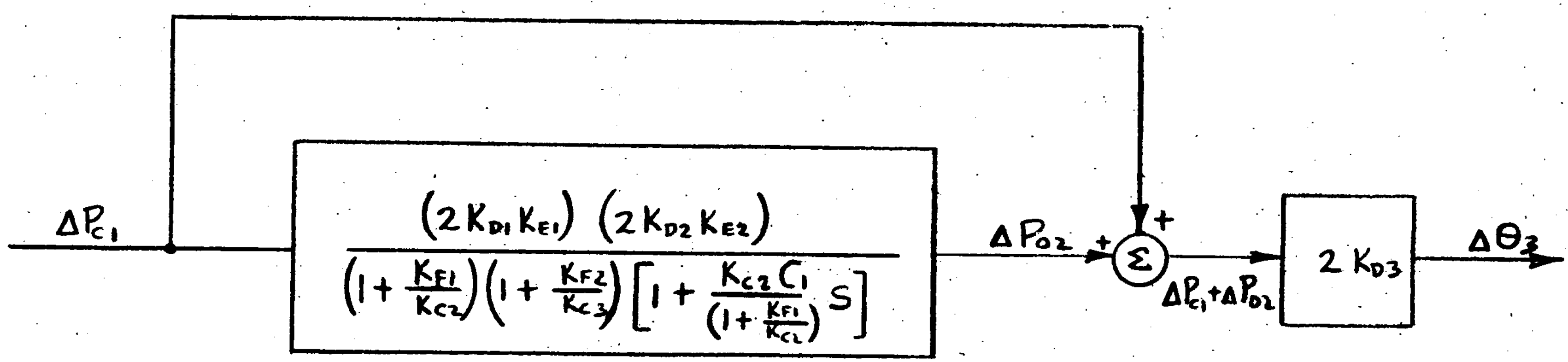


Exhibit 4.9 Simplified Block Diagram of Lag-Lead

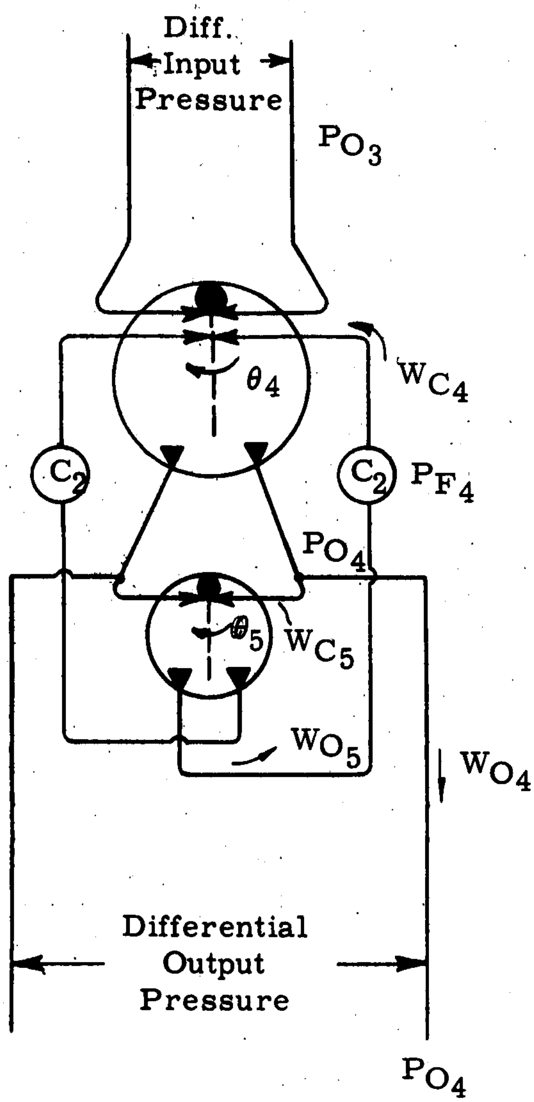


Exhibit 4.10 Recommended Lead-Lag Circuit

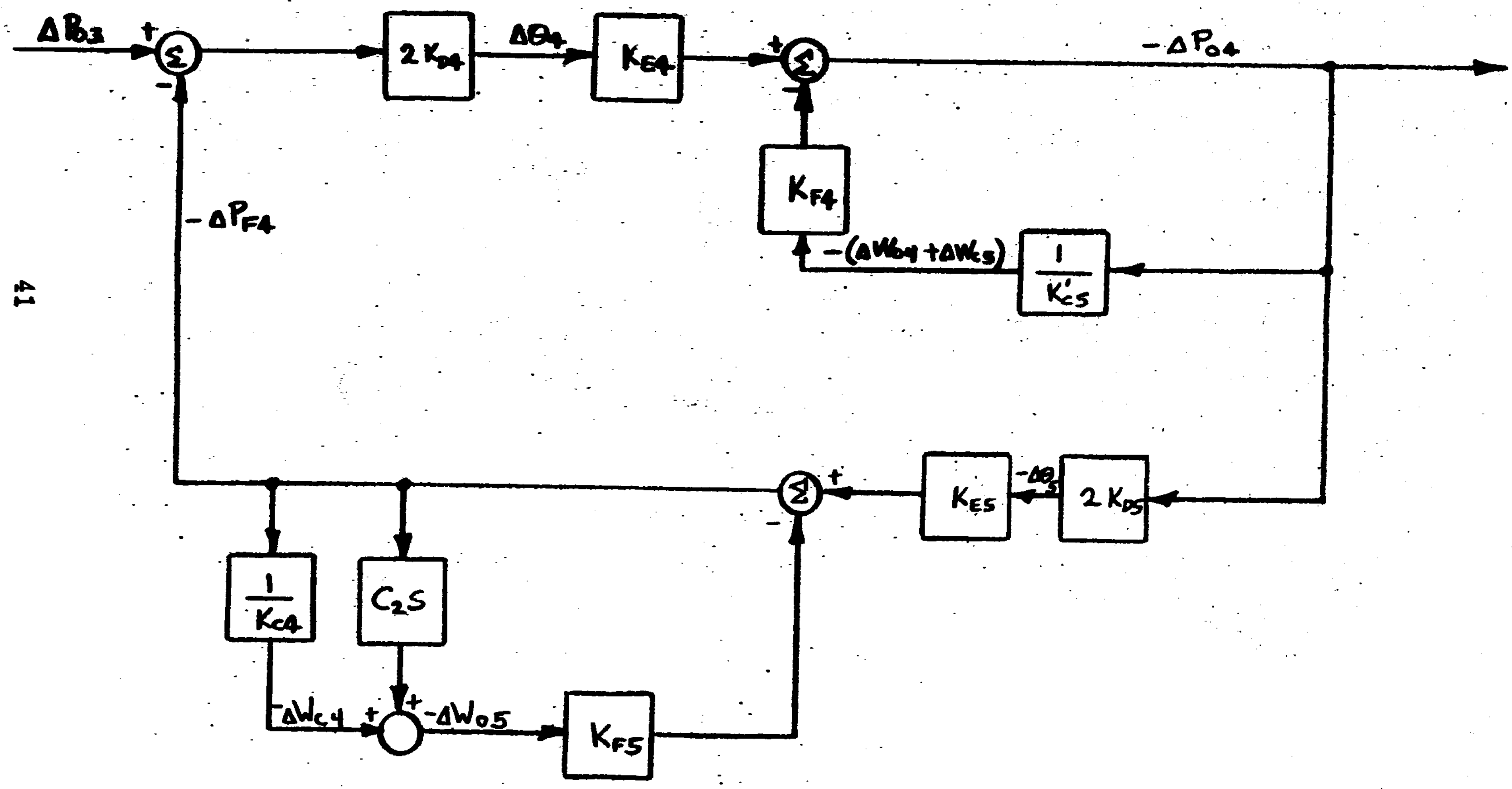


Exhibit 4.11 Initial Block Diagram of Lead-Lag Circuit

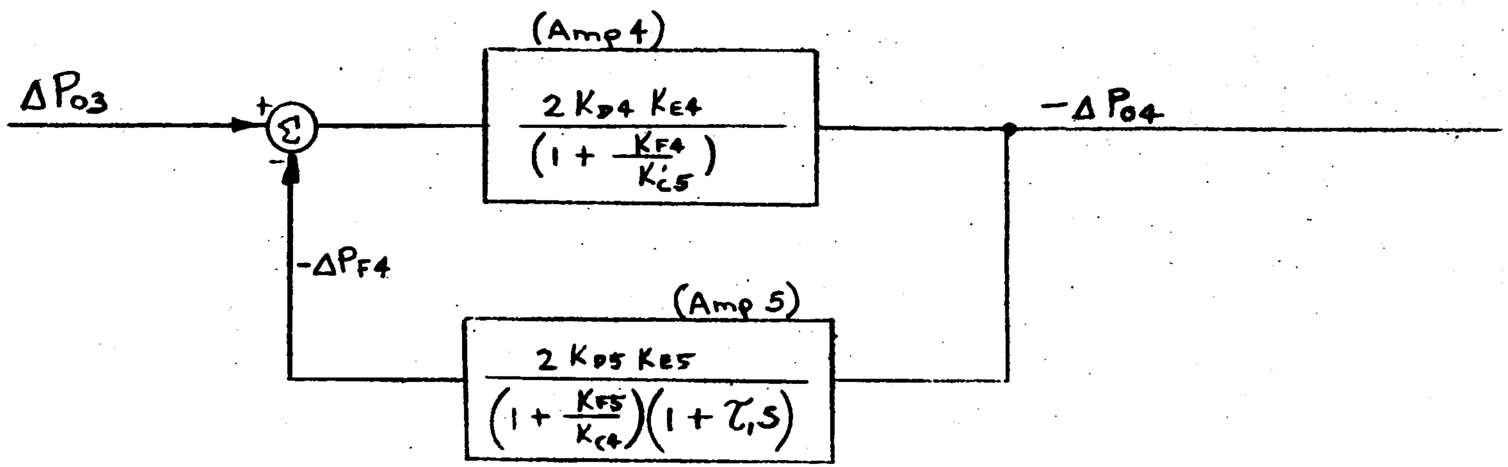


Exhibit 4.12 Simplified Block Diagram of Lead-Lag Circuit

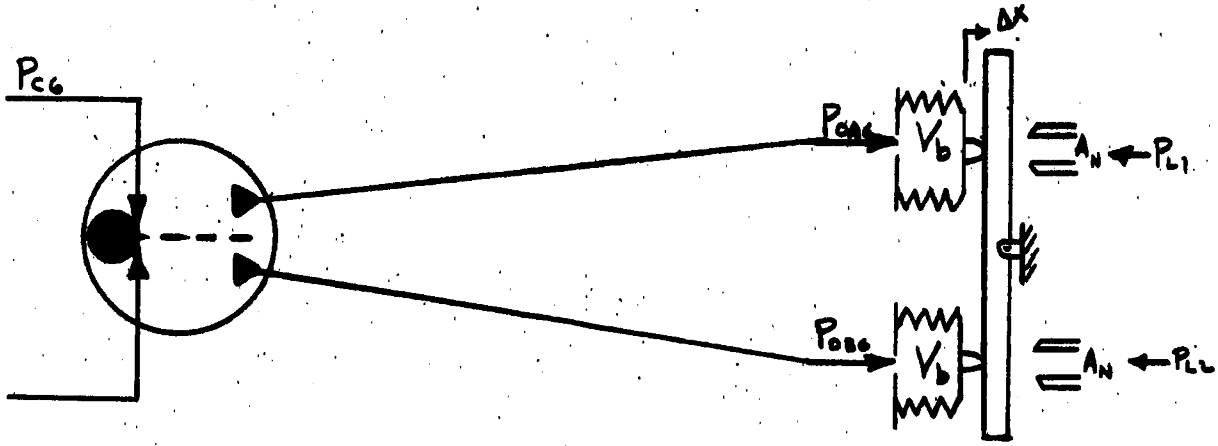


Exhibit 4.13 Driver Amplifier Schematic

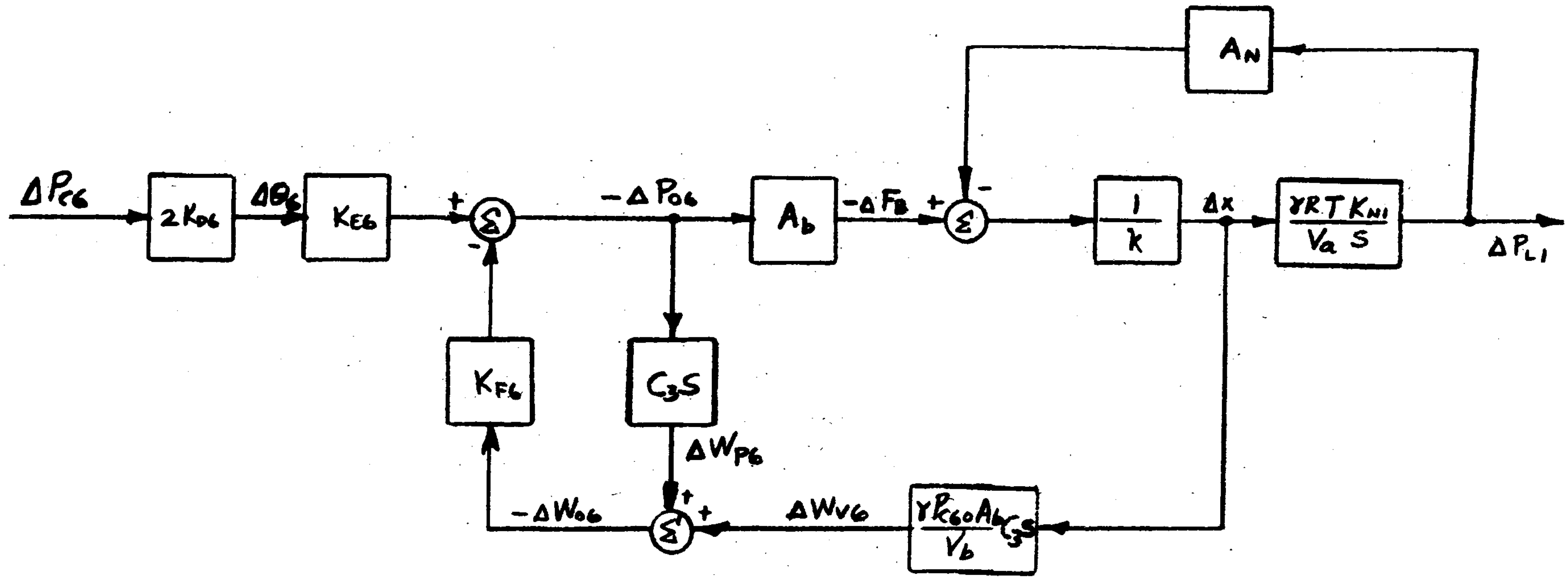


Exhibit 4.14 Block Diagram of Driver Amplifier Dynamics

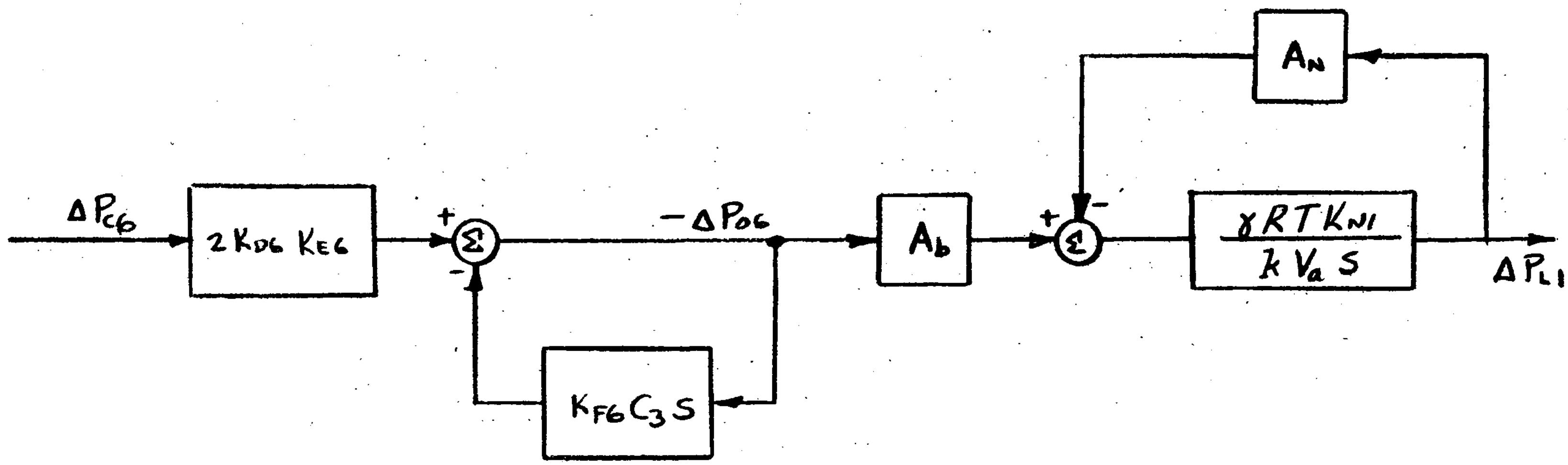


Exhibit 4.15 Simplified Driver Amplifier Block Diagram Neglecting Velocity Flow

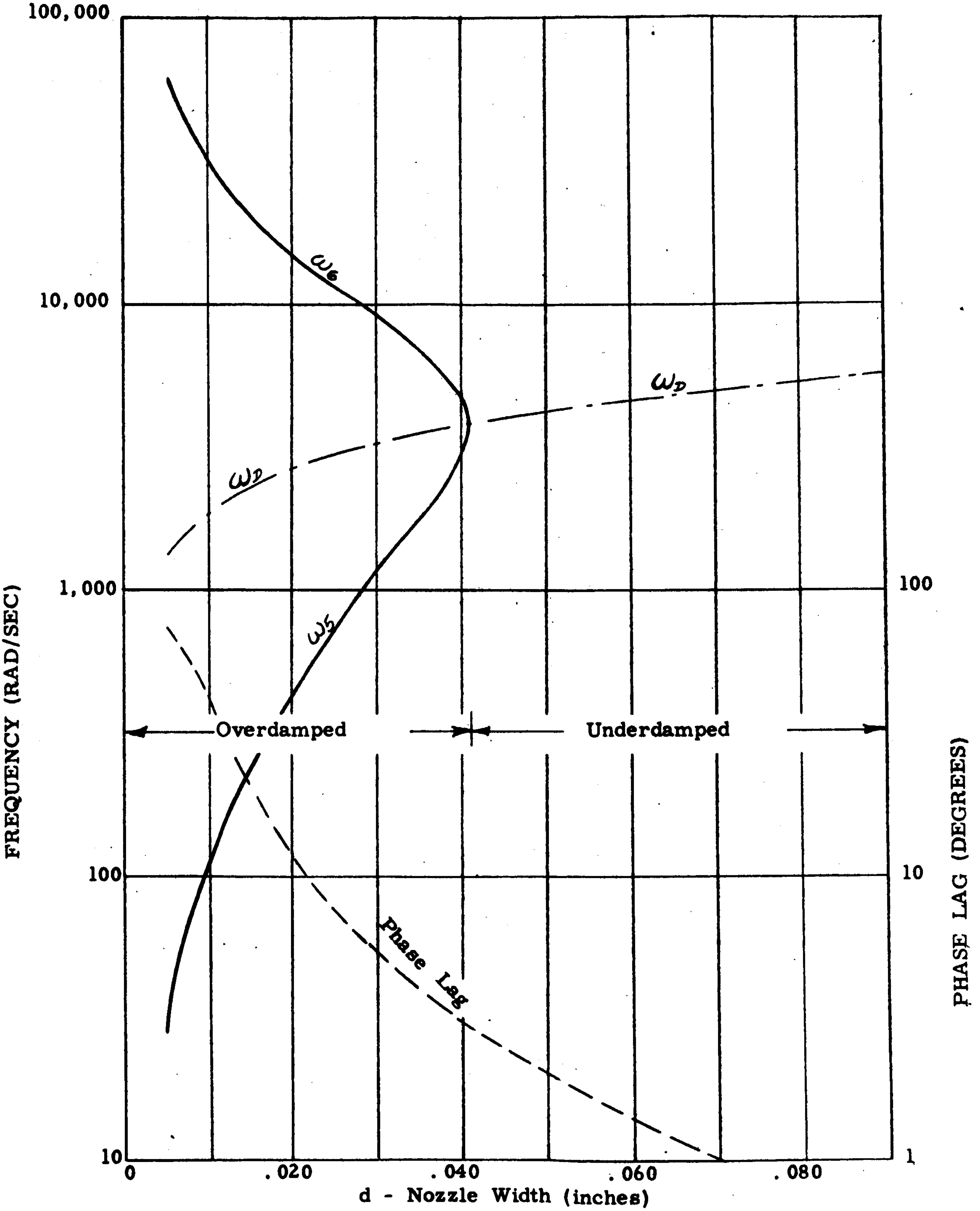


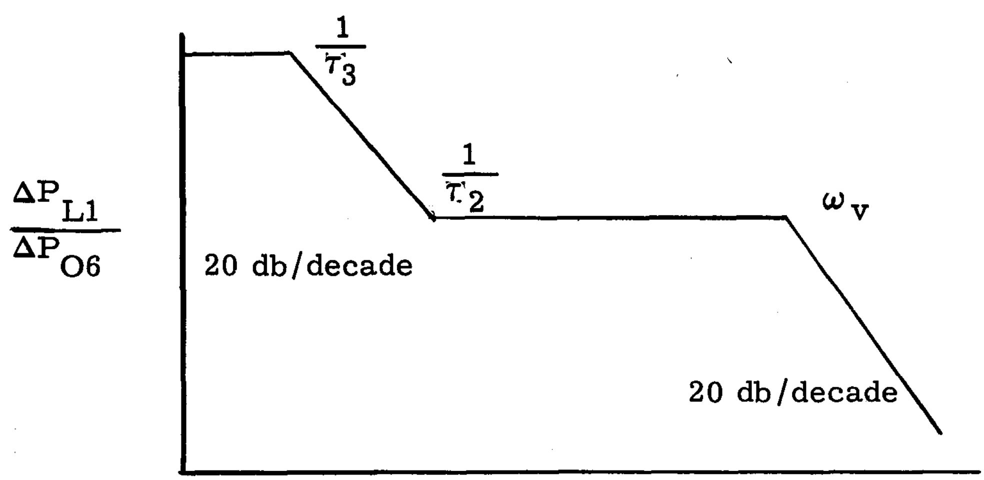
Exhibit 4.16 - Effect of Nozzle Width on Driver Amplifier Dynamics

5.0 COMBINED CONTROL SYSTEM USING PRESENT SINGLE STAGE POWER CONTROL VALVE

The present power control valve is driven by a torque motor and contains its own lag-lead compensation. It is proposed, as the simplest step forward, to replace the torque motor with the driving bellows as described in the previous section. The resulting arrangement will be as shown in Exhibit 5.1.

5.1 Valve Characteristics

The power valve of Exhibit 5.1 will have a different response from the torque-motor driven electropneumatic valve. As a result, the transfer function from input pressure P_{O6} to output load pressure P_{L1} will have the following characteristic:



In this case the break at ω_v is a first order break instead of a slightly under-damped resonance as in the case of the electropneumatic valve. Currently, ω_v is 300 to 360 rad/sec in the electropneumatic valve. It is proposed to increase this value of ω_v to 470 rad/sec by valve geometry changes which specifically involve a 9.3% increase in nozzle diameter and a 19.4% increase in feedback bellows area.

5.2 Shaping Network

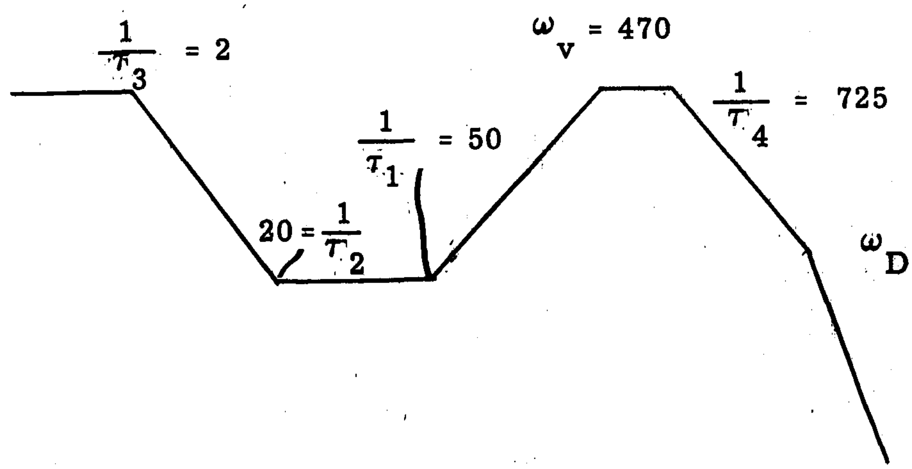
Since the lag-lead function is built into the valve, the only compensation necessary is the lead-lag network of section 4.4, and Exhibit 4.10. This will produce a lead at 50 rad/sec and a lag at 725 rad/sec.

5.3 Driving Amplifier

The force to drive the valve is approximately three pounds maximum.

To avoid excessive "velocity flow" effects described in Section 4.5, the driving bellows area must be 0.25 in^2. This implies a pressure swing of 12 psi in the bellows to obtain the three pound force. Such a swing is possible if the driver amplifier supply pressure is 70 psia for a 50 psia vent.

At this point, we must consider overall phase lag of the system. The attenuation from P_{O6} to P_{L1} will now be as follows:



It is necessary to determine ω_D to give phase lag equivalent to the electro-pneumatic components. ω_D cannot produce more than 3 to 3.5 degrees phase lag at 100 rad/sec. From Exhibit 4.16 this indicates a driver amplifier with a .035" nozzle width.

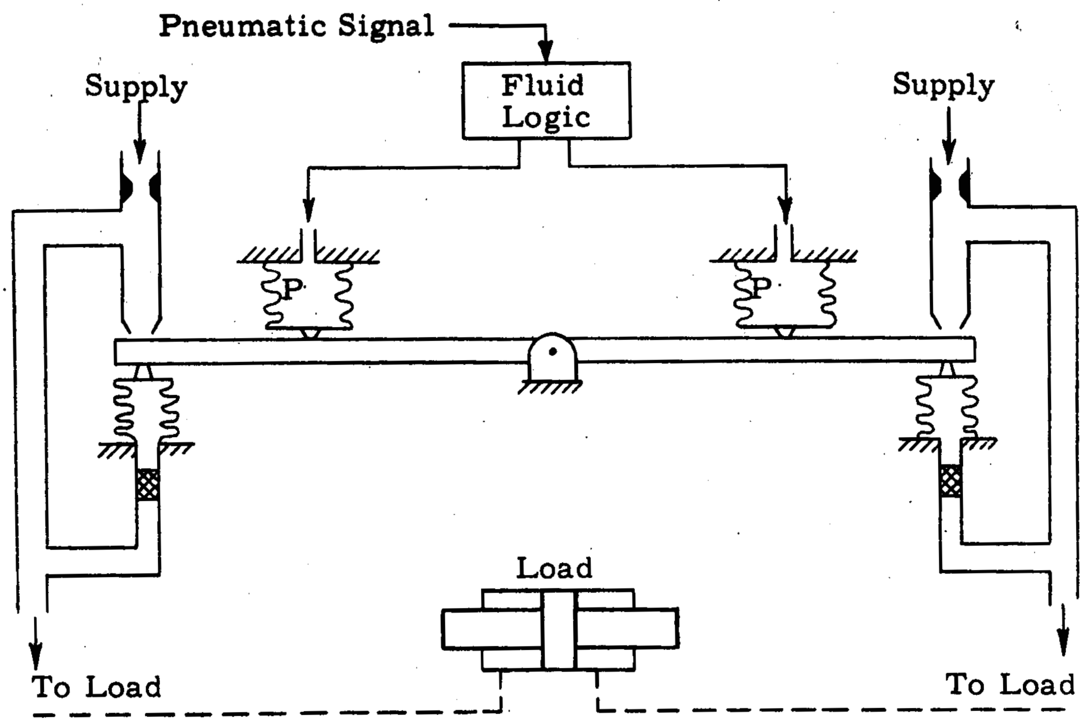


Exhibit 5.1 Single Stage Power Valve Based on Present Electropneumatic Valve

6.0 COMBINED SYSTEM USING SIMPLIFIED SINGLE STAGE POWER VALVE

By removing the feedback bellows from the valve of Exhibit 5.1, a considerable simplification can be obtained and potential reliability improved. The feedback bellows must contain full load pressure (up to 165 psid) as compared with the driver bellows which will see only 20 psid. The resulting valve is shown in Exhibit 6.1.

6.1 Valve Characteristics

In this case, the valve can be considered a first order break since the lag-lead circuit is removed. The break will again occur at 470 rad/sec by making the minor modifications of Section 5.1.

6.2 Shaping Network

The necessary shaping network must have both a lag-lead and a lead-lag. Using the results of Sections 4.3 and 4.4, the shaping network of Exhibit 6.2 will result. This will produce lags at 2 and 725 rad/sec, and leads at 20 and 50 rad/sec.

6.3 Driver Amplifier

Driver amplifier requirements are identical with those of Section 5.3 and can be satisfied if

$$d = .035''$$

$$P_S = 70 \text{ psia}$$

$$P_D = 50 \text{ psia}$$

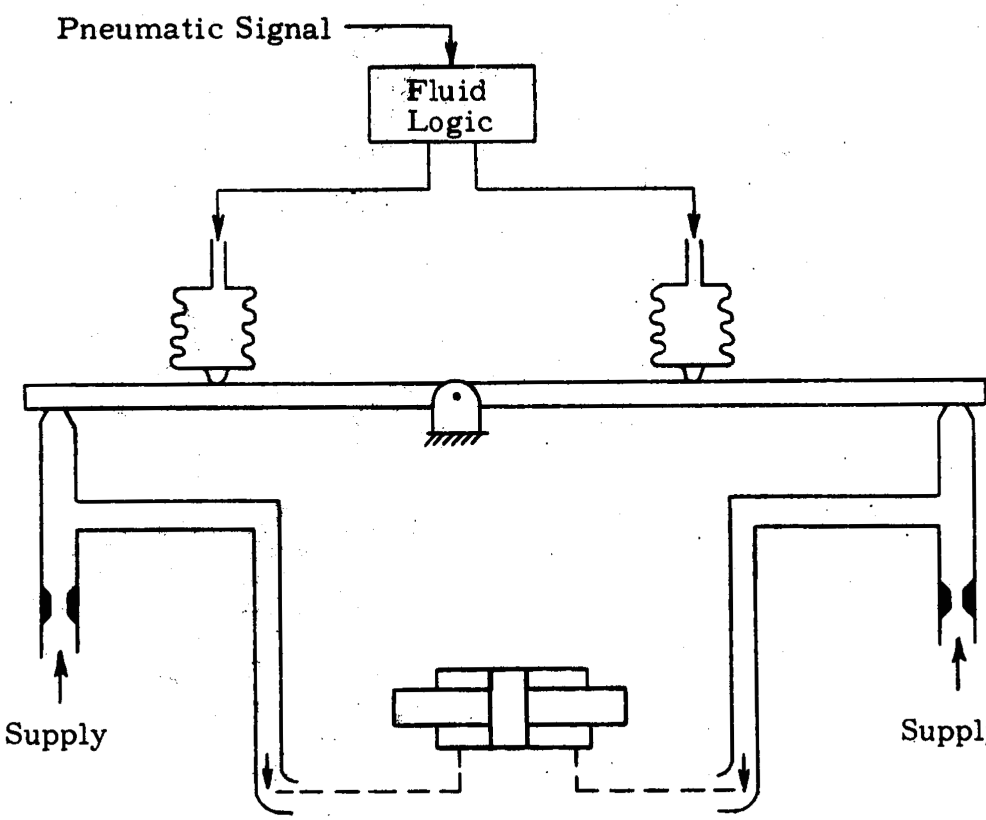


Exhibit 6.1 Simplified Single Stage Power Valve

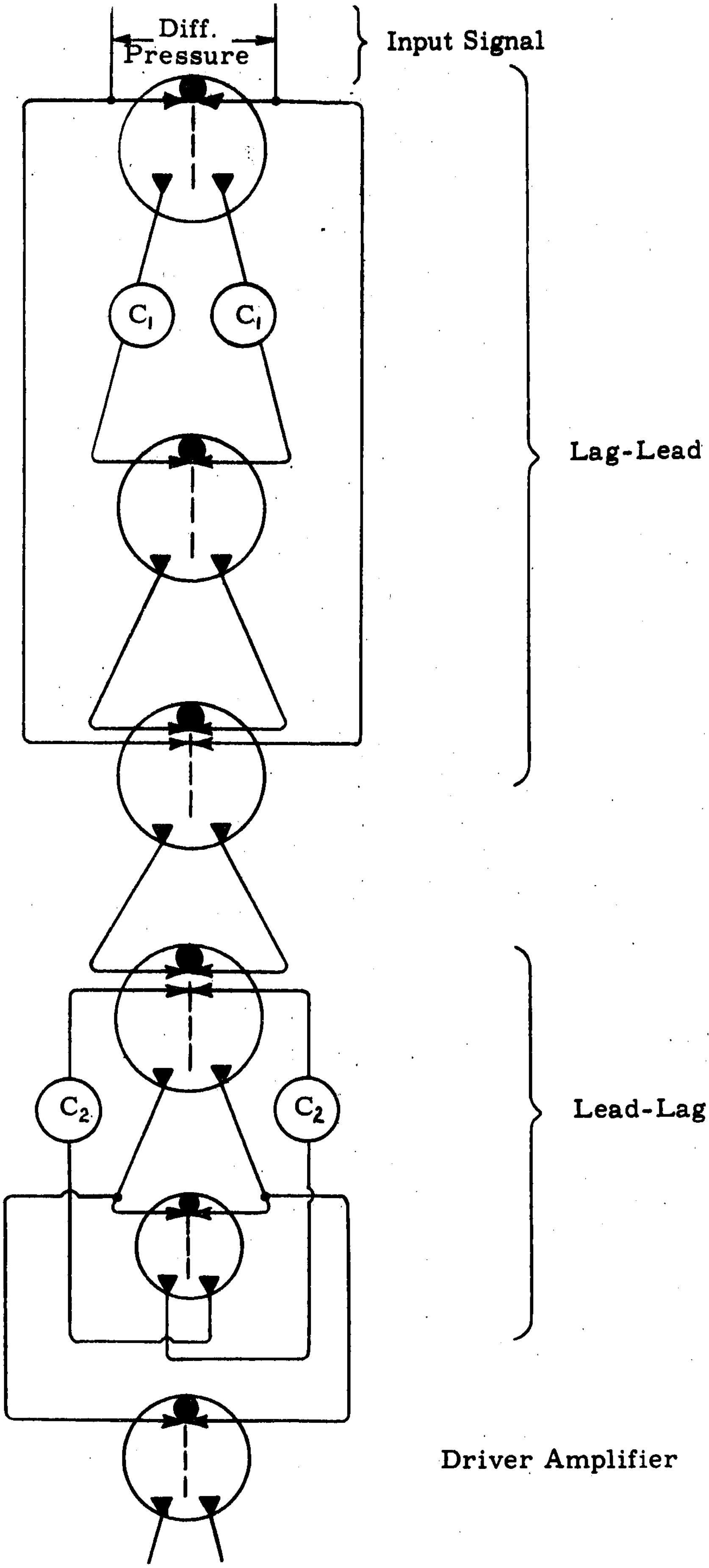


Exhibit 6.2 Combined Shaping Networks and Driver

7.0 COMBINED SYSTEM USING TWO STAGE POWER VALVE

The two-stage power control valve has more moving parts but requires virtually no quiescent power flow. The valve of this type is shown in Exhibit 7.1.

7.1 Valve Characteristics

A detailed study of the valve was not carried out on this project. However, one thing is self evident from Exhibit 7.1. It can be seen that, to get a force balance on the driver bellows, the driver amplifier's output pressure must equal the load pressure. This implies either a separate high pressure supply for the driver amplifier or else a reduced output from the power valve.

7.2 Shaping Networks

Again, both the lead-lag and lag-lead must be provided. The shaping network will be identical to Exhibit 6.2.

7.3 Driver Amplifier

Since typical maximum recoveries of analog amplifiers can be on the order of 70%, a 285 psia supply must be provided to the driver stage if 215 psia is to be recovered at the driver bellows. No attempt was made to accurately size the driver for this case. However, it was assumed that a .035" nozzle width would be satisfactory for purposes of estimating gas flows. The gas flow estimates are given in Section 9.0.

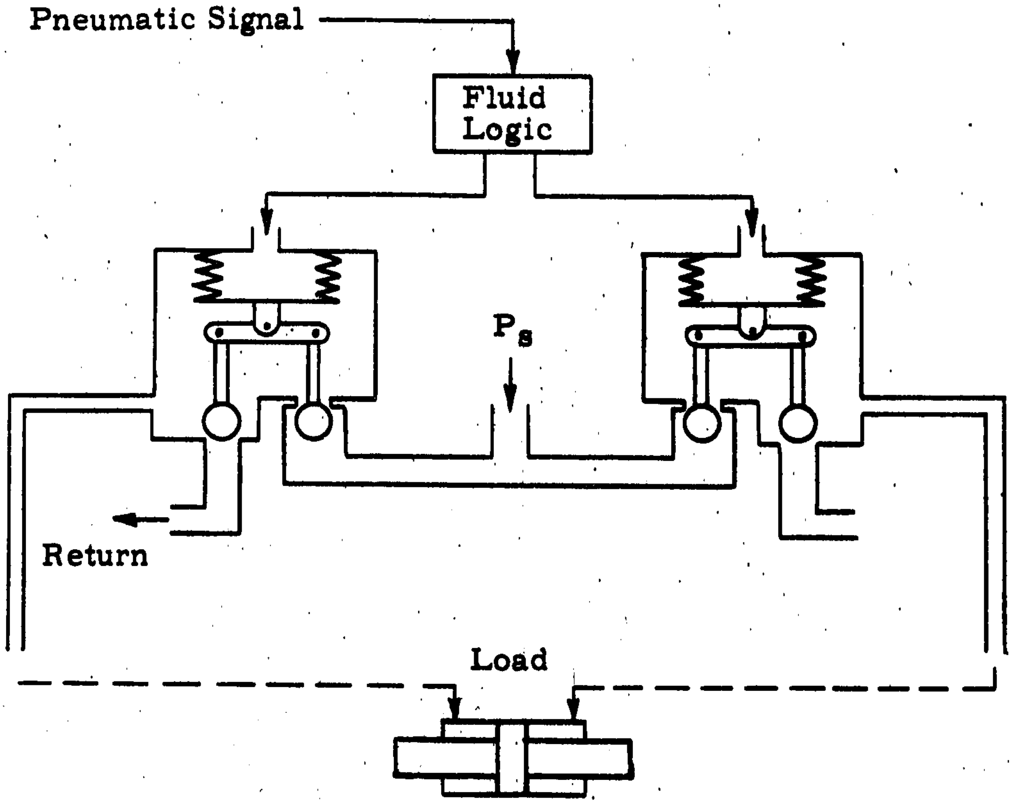


Exhibit 7.1 Two-Stage Power Valve

8.0 COMBINED SYSTEM USING VORTEX TYPE POWER CONTROL VALVE

The vortex valve is one promising means of controlling fluid flow without using moving parts. In this section, the most effective approach to the use of vortex valves will be discussed. To get the necessary signal shaping, beam deflector analog amplifiers will still be used.

8.1 Valve Characteristics

The vortex valve is a variable restrictor with two inlets and one common outlet. The man inlet flow is usually referred to as Q_S, the smaller control (tangential) inlet flow is called Q_C. For a given pressure P_R in the main inlet, Q_S can be decreased to zero by raising Q_C to a high enough value. Q_C is raised as P_C is raised. Exhibit 8.1 shows the non-dimensionalized variation of Q_S with P_C. The value of Q_S is that for which $P_C = O$. The curve is extracted from data taken with oil and applies for incompressible operation only. To date, the bulk of data has been taken on oil and low pressure air. As yet, a non-dimensionalized presentation of data for compressible flow has not been devised. As a result, the ensuing discussion is limited to the incompressible case. Additional work is called for in investigating compressible effects in vortex valves (A).

Regardless of compressible effects, the discharge flow is the sum of Q_C and Q_S. It obviously cannot go to zero. Therefore it will be more effective to place the vortex valve downstream of the load. To get push-pull operation, the valves are arranged in a bridge as shown in Exhibit 8.2. Let Kv represent the flow through the fixed orifice at a given pressure drop divided by the flow Q_S through the vortex valve at the same pressure drop with no control flow. Then Exhibit 8.3 shows variation of the blocked load pressure, P_A, of one side of the bridge for two values of Kv. Kv was chosen as $\sqrt{5}$ and $\sqrt{49}$ to get results over a fairly wide range. The curves of Exhibit 8.3 show that the level of P_A is generally higher for $Kv = \sqrt{5}$ than for $Kv = 7$. This is to be expected, for $Kv = 7$ will take a larger proportionate drop across the fixed orifice. Now, if the operation is push-pull, some quiescent value of P_C must be chosen. In the case of $Kv = \sqrt{5}$, $P_{CO}/P_S = 0.7$ was used. In the case of $Kv = 7$, $P_{CO}/P_S = 0.45$ was used. With these quiescent values of P_C, the push-pull blocked load characteristics for $Kv = 7$ and $Kv = \sqrt{5}$ are plotted in Exhibit 8.4. Although a higher gain is exhibited with $Kv = 7$, the output saturates at $(P_{CA} - P_{CB})/P_O \approx .9$ when one control pressure goes to zero. In general, the characteristic when $Kv = \sqrt{5}$ is more desirable. Further decrease of Kv does not result in improvement of the operation.

Exhibit 8.4 shows that the maximum output swing is 40% of the supply pressure and corresponds to a control pressure swing of 160%. This is an

Note A - A discussion of compressible vortices may be found in: Shapiro, A.H.; "The Dynamics and Thermodynamics of Compressible Flow," Vol. II, pp 776 ff.

attenuation in pressure signal, and not encouraging. However, it is felt that refinements in vortex valve design may improve performance. Although pressure gain is less than unity, flow gain can be fairly large.

8.2 Shaping Networks

The vortex valve is assumed to have negligible lags. Actual time constants will be on the order of the "fill time" of the valve, which is small. The shaping networks will again consist of the lead-lag plus lag-lead of Exhibit 6.2.

8.3 Driving Amplifier

The driving amplifier of the vortex valve circuit was not analyzed since the input requirements to the vortex valve are not yet fully defined. However, one generalization can be made. The output pressure of the driving amplifier must be considerably larger than the required load pressure. This implies either a separate high pressure gas supply for the shaping networks and driver amplifier or else a very de-rated power valve if pressures greater than the present 215 psia are not obtainable. Taking the incompressible case as a guide in selecting values, the implications of holding supply pressure at 215 psia are:

a. The max pressure swing of the driver amplifier will be 0.6 (215-50) = 99 psi.

b. 99 psi corresponds to 1.6 x $(P_O - P_D)$ (the bridge supply pressure). Thus

$$P_O - P_D = \frac{99}{1.6} = 61.9 \text{ psi}$$

c. The maximum output pressure swing of the vortex valve bridge is 40% of the bridge differential supply pressure. Thus load pressure swing = $\pm$ 24.76 psi.

d. Theoretically the present electropneumatic valve can swing from 50 to 215 psia for a swing of 165 psia.

e. The resulting actuator for use with a vortex valve must have an area 6.67 times that used with the present electropneumatic valve.

Since the above conclusions are based on incompressible flow calculations, they should be approached with caution. It is believed that they give at least a qualitative insight into the problems to be expected.

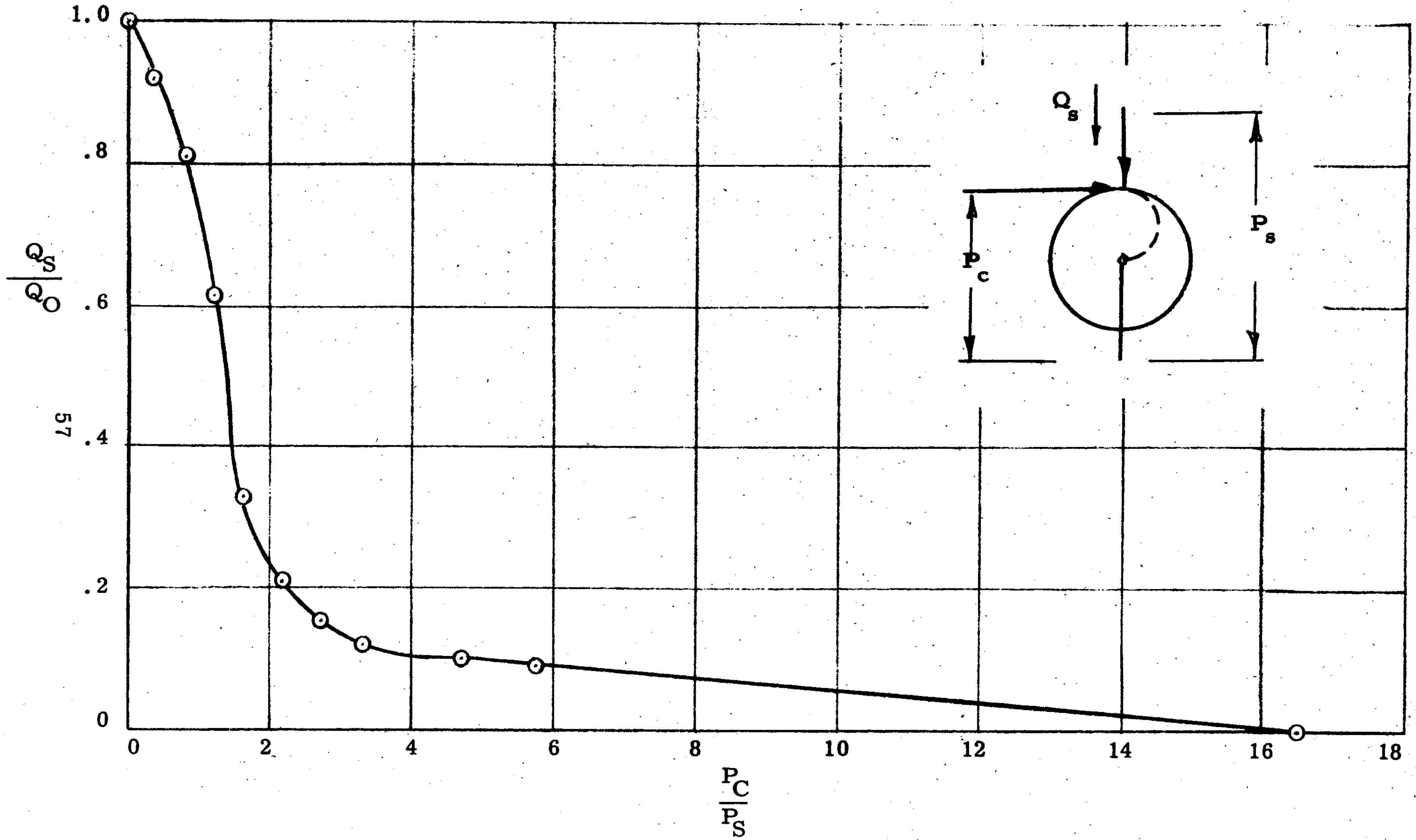


Exhibit 8.1 - Normalized Vortex Valve Characteristic

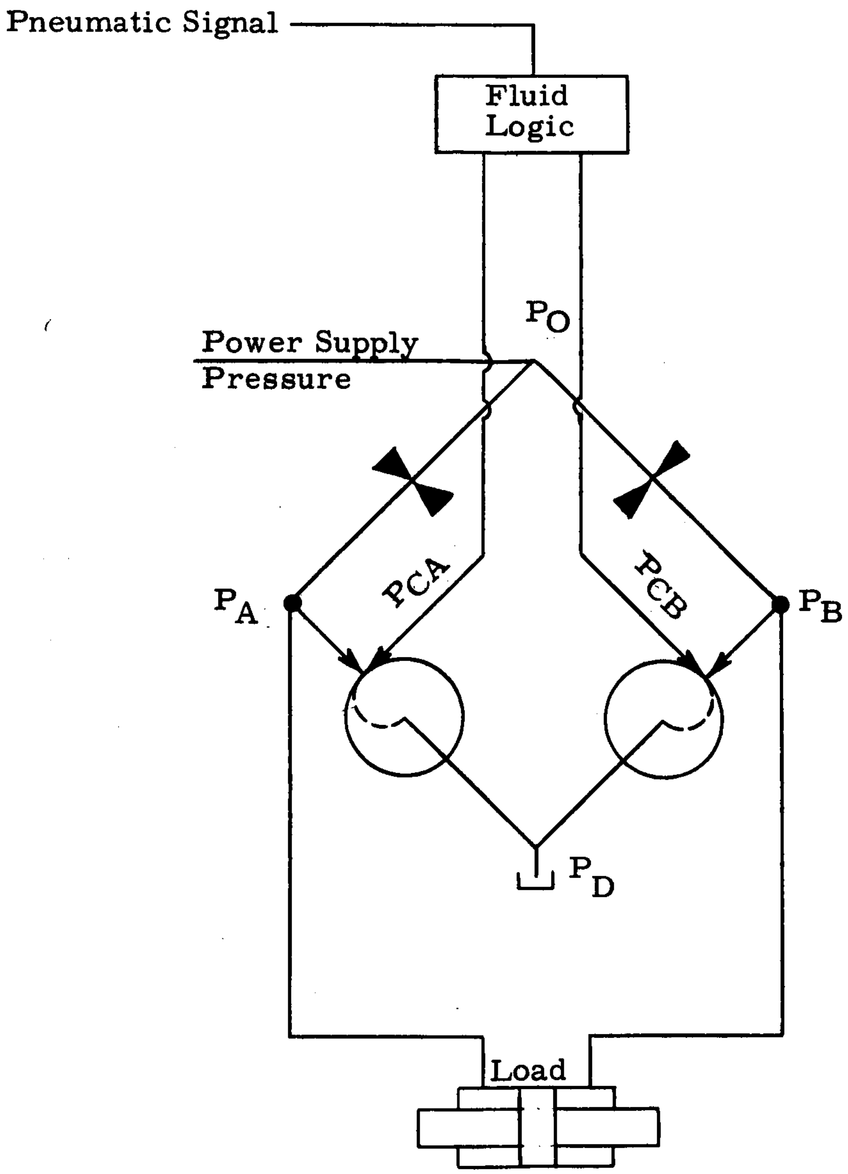


Exhibit 8.2 Vortex - Bridge Type Power Control Valve

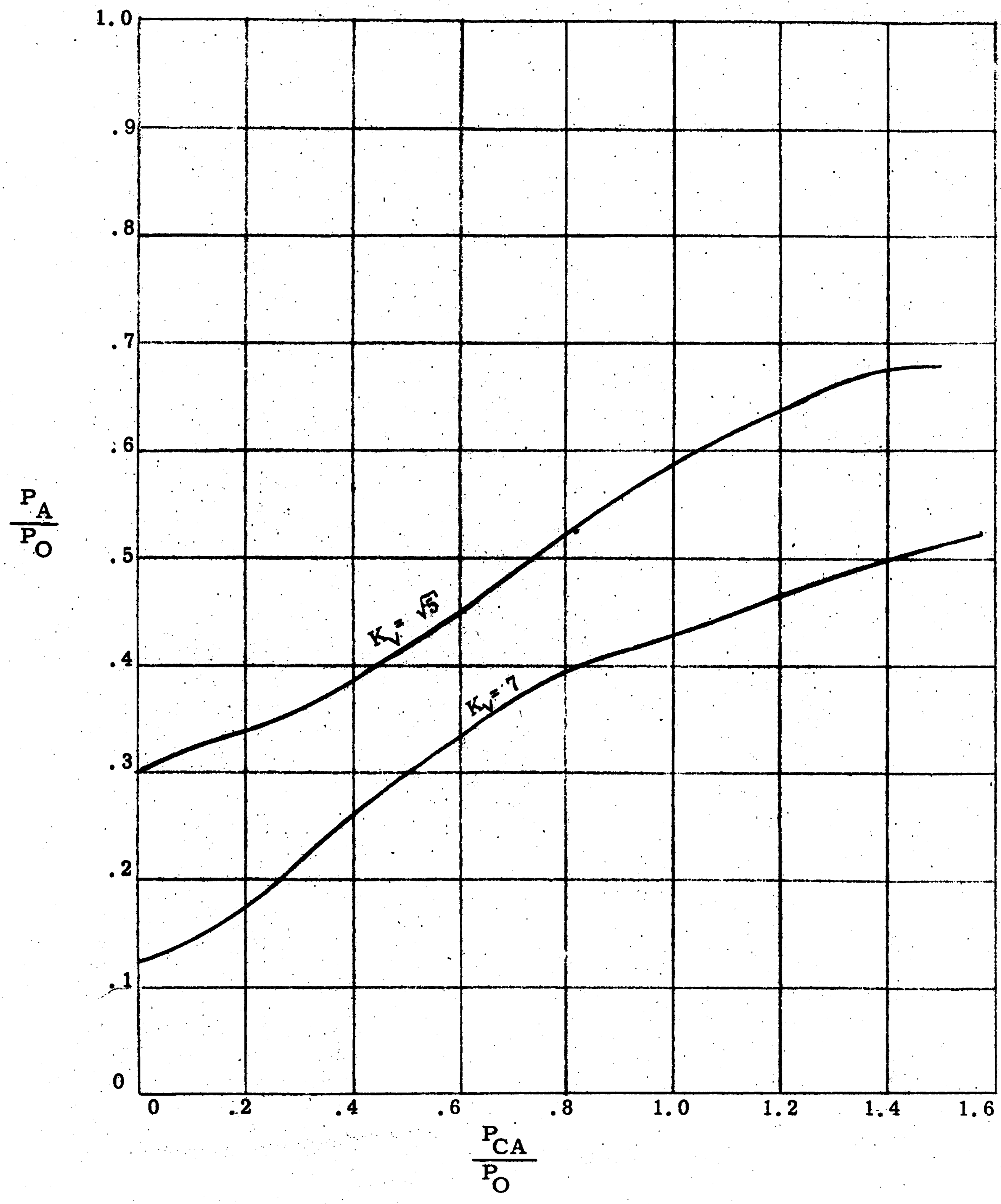


Exhibit 8.3 - Blocked Load Characteristics of One Side of Vortex-Bridge

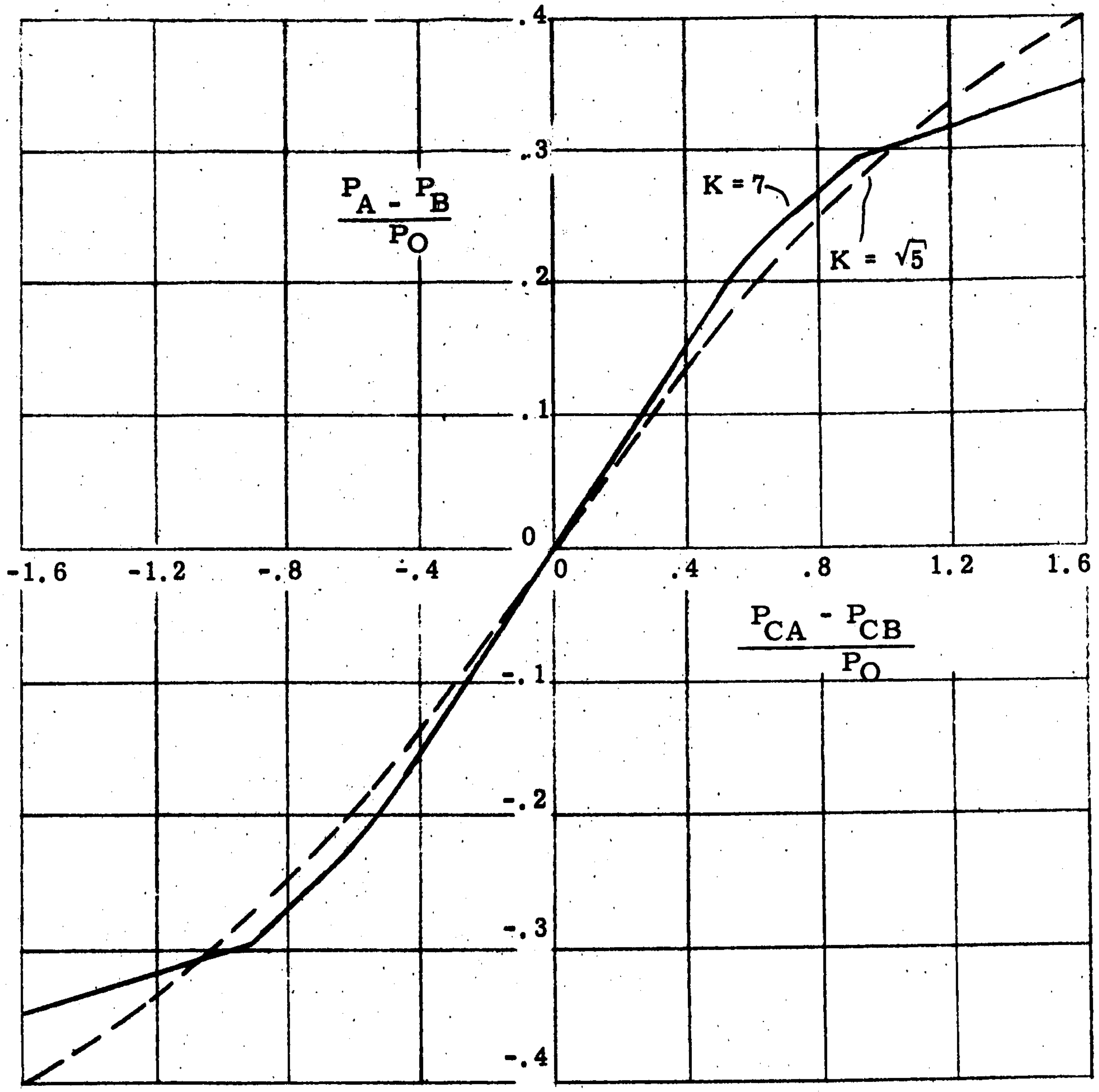


Exhibit 8.4 - Blocked Load Characteristics of Complete Vortex Bridge

9.0 HYDROGEN FLOW REQUIREMENTS

Hydrogen flow requirements were computed from perfect gas relationships using the following constants:

α = specific heat ratio = 1.5

R = gas constant = 9300 in/^{O}R

T = supply temperature = 100^{O}R

The system being considered will have a maximum pressure of 215 psia and all exhaust or vent flow is to a 50 psia return line.

Exhibit 9.1 shows hydrogen flow through various size amplifiers where supply pressure of the amplifier is held constant at 215 psia and the back pressure of the amplifier is varied from 50 to 215 psia.

Exhibit 9.2 shows the other alternative. Here hydrogen flow for various size amplifiers is shown as a function of supply pressure with back pressure held at a constant 50 psia.

Exhibit 9.3 is a tabulation of the expected hydrogen flows of the systems considered. Time did not permit a complete evaluation of hydrogen flows in the vortex valve system. However, it was assumed that 215 psia would be used in the logic of both the vortex and two-stage valve systems since they will require high pressure levels at the inputs to the power control valves.

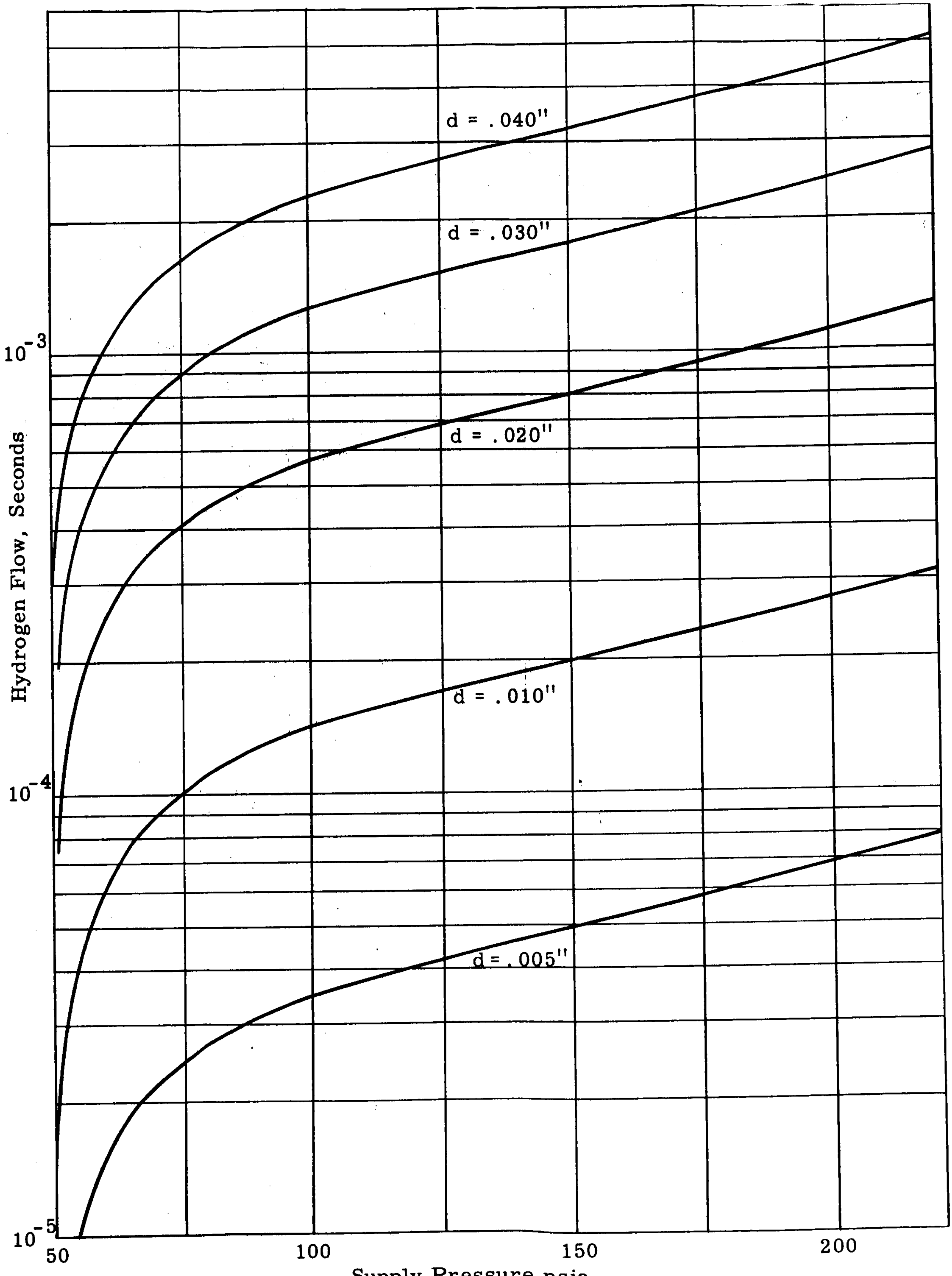


Exhibit 9.1 Hydrogen Flow as a Function of Amplifier Size and Supply Pressure Assuming 50 psia return Pressure

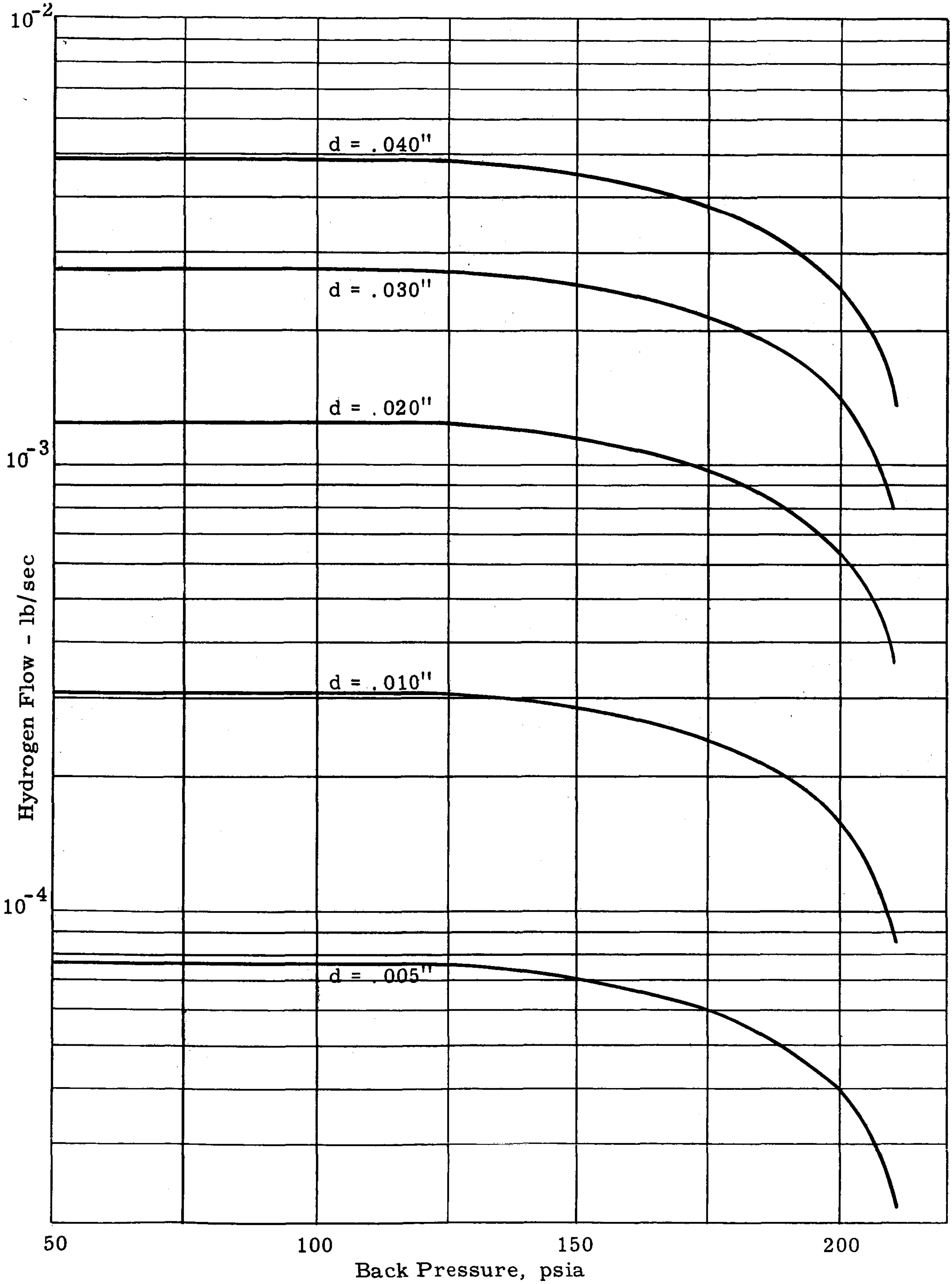


Exhibit 9.2 Hydrogen Flow as a Function of Amplifier Size and Return Pressure Assuming 215 psia Supply Pressure

System	No. of Stabilizing Stages	Stabilizing Stage Pressure (psia)	Total Stabilizing Stage Flow (Lb/sec)	Driver Stage Flow (Lb/sec)	Position Error Stage Flow (Lb/sec)	Total "Logic" Flow (Lb/sec)	Power Valve Leakage (Lb/sec)	Total System Flow (Lb/sec)
Section 5.0 (Normal 1-Stage Power Valve)	2	60	.000124	.001100	.000062	.001286	.0055	.00679
Section 6.0 (Simple 1-Stage Power Valve)	5	60	.000310	.001100	.000062	.001472	.0055	.00697
Section 7.0 (2-Stage Power Valve)	5	215	.001500	.003800	.000300	.005600	≈ 0	.00560
Section 8.0 (Vortex Power Valve)	5	215	.001500	?	.000300	.0018+?	?	?

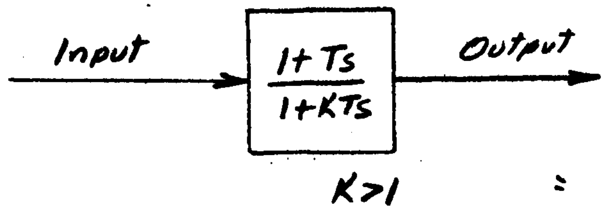
Exhibit 9.3 - TABLE OF EXPECTED HYDROGEN FLOWS

APPENDICES

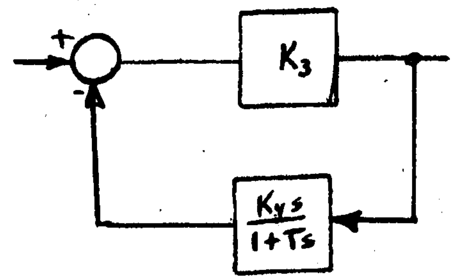
APPENDIX A

The following diagrams illustrate various alternate approaches to the lag-lead circuit that were considered in the study. These were eliminated for one or more of the following reasons: complexity, nonlinearities due to compressible flow through the orifices used in each circuit, and expected problems in maintaining tolerances of the restricting orifices.

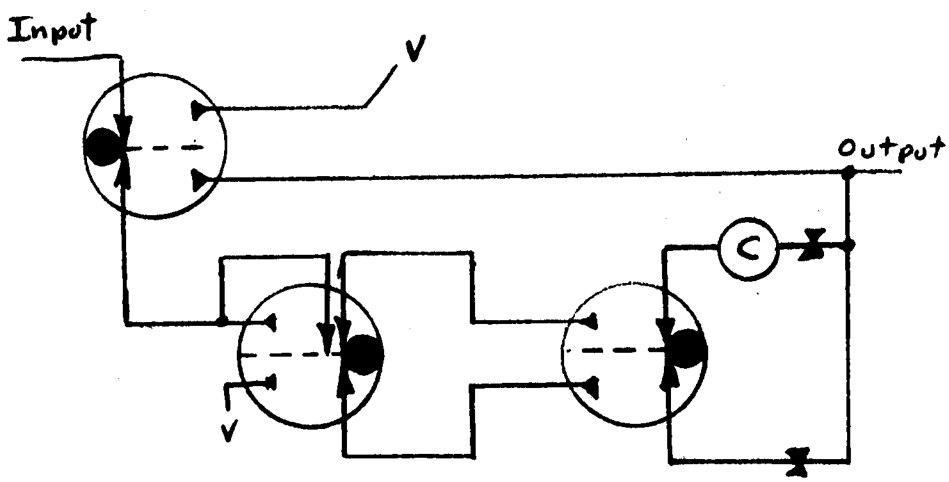
Lag-Lead CKt



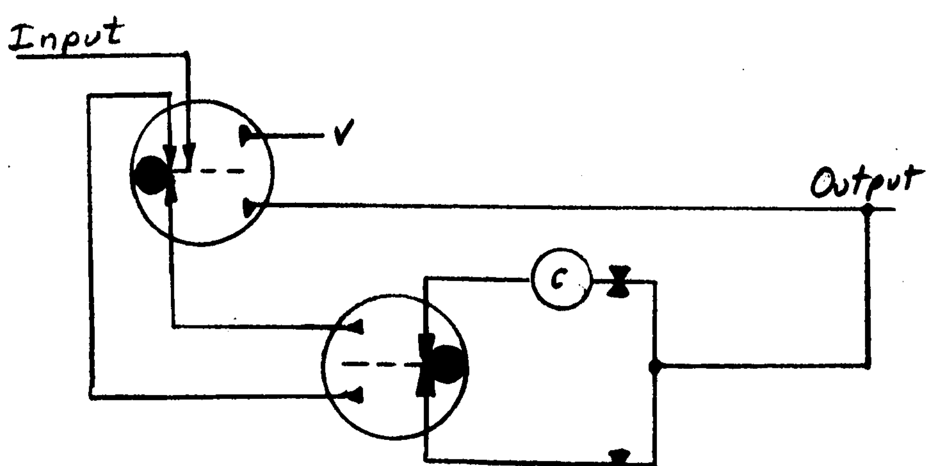
=



Single Output Approach (1)

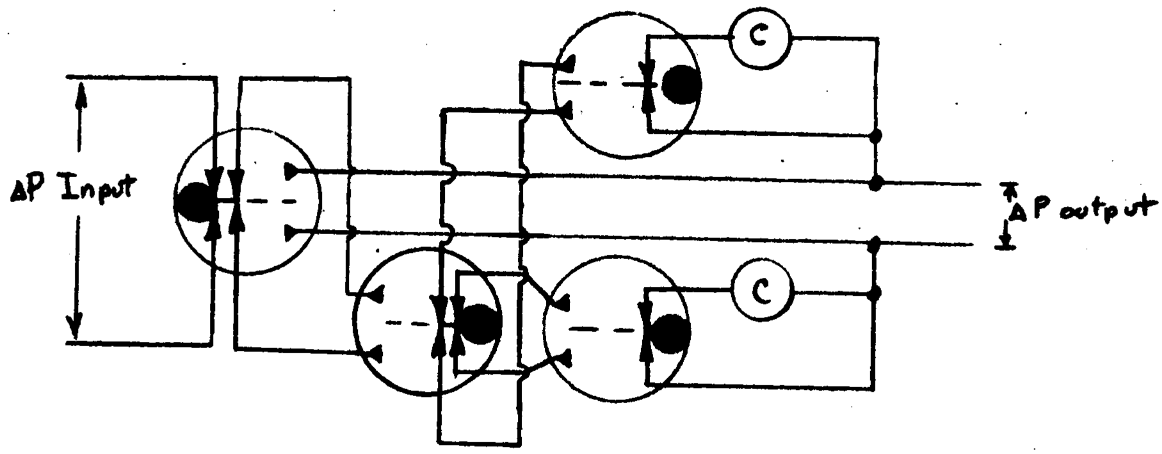


Single Output Approach (2)



Lag Lead (Continued)

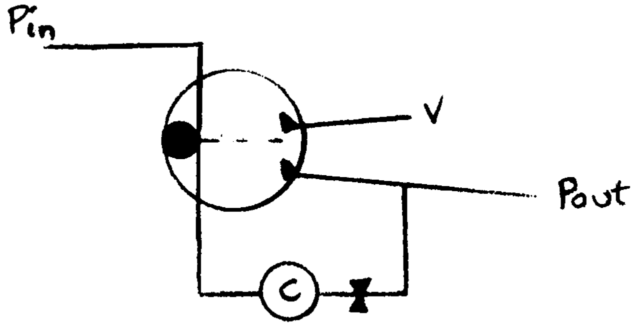
Double-Ended Output



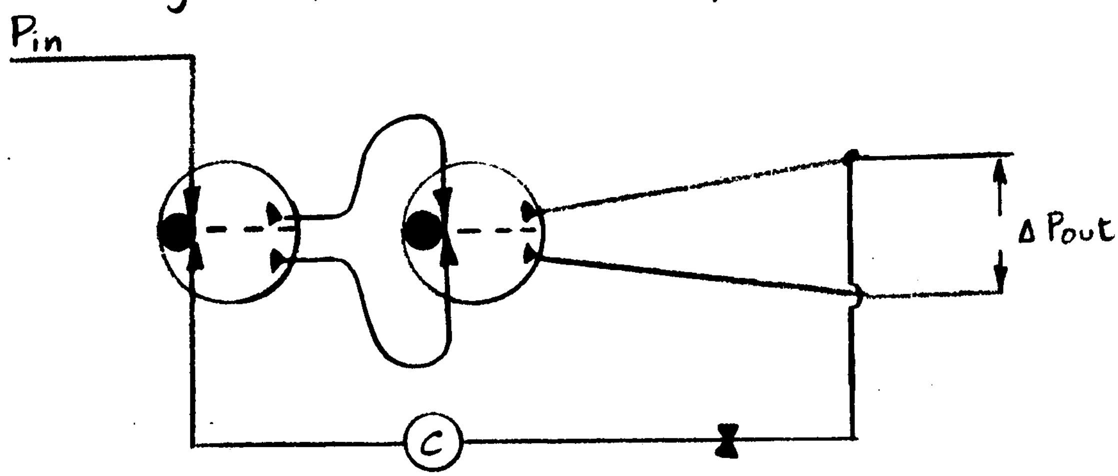
APPENDIX B

The following diagrams illustrate various approaches to the lead-lag circuit that were considered in the study. These were eliminated for the same reasons given in Appendix A.

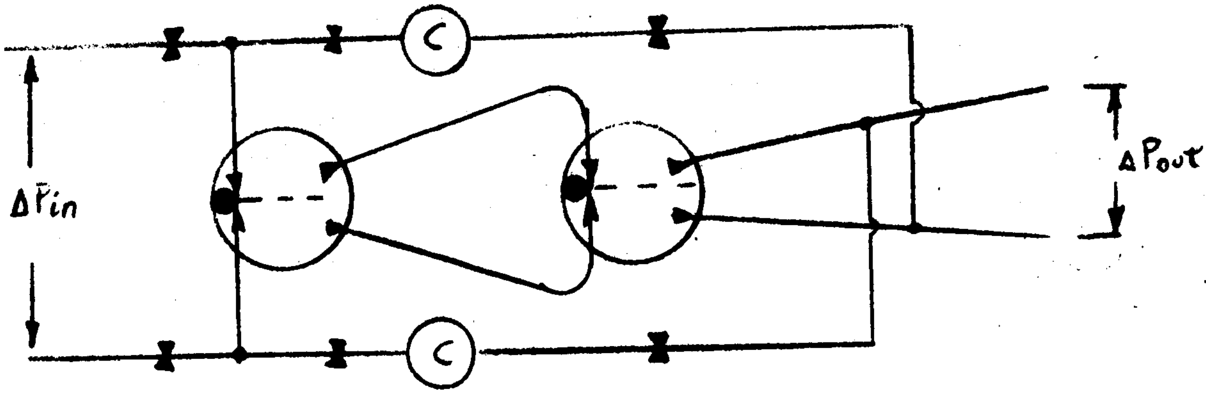
(1) Single input - single output



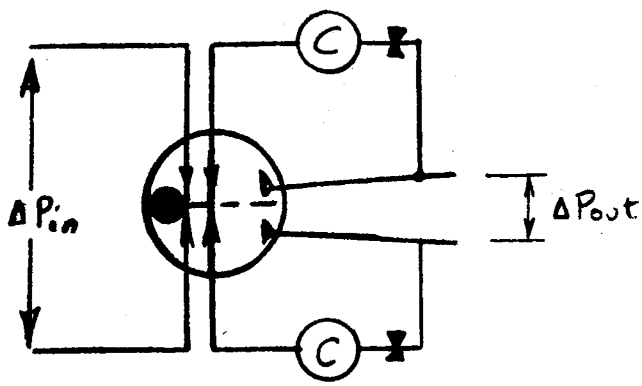
(2) Single input - double output



(3) Push-pull with two input elements



(4) Push-pull with 4 input element



APPENDIX C

SCHEMATIC SYMBOLS FOR FLUID TRANSISTORS AND CIRCUITRY

Extracted from a paper by W. A. Boothe and J. N. Shinn presented to the 1962 DOFL Fluid Amplifier Symposium.

APPENDIX C

SCHEMATIC SYMBOLS FOR FLUID TRANSISTORS AND CIRCUITRY

C.1.1 Fundamental Delineations

Fluid amplifiers can be categorized in many ways. However, several basic questions about a fluid amplifier element come to mind immediately. Is it digital or analog in nature? Is it a beam deflector type element or a vortex element? Is it active or passive? These questions can be answered quite simply in schematic form. Our usage has been to denote the flow path of the power jet of an analog valve with a dashed line whereas a digital element is represented with solid lines throughout. Exhibit C-1 shows this usage applied to simple beam deflector amplifiers. The use of the enclosing circle around the element has been optional with us. In simpler schematics it is not used, while in more complicated ones it makes the element stand out from the connecting lines. The input and output lines of the elements appear in the schematic at the same points where they normally would on the actual element, as pointed out in Exhibit C-1. Exhibit C-2 shows the symbols used for vortex amplifiers which may also be digital or analog in form.

As shown in Exhibit C-3, the designation as to whether a valve is active or passive is done by means of a solid circle at the base of the power nozzle line to indicate that this line is connected to the circuit supply pressure. If more than one pressure supply level is used in a circuit, a letter or number code can be used to differentiate between those used.

C.1.2 Schematics for Analog Devices

The basic form of analog valve symbols are given in Exhibits C-1(b) and C-2(b), where the main distinguishing feature is the dashed line to represent the flow path of the power jet. The possible variations of these basic representations are so numerous that they can not be covered completely in this paper. However, one shorthand representation believed worth mentioning is that of the operational amplifier. Exhibit C-4a shows an arbitrary example of a schematic for a high gain four stage operational amplifier. The outputs in this example will be a function of the difference between input A and input B, the function depending on the feedback impedances Z_1 and Z_2 which provide in this instance negative and positive feedback, respectively. Exhibit C-4b shows the shorthand symbol for the same circuit. In this symbol the asterisk is used to indicate the sense or polarity. For example, in Exhibit C-4b this notation indicates an increase in input A results in an increase in output C to correspond with the circuit in Exhibit C-4a. If an odd number of stages were used, the asterisk would, of course, appear behind D. This convention permits the schematic to have close correspondence with the physical circuit layout.

C.1.3 Schematics for Digital Devices

The schematic for a basic flip-flop, shown in Exhibit C-5, is quite similar to the physical layout of the device. An input of A will cause an output at D and an input at B will switch the flow to C. The symbol for a fluid source indicates that the flip-flop in the example is an active device. The schematic for the binary flip-flop, such as the counter stage developed by R. W. Warren at DOFL, is shown in Exhibit C-6. Input pulses at A switch the flow alternately to outputs C and D. A re-set signal pulse applied at the RS input will switch the second stage jet to output D. The schematic indicates the second stage of the binary flip-flop to be an active device.

The schematic for an active or--nor element is shown in Exhibit C-7(a). Inputs at C or D or E will cause an output at B, thus performing the "or" function. With no input signal the output is at A, performing the "nor" function. Using conventional logic notation the element is identified as an or-nor by including the + sign. The choice of three inputs for the example in Exhibit C-7(a) was arbitrary; an "n" input element would be shown schematically with "n" input lines. Exhibit C-7(b) shows a passive "or" element.

Exhibit C-8 shows the schematic for the active and passive "and" elements. Using standard logic notation for an "and", the function of the element is identified by a dot. An output at B will occur only when inputs C and D and E all are present.

The "half adder" or "exclusive or" schematic is shown in Exhibit C-9. An input at either C or at D, but not both simultaneously, will provide an output at B while simultaneous inputs at C and D provide an output at A. The half adder can also be used as a two input "and" element. This schematic follows closely the general physical layout of one form of a half adder now in use. Although half adders quite different from that shown in the schematic have been devised, this schematic was chosen because it is believed to represent simply and clearly the functioning of the half adder element.

C.1.4 Memory and Biasing

Some devices have memory and thus can operate with input signals in pulse form while others require a continuous input signal for operation. This difference in operating characteristics is delineated on the schematics as illustrated in Exhibit C-10. The arrowheads on the input lines indicate that a continual flow is required to maintain the state of the element. Note that in Exhibits C-7, C-8, C-9 this notation was used to indicate steady state inputs are required to provide the desired performance.

Bias signals are often used to provide desired characteristics. Exhibit C-11 illustrates how a bias signal would be represented schematically on a flip-flop and an "or" element. If an "and" or "or" element is shown without the biasing input line then it is implied to be geometrically biased.

C.1.5 Other Circuit Elements

A fluid circuit would not be complete without the many passive impedance elements such as orifices or restrictions and without showing connections such as vents or drains. To do this we have drawn heavily on JIC practice where practical.

Exhibit C-12(a) shows the general symbol for impedance. Exhibit C-12(b) shows the representation for an orifice which would obey a square-law relationship if an incompressible fluid is used. (No attempt is made here to differentiate between a choked and unchoked flow if the fluid is compressible.) Exhibit C-12(c) represents a laminar restriction where pressure drop varies linearly with flow and where friction effects predominate over inertial effects. Exhibit C-12(d), in turn, shows fluid inductance where inertial effects predominate over friction. A relatively pure fluid inductance is found primarily in liquid circuits.

Exhibit C-12(e) shows the symbol for a fluid capacitor which, in some instances, is analogous to an electrical capacitor. A fluid capacitor consists of a fixed volume if the fluid is compressible, or a hydraulic accumulator or equivalent for an incompressible fluid. In drawing an electrical analogy, where voltage and current are analogous to pressure and flow, respectively, a fluid capacitor such as the volume or accumulator can only be the equivalent to shunt capacitance from the point in question to ground. It is never the equivalent of a blocking capacitor. The equivalent of blocking capacitors must be obtained by using other devices.

Exhibit C-12(f) shows the symbol for a fluid delay line which has the characteristic of providing a pure time delay in the signal transmitted with a minimum of attenuation.

Exhibit C-13(a) and C-13(b) show that crossing and connecting lines follow a practice identical to JIC hydraulic practice as well as some electrical standards.

Vent connections are shown in Exhibit C-13(c) and should be used in any open cycle circuit where the excess fluid is merely vented to atmosphere or drained off.

If a closed cycle circuit is used, the excess and exhaust fluid must be returned to the reservoir. To decrease the number of lines in the schematic it is recommended that the JIC symbol of Exhibit C-13(e) be adopted.

BEAM DEFLECTOR AMPLIFIERS

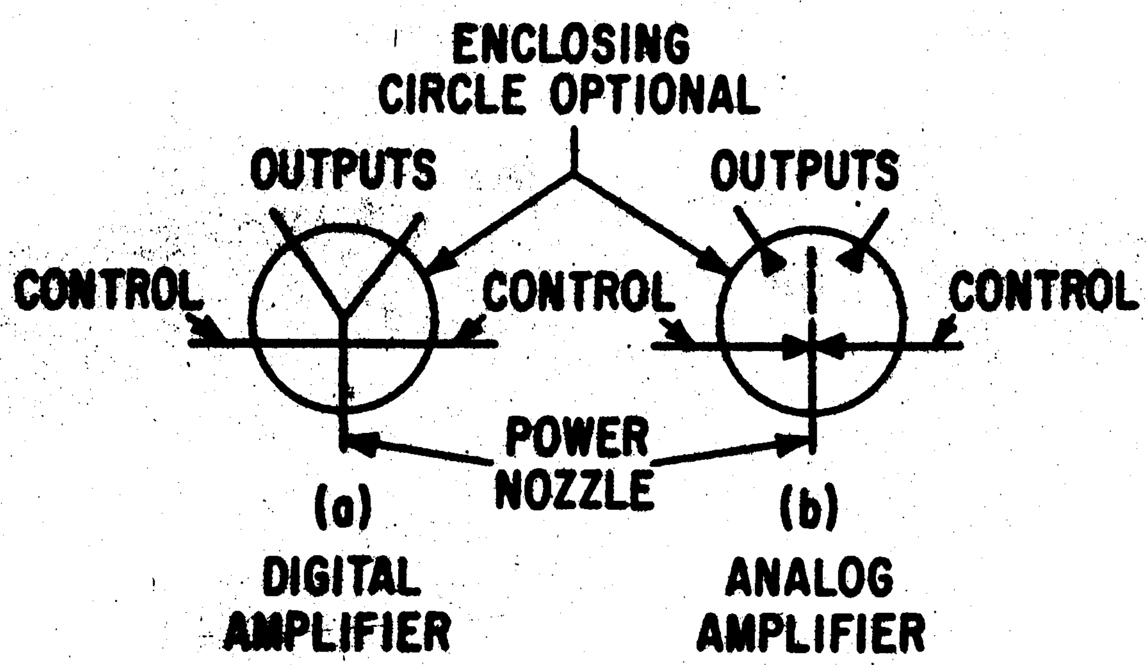


Exhibit C-1

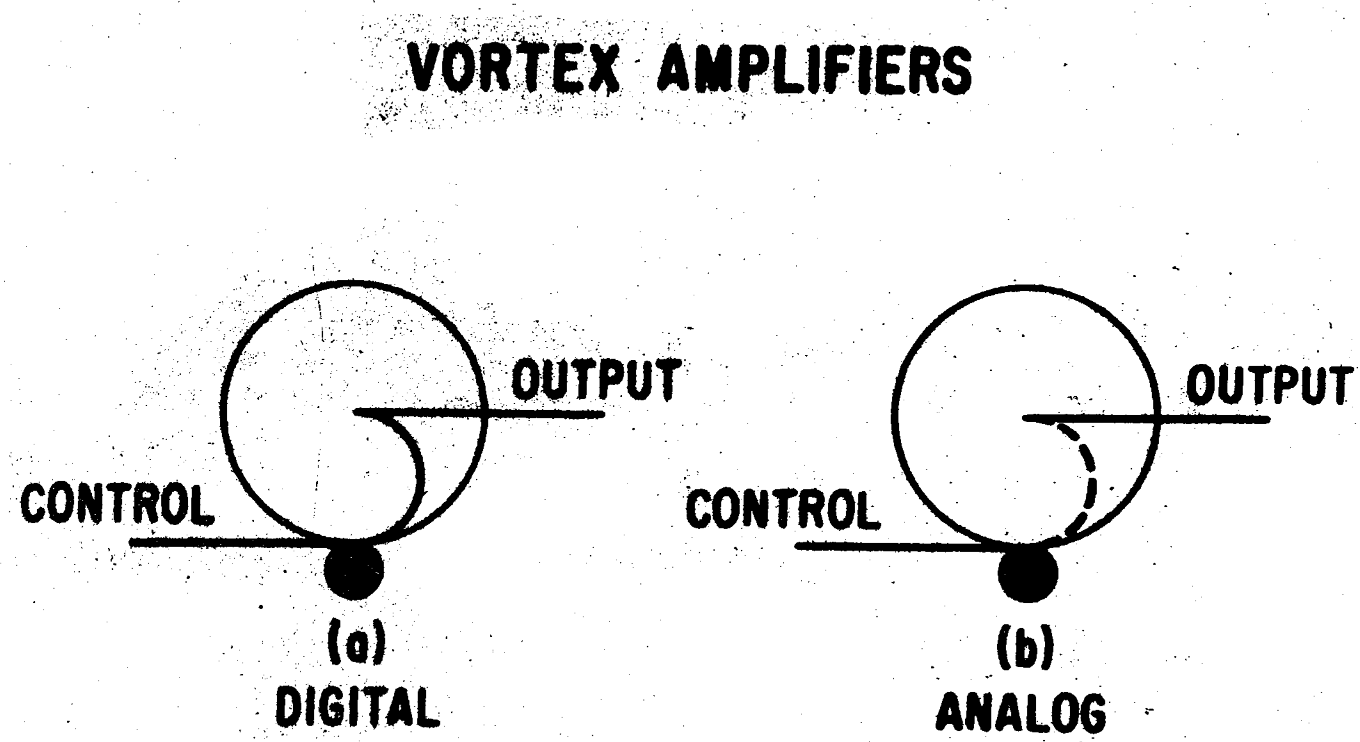

VORTEX AMPLIFIERS
CONTROL
OUTPUT
(a)
DIGITAL
CONTROL
OUTPUT
(b)
ANALOG

Exhibit C-2

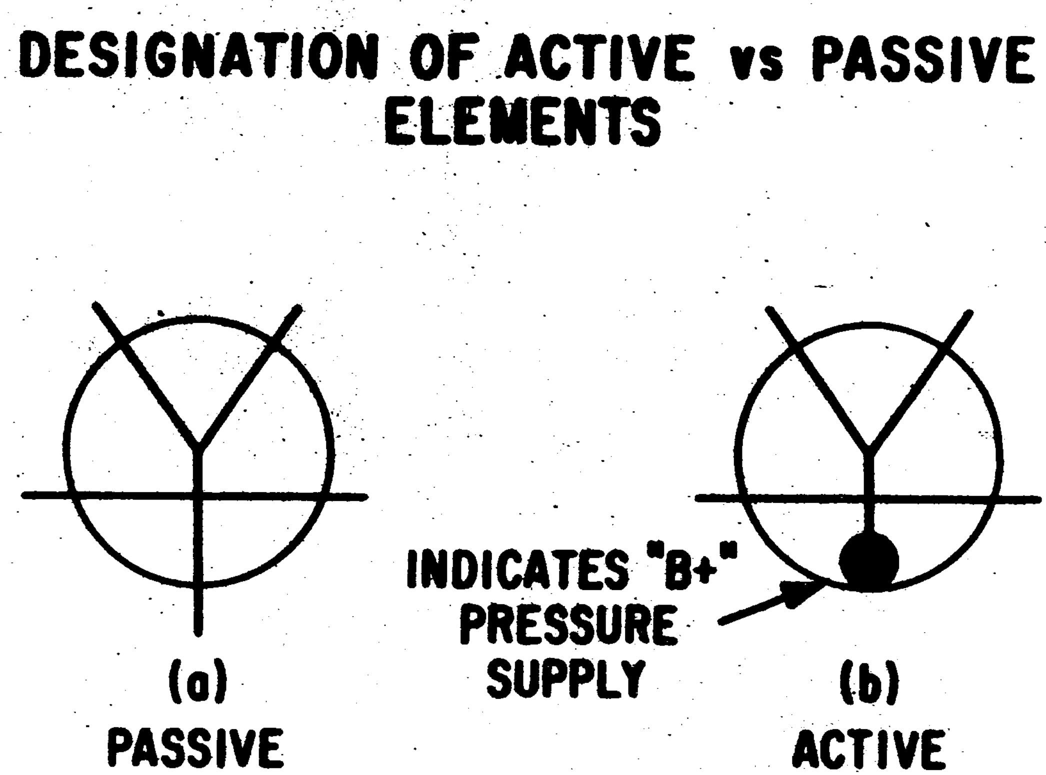

DESIGNATION OF ACTIVE vs PASSIVE ELEMENTS
INDICATES "B+" PRESSURE SUPPLY
(a) PASSIVE
(b) ACTIVE

Exhibit C-3

SCHEMATIC OF 4 STAGE OPERATIONAL AMPLIFIER

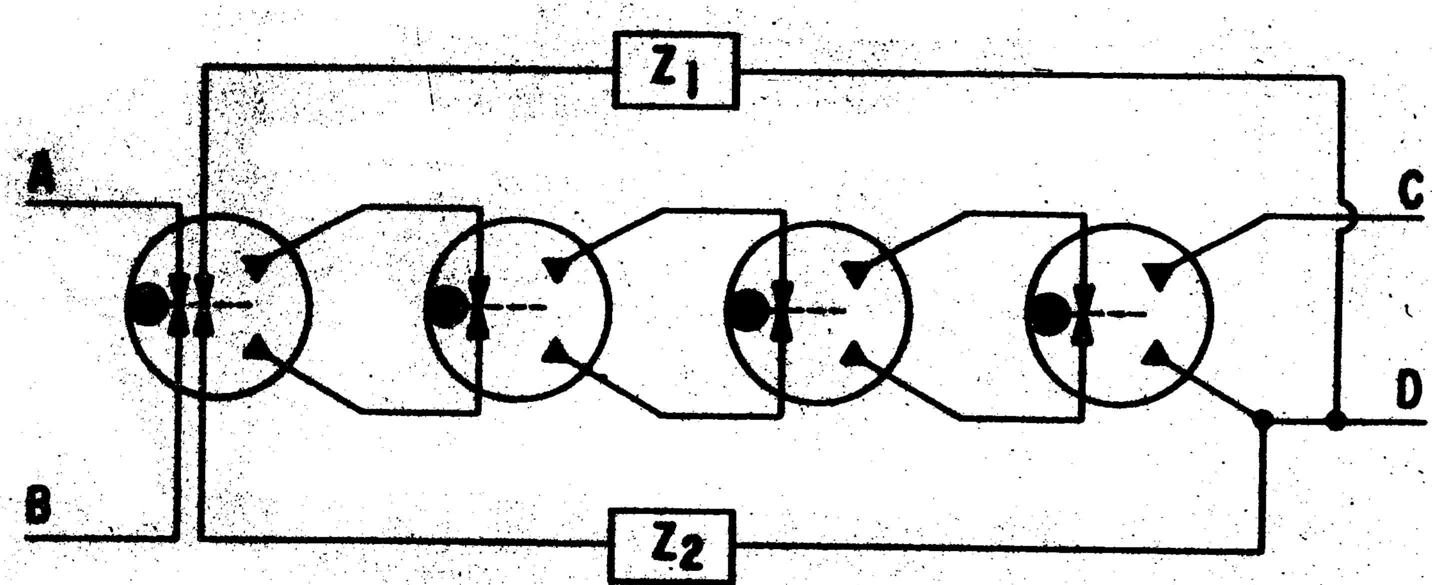


Exhibit C-4(a)

SIMPLIFIED DIAGRAM FOR OPERATIONAL AMPLIFIER

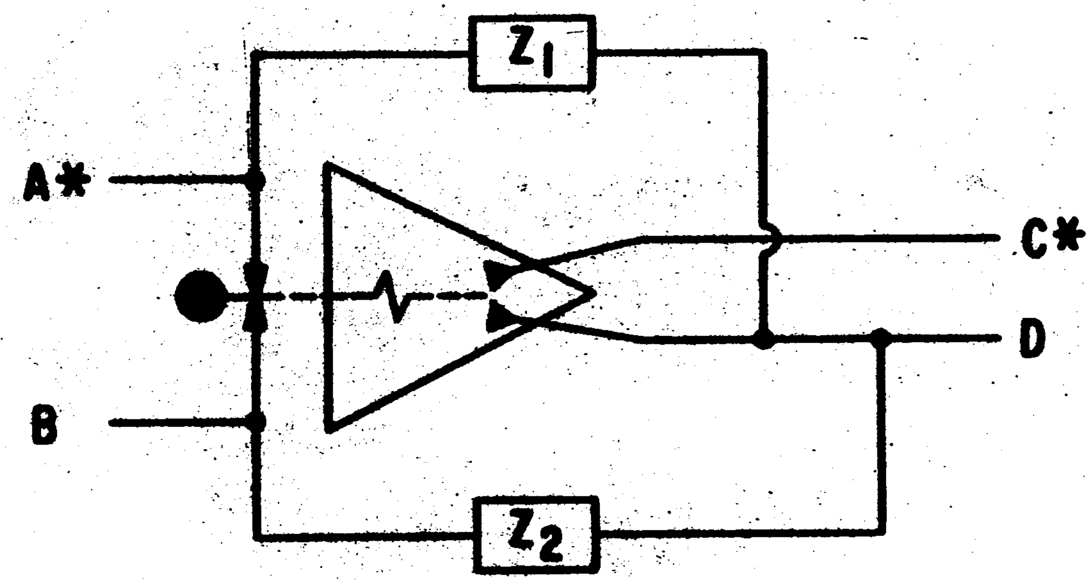


Exhibit C-4(b)

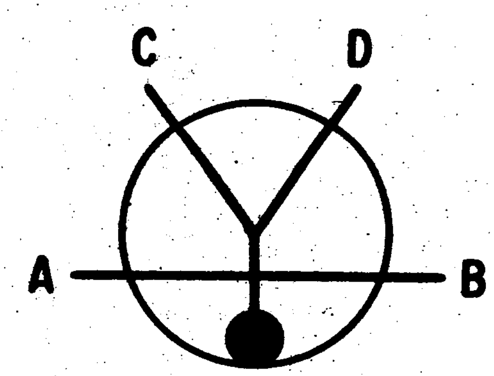


Exhibit C-5

BINARY FLIP-FLOP

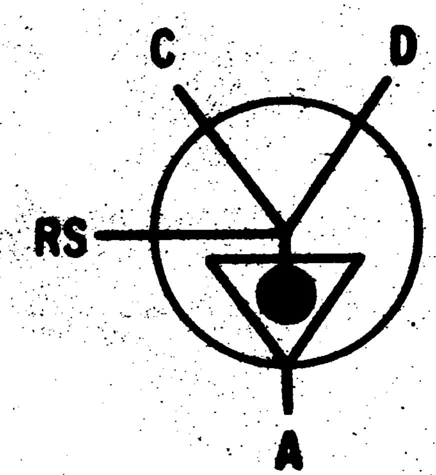
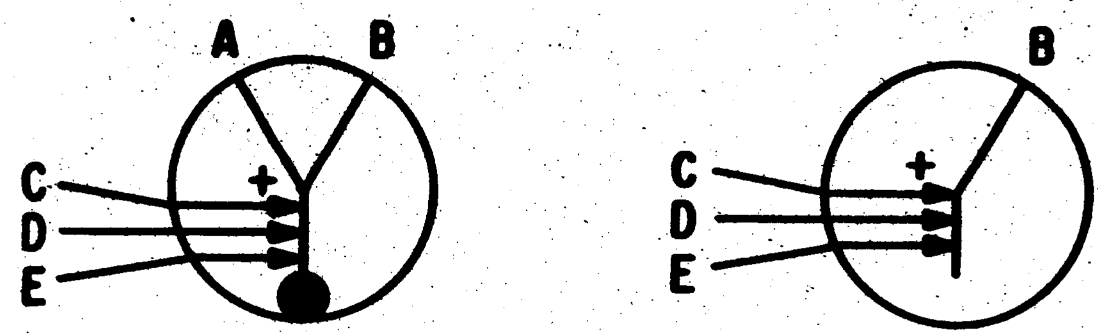


Exhibit C-6

"OR" LOGIC ELEMENTS

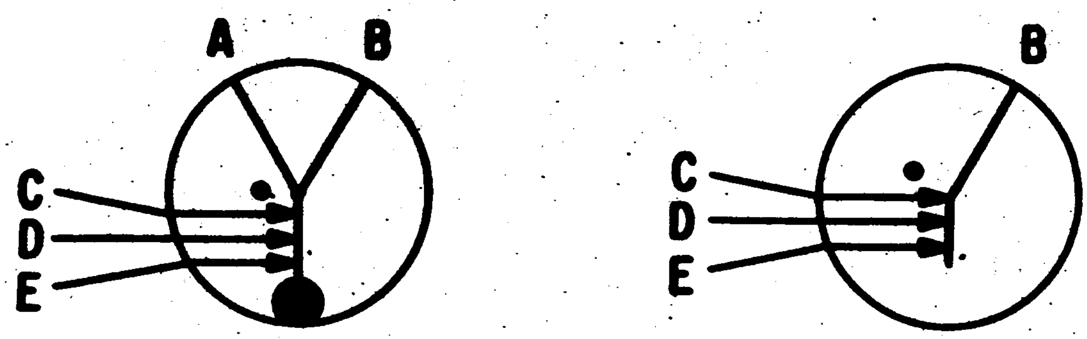


(a) ACTIVE OR-NOR

(b) PASSIVE "OR"

Exhibit C-7

"AND" LOGIC ELEMENT



(a) ACTIVE

(b) PASSIVE

Exhibit C-8

HALF ADDER, EXCLUSIVE OR

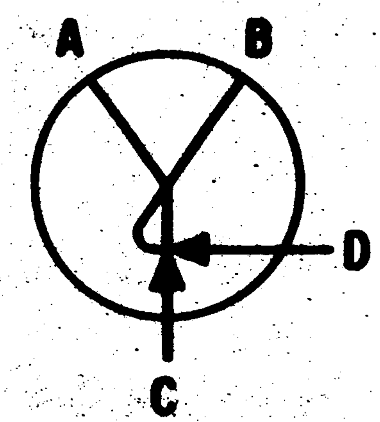
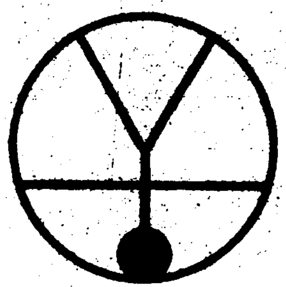
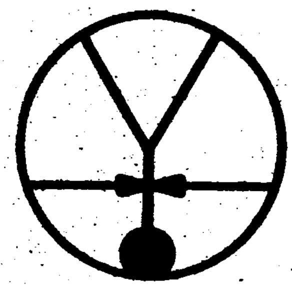


Exhibit C-9

FLIP-FLOPS WITH AND WITHOUT MEMORY



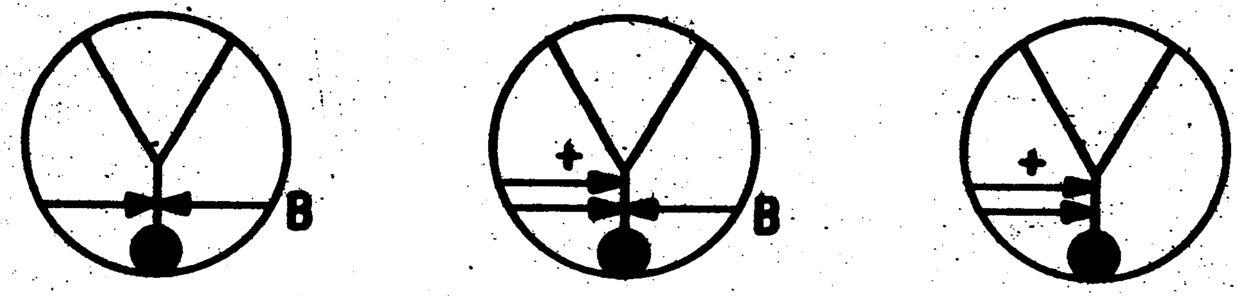
(a)
MEMORY



(b)
NO MEMORY

Exhibit C-10

REPRESENTATION OF BIASING SIGNALS



(a) BIASED FLIP-FLOP

(b) "OR"-SIGNAL BIASED

(c) "OR"-GEOMETRICALLY BIASED

Exhibit C-11

SYMBOLS FOR LINE IMPEDANCES

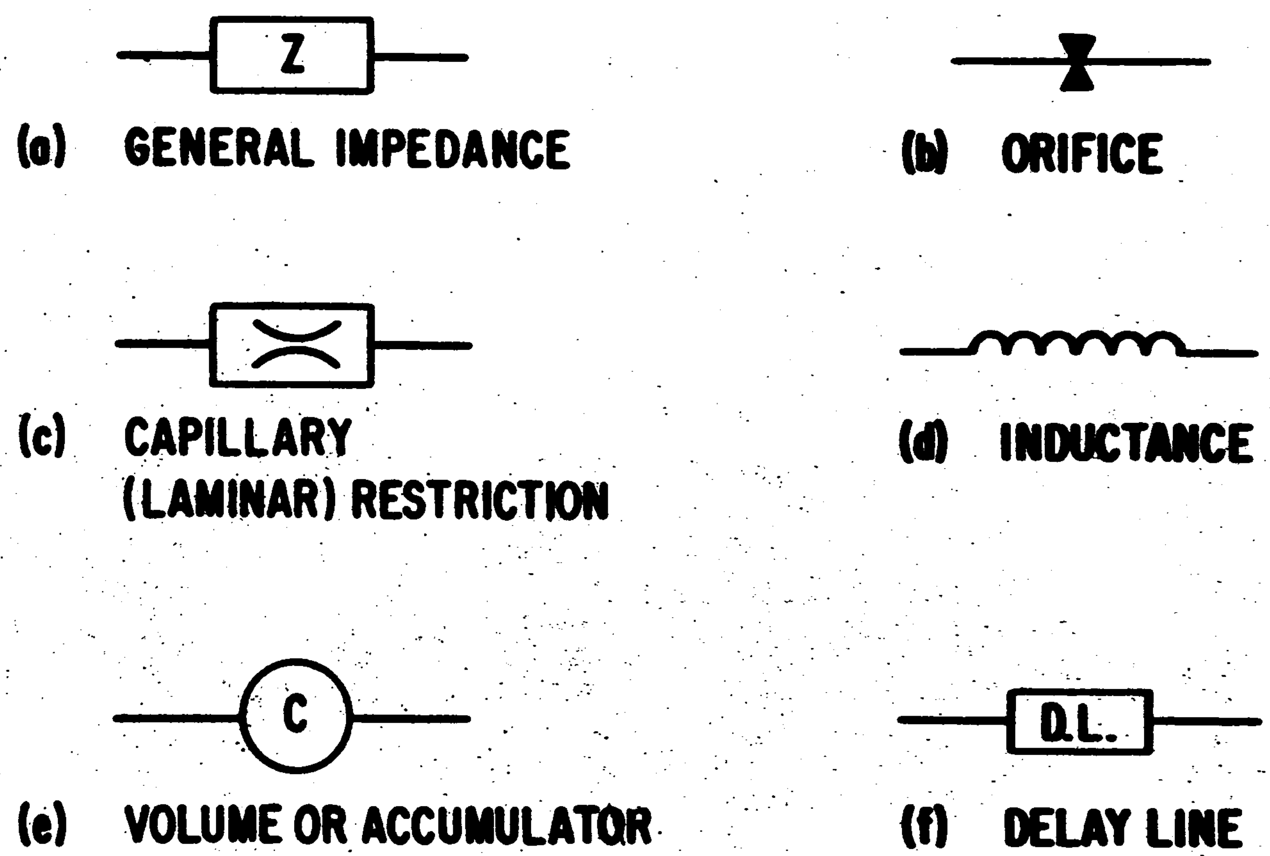


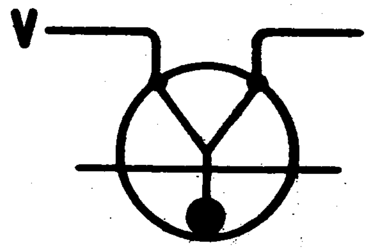
Exhibit C-12

SYMBOLS FOR CONNECTIONS

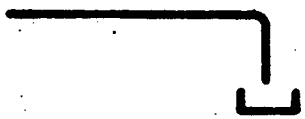
(a) CROSSING LINES

(b) CONNECTING LINES

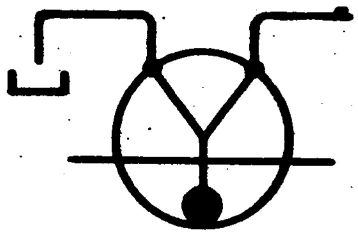
(c) VENT CONNECTION



(d) EXAMPLE OF VENT



(e) RETURN TO RESERVOIR



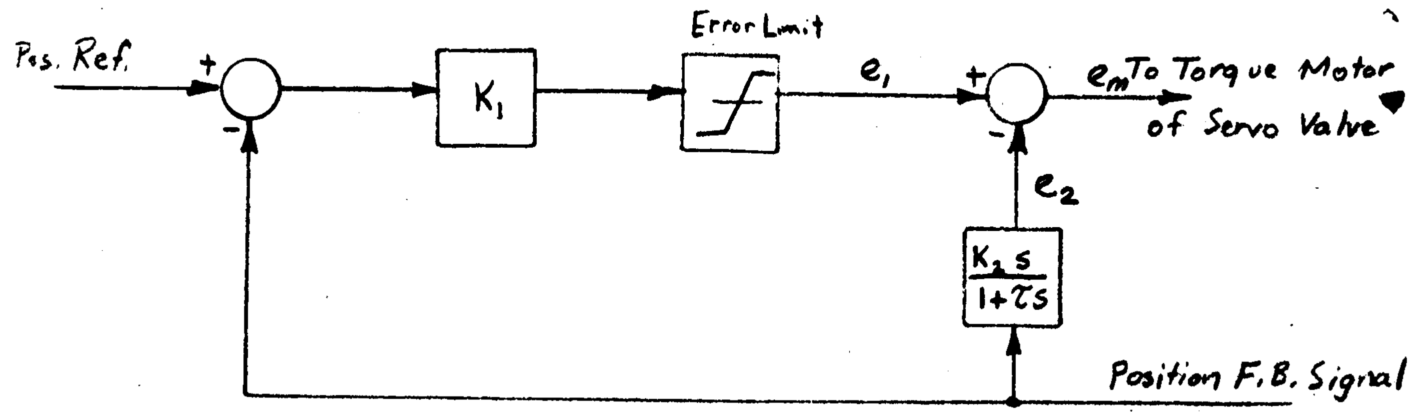
(f) EXAMPLE OF RESERVOIR RETURN

Exhibit C-13

APPENDIX D

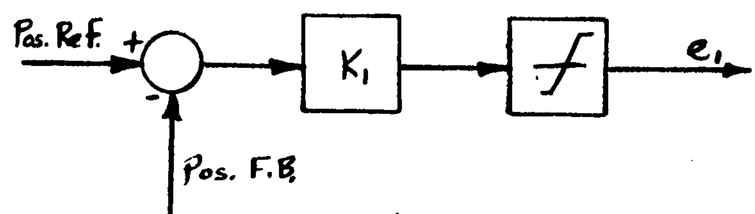
The following derivation is for a rate limiting circuit. This particular function is no longer required in the individual rod control circuit due to other system considerations.

One electronic circuit used in GE-AAT hot gas servos is block diagrammed as follows:

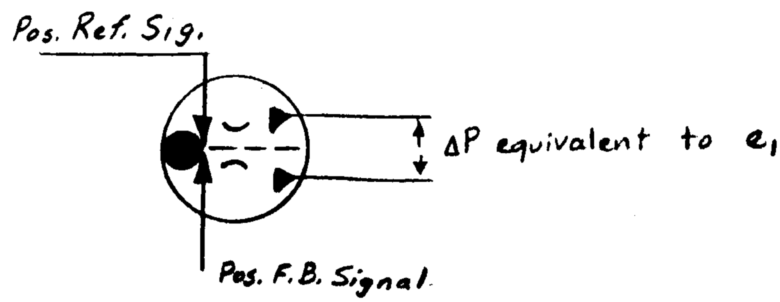


The above functions can be broken down to individual pneumatic equivalents.

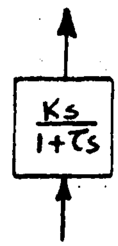
(a.)



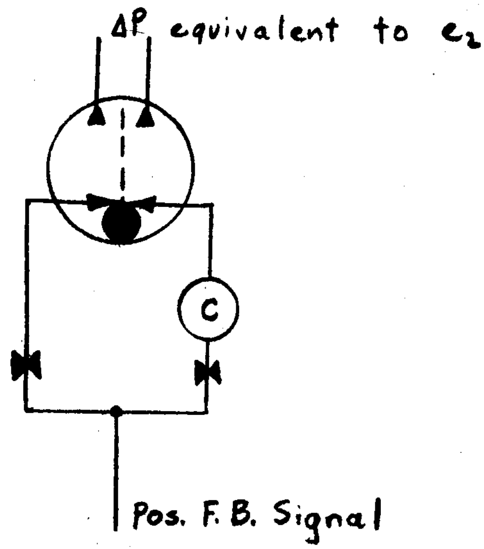
This can be handled by one fluid amplifier that has deflection limiters. The deflection limiter prevents the jet from being deflected beyond a certain point, resulting in a saturation affect. Therefore, this function is handled by the following schematic:



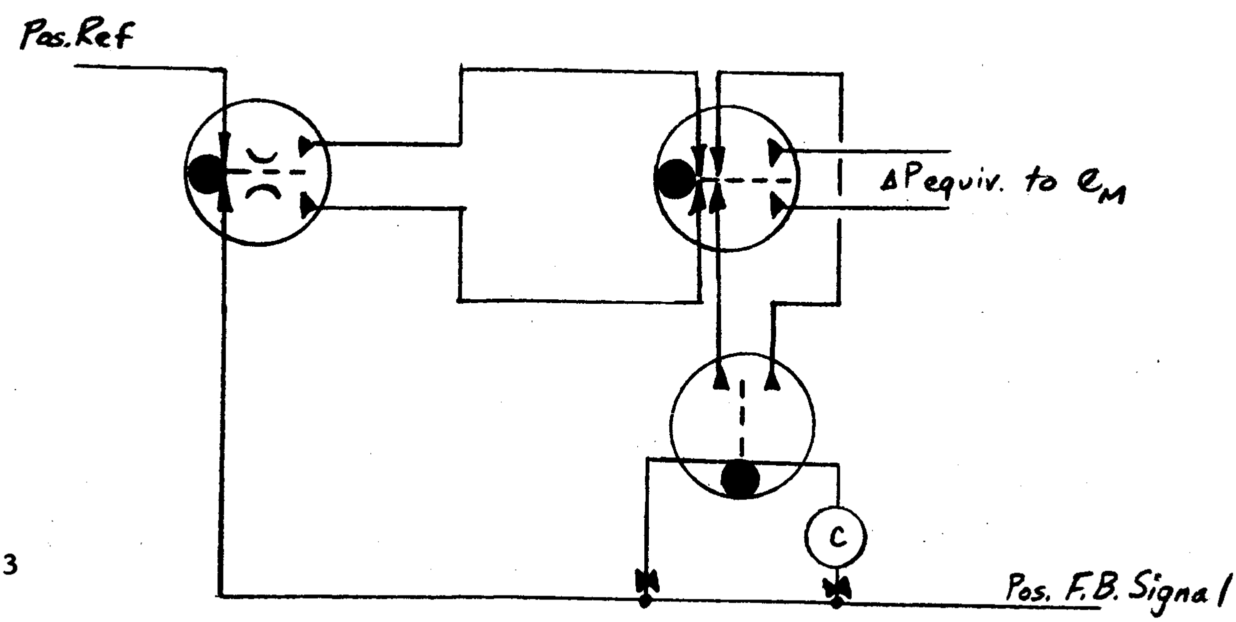
(b)



This also can be handled by one amplifier with shaping of the input as follows:



(c) The combined circuit equivalent to the block diagram will be:



REPORT DISTRIBUTION LIST FOR
CONTRACT NO. NAS 3-2567

NASA Lewis Research Center (3)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: Vernon D. Gebben

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: John J. Fackler
Contracting Officer

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: Normal T. Musial

NASA Scientific and Technical Information Facility (6)
Box 5700
Bethesda, Md.
Attention: NASA Representative

NASA Lewis Research Center (2)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: Library

NASA Lewis Research Center (1)
21000 Brookpark Road
Cleveland, Ohio 44135
Attention: Report Control Office

U. S. Atomic Energy Commission (3)
Technical Reports Library
Washington, D. C.

U. S. Atomic Energy Commission (3)
Technical Information Service Extension
P. O. Box 62
Oak Ridge, Tenn.