THE DESIGN AND IMPLEMENTATION OF A FLUIDIC HYDROSTATIC TRANSMISSION CONTROLLER

BY

DAVID LEE SMITH

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1971

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
July, 1972

THE DESIGN AND IMPLEMENTATION OF A FLUIDIC

HYDROSTATIC TRANSMISSION CONTROLLER

Thesis Approved:

Karl N. Reid

Thesis Adviser

James E. Bose

D. Durham

Dean of the Graduate College

PREFACE

This thesis is concerned with the initial stages of development of a Hydrostatic Transmission controller. Design methods are presented which permit implementation of the controller and possible implementations are discussed.

The author is indebted to the U. S. Army Tank Automotive Command, Propulsion Systems Laboratory, for the loan of equipment required in the thesis work to the Oklahoma State University. This equipment was originally provided for use under contract DAAE07-67-C-5639. The advice and encouragement of Mr. Walter Slabiak of TACOM is also gratefully acknowledged.

The author wishes to express his appreciation to his major advisor, Dr. Karl N. Reid, for his guidance and assistance throughout this study.

TABLE OF CONTENTS

LIST OF FIGURES

NOMENCLATURE

A	cross-sectional area
b	nozzle width
c	polytropic constant
C_h	hydraulic capacitance
C_p	pneumatic capacitance
D_e	equivalent diameter
D_p	pump displacement
ΔE	error
F	applied force
G	grade
h	nozzle height
J	performance criterion
k	polytropic coefficient
K	spring constant
k_1, k_2, k_3	flow-pressure proportionality constants
$\dot{m}$	fuel flow rate
μ	dynamic coefficient of viscosity
n_e	engine efficiency
n_t	transmission efficiency
P	pressure
P_a	ambient pressure
ΔP_c	control pressure

P_e	engine power
P_i	input pressure
P_L	load power
ΔP_o	differential output pressure
P_o	output pressure
P_s	supply pressure
q	throttle
ρ	density
R	universal gas constant
R_e	Reynolds number
R_i	input fluidic resistance
R_s	speed ratio
s	Laplace transform variable
S_d	optimum (desired) engine speed
S_e	engine shaft speed
S_L	load speed
t	time
T	absolute temperature
T_e	engine torque
T_L	load torque
V	volume
V_a	actual engine manifold vacuum
V_d	optimum (desired) vacuum
W	mass flow rate
ΔW_c	control flow
x, X	displacement

CHAPTER I

INTRODUCTION

The Hydrostatic Transmission and Controller

Ever since its invention, the internal combustion engine has challenged controls engineers to utilize its power effectively. The Hydrostatic Transmission (HST) is one of the more recent, and more promising, developments to help accomplish this task. According to Heinrich (1), the HST is "more compact, easier to apply, functionally superior, and utilizes engine horsepower over broader vehicle speed ranges"[1] than other types of transmissions. The HST consists of a pump coupled hydraulically to a motor, both of which may have variable displacements. If variable, the displacements are varied mechanically and have an infinite number of settings, that is, they are continuously variable over their range. Now the promise of the HST for the controls engineer shows through. With an infinite variance, it can be controlled to maximize any reasonable performance criteria for the engine-HST power train that can be established.

Some of the performance criteria that have been established in the past are maximum vehicle acceleration, maximum engine efficiency, or minimum fuel consumption. Wilson (2) proposed to govern engine speed

[1]A. Heinrich, "Application of Mobile Hydrostatic Transmission," Abstract of S.A.E. Paper No. 670696, Presented at the 1967 S.A.E. Meeting.

to produce maximum power output while controlling the pump displacement to give maximum vehicle acceleration (motor displacement varied by operator). A controller proposed by Howard (3) adjusts the ratio of input speed to output speed (speed ratio) to give maximum load at maximum engine throttle. This type of controller would find its best application in a situation like a farm tractor where maximum load and maximum throttle are simultaneously and continuously required. Finally, Woods, et al. (4) have developed a controller which varies the load on the engine to maximize overall system efficiency and, therefore, minimize fuel consumption.

Selection of a Controller Concept

The controller developed by Woods, et al., the V-S controller, was selected for further study since it offers flexibility of concept. The V-S controller was so named because it senses the engine speed (S_e) and the engine vacuum (V_a), then controls the transmission speed ratio to optimize the overall system efficiency; hence, vacuum-speed or V-S controller. The concept of a vacuum-speed type controller was developed for a nominal load (zero grade), but experiment and theory showed that off-nominal performance was good. In order to develop a more sophisticated controller (one that controls for an arbitrary load), a third engine variable must be measured. This allows the controller to calculate the exact operating point on the engine operating map. However, the locus of all optimum vacuum-speed operating points (i.e. those which give minimum fuel consumption) is a rather narrow band on the engine vacuum-speed map. Therefore, there is little difference between an arbitrary load and a nominal load in the vacuum-speed relationship. Consequently, vacuum-speed controllers offer three-variable performance at the expense of measuring only two engine variables.

The Fundamental Limitation of the V-S Controller

Woods, et al. chose to implement the V-S controller with fluidics. From a practical standpoint, this means that a regulated pneumatic pressure supply must be furnished. Boothe and Kelley (5) have shown that conventional fluidic amplifiers will run satisfactorily on hydraulic fluid as long as certain Reynolds number considerations are observed. The entire V-S controller circuit could be run on hydraulic fluid. The HST is usually equipped with an auxiliary pump to make up internal leakage. This pump could be pressure compensated to form a ready hydraulic supply and the pneumatic supply could be discarded. A fundamental limitation of the present V-S controller then is that it runs on compressed air.

This limitation is more severe than it appears at first since the implementation methods of the V-S controller took advantage of the pneumatic implementation, and do not lend themselves to easy conversion to hydraulic operation. The V-S controller capitalized on the fact that the vacuum is a pneumatic signal and was therefore compatible with the remaining pneumatic fluidic circuitry. The engine speed was sensed by a fairly common AC fluidics method. In order to convert directly to hydraulic operation, some boundary, or interface, must be supplied between the pneumatic vacuum and the hydraulic controller. Furthermore, the engine speed must be sensed hydraulically. Several techniques exist for hydraulic sensing of the engine speed--all of which are relatively bulky and awkward compared to the V-S controller fluidic circuitry.

The V-S controller was based on the fact that the engine vacuum is a DC signal which varies in direct proportion to the load on the engine. However, the total vacuum signal also has an alternating pressure signal (AC) which pulses in direct proportion to the speed of the engine. Therefore, the vacuum contains both DC and AC information and this fact forms the basis of the Modified V-S controller. The AC information in the vacuum signal eliminates the need for a separate circuit to generate the speed signal.

Purpose

The first step toward successful implementation of the Modified V-S controller requires that AC and DC information be extracted from the single engine vacuum signal. Furthermore, the device(s) employed to isolate each part of the total vacuum signal must be able to function as fluidic/hydraulic interfaces since the Modified V-S controller will run on hydraulic fluid. Consequently, it is the purpose of this thesis to determine the feasibility of extracting AC and DC information from the total vacuum signal in such a manner that it be compatible with hydraulic controller operation.

Summary

An outline of the development of the vacuum-speed controller concept and the V-S controller is presented in this thesis. The design of devices (AC and DC isolators) which perform the tasks of interfacing and AC and DC vacuum signal isolation is presented. A fluidic circuit implementation which employs the AC and DC isolators (the Modified V-S controller) is discussed. Results of laboratory tests on alternate

methods of obtaining frequency-to-analog conversion for use in the Modified V-S controller are presented and analyzed. Finally, operational considerations for a hydraulic Modified V-S controller are discussed.

CHAPTER II

THE VACUUM-SPEED CONTROLLER

In this chapter, the necessary graphs and equations are presented to allow the reader to follow the development of the concept and implementation of the vacuum-speed controller. Both the V-S controller and the Modified V-S controller utilize the same basic functional approach. That is, both control the vacuum-speed relationship. Therefore, performance mappings carried out by Woods, and summarized in this chapter, were relied upon to predict engine and transmission behavior during the development of the Modified V-S controller.

Establishing the Performance Criterion

Shown in Figure 1 is a block diagram representation of an uncontrolled power train. In the simplest applications of HST's, the operator provides both the throttle position, q, and the speed ratio, R_s, inputs. The operator "closes the loop." However, even with a highly skilled operator, this may be a very inefficient mode of operation by any standard. Therefore, some sort of automatic control is often desired to schedule q or R_s for optimum operation and, therefore, take fuller advantage of the potential of the HST.

Stated simply, Woods, et al. sought a transmission controller to yield the highest load power at the lowest fuel consumption rate. Thus,

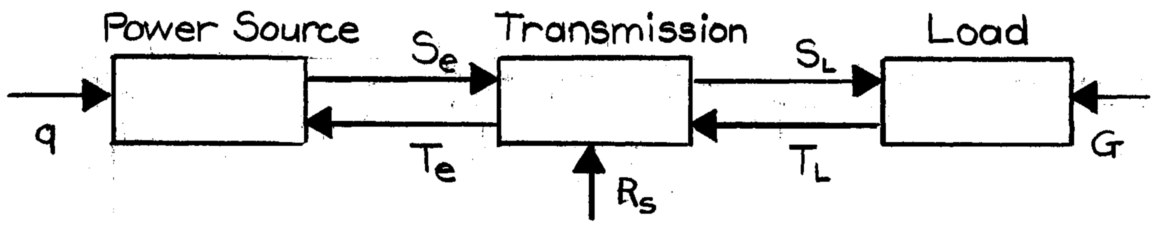


Figure 1. The Flow of Information in the Uncontrolled Power Train

a performance criterion, J, was established to be maximized

$$J = \frac{P_L}{\dot{m}}$$

but, $P_L = S_L T_L$ and therefore

$$J = \frac{S_L T_L}{\dot{m}}$$

the engine efficiency is defined as

$$n_e = \frac{S_e T_e}{\dot{m}}$$

inserting this expression yields

$$J = \frac{S_L T_L}{S_e T_e} n_e$$

furthermore, the transmission efficiency may be defined as

$$n_t = \frac{S_L T_L}{S_e T_e}$$

so that the performance criterion becomes

$$J = n_e n_e \tag{1}$$

Therefore, maximization of the performance criterion (maximum power for minimum fuel consumption) is accomplished by maximizing the product of the engine and transmission efficiencies.

Maximizing the Performance Criterion

In order to perform the actual maximization of (1), descriptions of both engine and transmission are necessary. Generally, the power output, P_e, of an internal combustion engine is as shown in Figure 2a. The line of maximum engine efficiency is the locus of all points of maximum engine efficiency at various power levels. The steady state mathematical model of the HST is well defined. The engine efficiency of Figure 2a could then be reduced to a set of data points and combined with the mathematical model of the HST in any one of several standard computer optimization techniques. Since J is a function of the four variables S_e, T_e, S_L, and T_L, the result of maximization appears as an area on the corresponding engine map of Figure 2b.

In order to simplify the problem for further discussion and analysis, only the case of nominal loading is considered. This case corresponds to the nominal load of a vehicle on a grade of zero slope as shown qualitatively in Figure 2c. By reducing the problem to one of nominal load only, the optimal region reduces to an optimal line. This line lies centrally in the optimal region and is shown in Figure 2b.

The Vacuum-Speed Controller Concept

The first step in implementation of an optimum controller requires that a set of engine variables be selected from the engine mappings. Woods chose to implement engine speed versus optimum vacuum since this curve is smooth and well behaved (Figure 3).

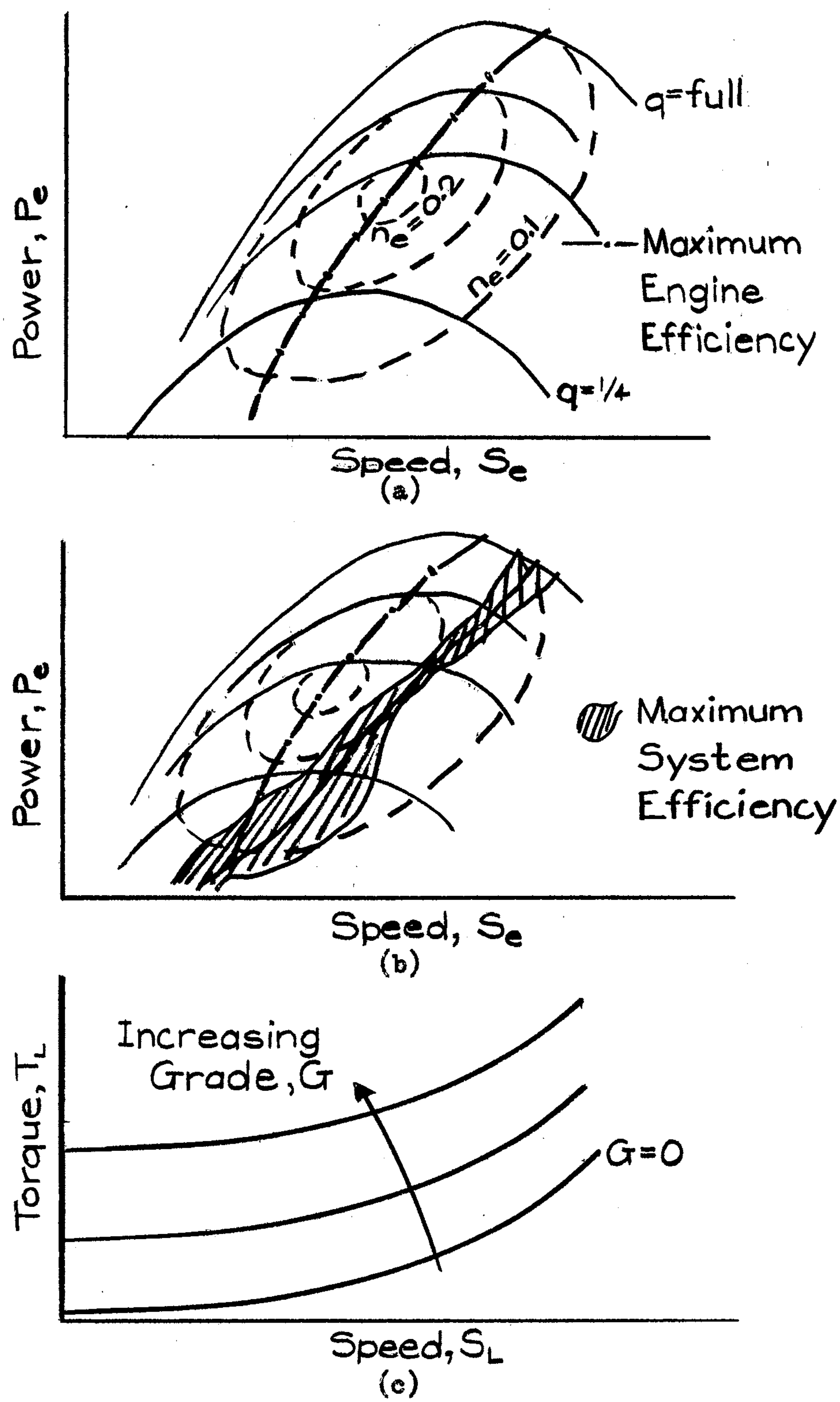


Figure 2. Engine and Load Characteristics. (a) Maximum Engine Efficiency Curve (Qualitative). (b) Zone of Maximum System Efficiency (Qualitative). (c) The Vehicle Load Description (Hypothetical).

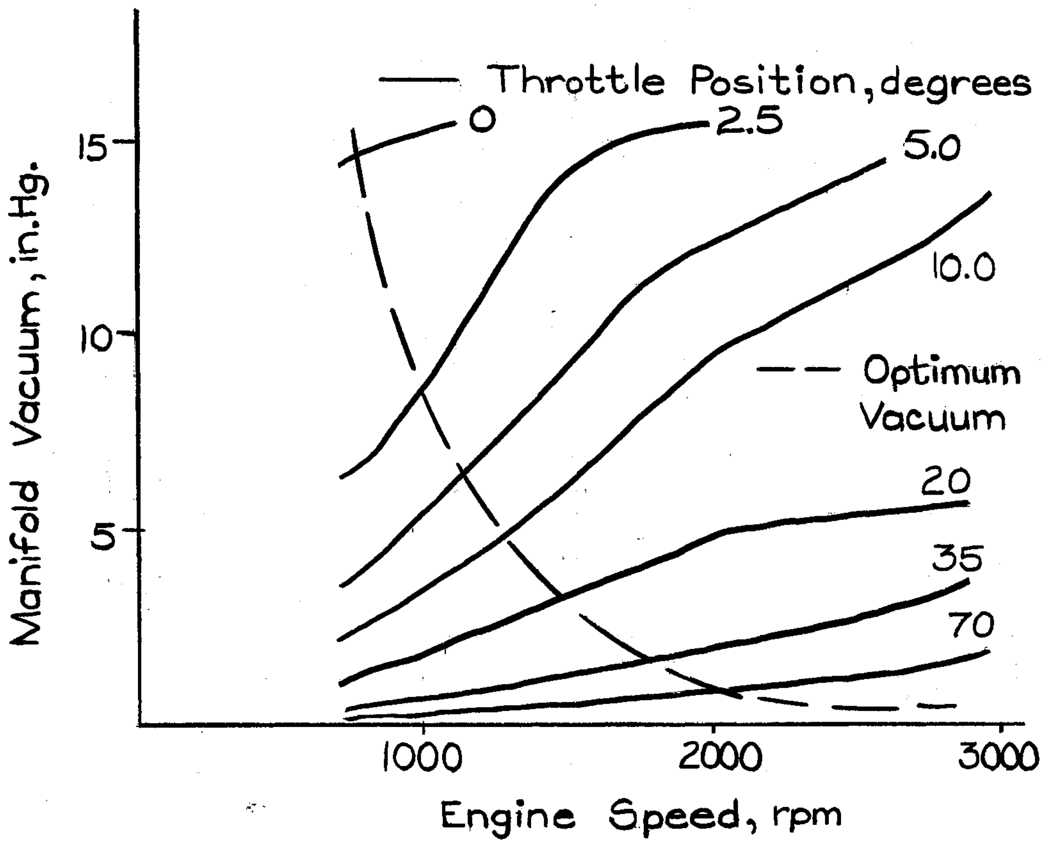


Figure 3. The Foundation of the Vacuum-Speed Controllers, Optimum Engine Vacuum Versus Engine Speed

The vacuum-speed controller concept is illustrated in block diagram form as in Figure 4. The engine speed is used in the function generator to produce the optimal vacuum, V_d. The V_d - S_e curve that the function generator must produce is shown in Figure 3. The actual vacuum, V_a, is then compared with the optimum vacuum at the summing junction to determine the error, ΔE, if any. A power actuator amplifies the error and produces a displacement, D_p, proportional to the error.

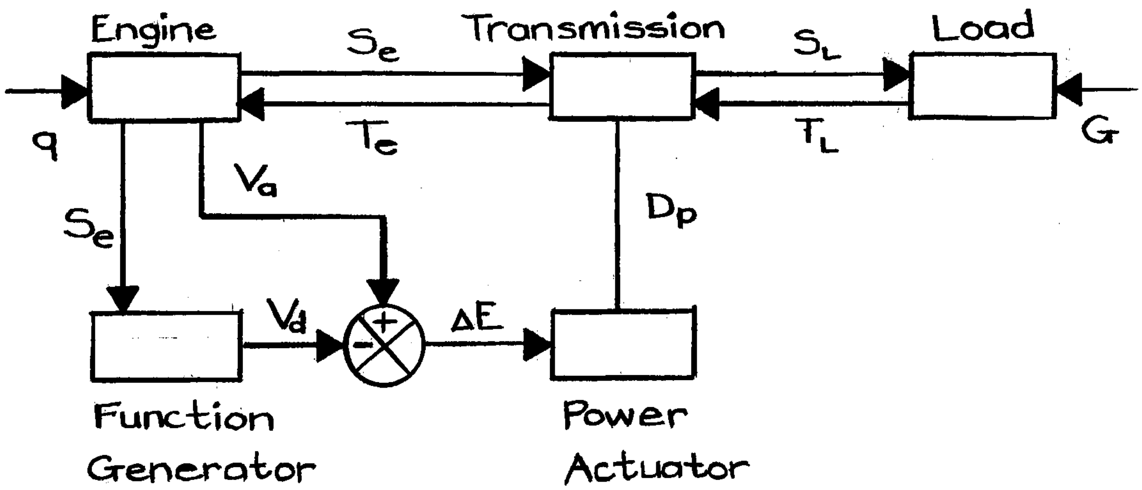


Figure 4. A Block Diagram of the Vacuum-Speed Controller Concept

The V-S Controller Implementation

Figure 5 shows the V-S controller in schematic form. The nozzle-disk speed sensor consists of two nozzles mounted radially with respect to a disk which rotates on the engine shaft. This arrangement comprises a four-way flapper-nozzle valve, with the teeth on the disk acting as the flapper, and produces an alternating pressure signal (AC) of frequency proportional to engine speed. This AC signal is then fed into a Frequency-to-Analog device (F/A, modified General Electric 24MC12A)[2] to convert it to a DC pressure signal proportional to the AC input frequency. The DC signal is then sent to the function generator. The desired vacuum vs speed relation has the same general shape as the

[2]Explanatory notes for most fluidic devices are included in Appendix A.

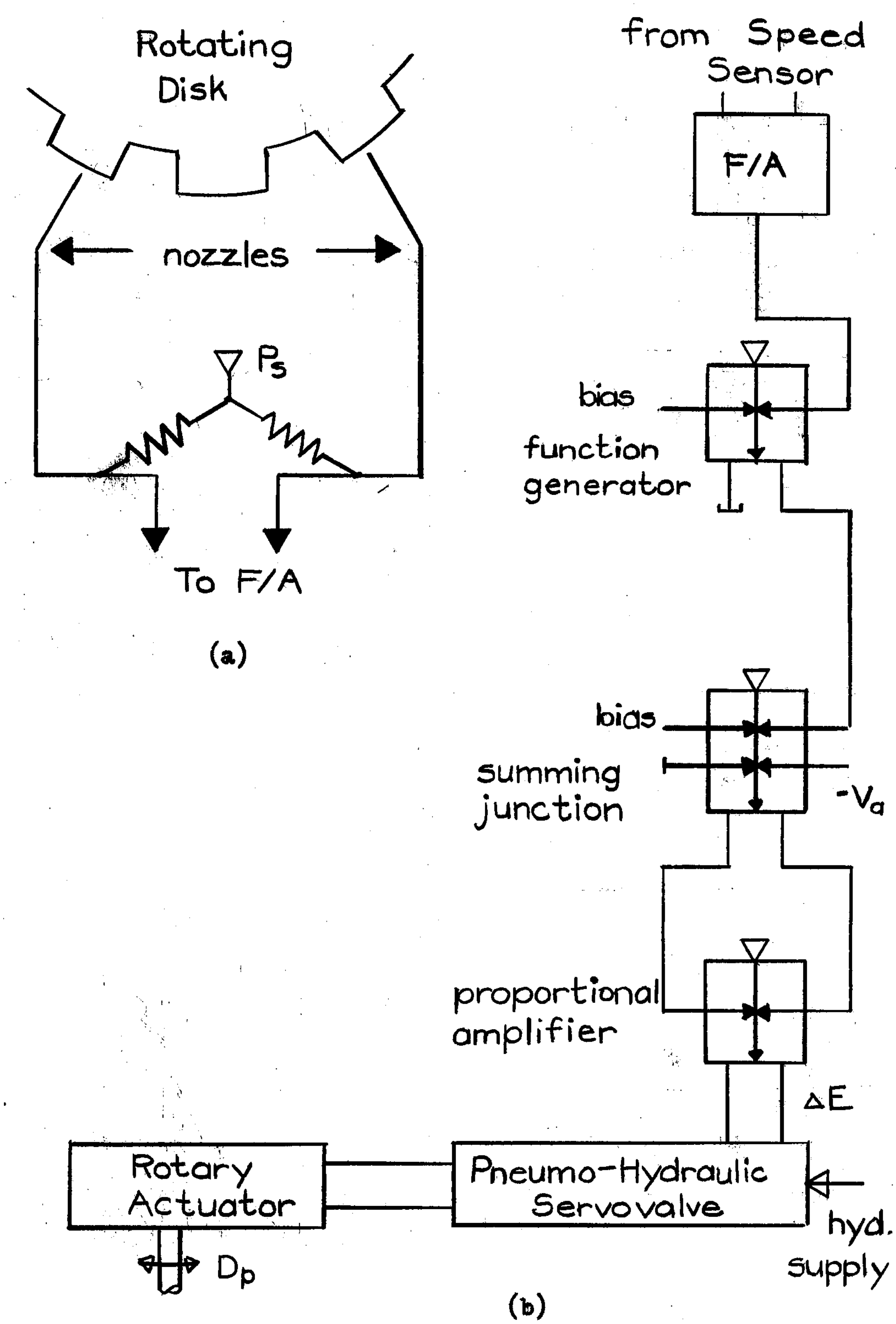


Figure 5. A Schematic of the V-S Controller. (a) The Nozzle-Disk Speed Sensor. (b) V-S Controller Fluidics.

single-ended gain characteristic of a fluid amplifier. Biasing is provided to locate the gain curve in the correct position with respect to the incoming F/A signal. Once the actual engine vacuum is attenuated, it can be compared directly to the desired vacuum at the summing amplifier. The error signal produced by the summing amplifier is usually quite small and must be amplified again prior to being sent to the pneumo-hydraulic interface. The pneumo-hydraulic interface converts the incoming pneumatic signal to a high pressure hydraulic signal so that actuation may be accomplished. This interface, together with a rotary vane actuator, provides the power amplification necessary to produce a pump displacement proportional to the error signal.

CHAPTER III

THE MODIFIED V-S CONTROLLER

All vacuum-speed controllers require some method of measuring the engine speed. The purpose of this study as stated in Chapter I requires the synthesis of a speed measuring technique that is compatible with hydraulic operation. The nozzle-disk method that Woods used was well suited to pneumatic operation but poorly suited to hydraulic operation. General Electric has recently developed a device which measures the pulses of the exhausted gases of an internal combustion engine and, from this information, regulates the rotational speed of the drive shaft (6). However, the details of the GE device are not presently available. Therefore, an essential part of this study is to develop some technique for measuring engine speed which is well suited to hydraulic operation. In fact, the development of just such a technique forms the basis of the Modified V-S controller.

The Vacuum Signal

The V-S controller was highly dependent upon the fact that the engine vacuum contains a DC signal which is nearly a function of load alone. However, the vacuum signal also contains an AC dynamic signal. Figure 6 shows that the amplitude of the AC signal is dependent on the amount of load as is the DC signal, and this fact must be accounted for in the development of the Modified V-S controller. The frequency of the

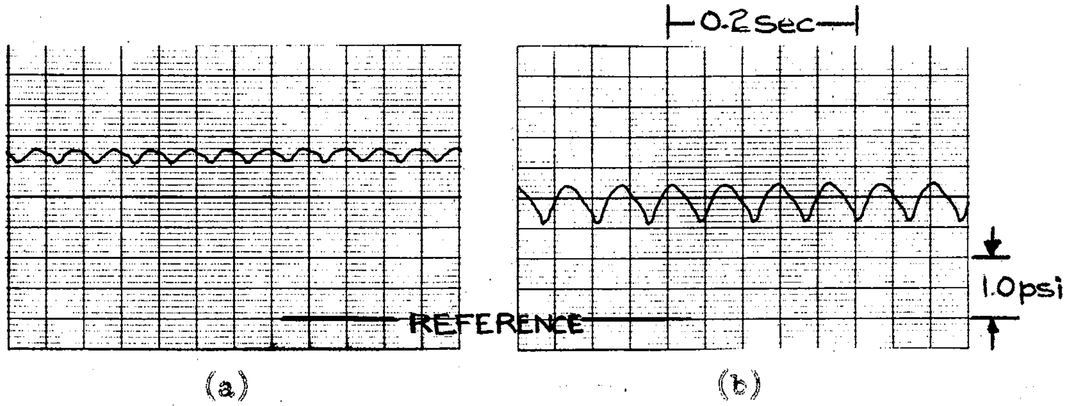


Figure 6. The Total Engine Vacuum Signal ($-V_a$ Attenuated), (a) Engine Lightly Loaded, (b) Engine Heavily Loaded, at About the Same Frequency.

AC part of the vacuum is directly proportional to the shaft speed only. Therefore, the AC and DC parts merely have to be extracted from the total vacuum signal to obtain the two bits of information necessary to implement the controller. Consequently, the Modified V-S controller does not need a separate speed signal generating circuit since all control is done with measurements made on the vacuum signal.

AC and DC Signal Isolation

Two devices play a key role in the functioning of the Modified V-S controller; these are the AC and DC isolators. The two isolators perform two important functions; first, they isolate the appropriate part of the incoming vacuum signal; second, they provide the necessary boundary, or interface, between the pneumatic vacuum signal and the remainder of the controller circuit which will eventually function on hydraulic fluid. Although these two devices will perform the function of interfacing in the hydraulic circuitry, their primary role in the Modified V-S controller is that of isolating the AC and DC signals; therefore, they are referred to as isolators in this thesis. The details of the development of these two isolators are discussed in Appendices B and C.

The Modified V-S Controller Implementation

The Modified V-S controller utilizes the basic vacuum-speed concept as outlined in Chapter II. That is, the AC signal from the AC isolator is run through an F/A circuit; the resulting DC signal is fed into the function generator. Finally, the output signal from the function generator is subtracted from the signal from the DC isolator to produce the error signal. This chapter is concerned with design considerations for implementation of a fluidic Modified V-S controller which utilizes the AC and DC isolators. Typical calculations necessary to accomplish fluidic implementation are presented and discussed.

Woods had a large advantage in that he controlled the input frequency to his circuit by simply choosing an appropriate number of teeth for his rotating disk speed sensor. For instance, if he chose eight teeth, the AC signal was eight times the speed of the rotating shaft. In this manner, a frequency of appropriate magnitude was obtained for use in off-the-shelf F/A circuitry. However, by isolating the AC vacuum signal, the unmultiplied frequency of the engine must be used. Unfortunately, commercially packaged F/A circuitry is not available in this frequency range (1000 - 4000 rpm or 17 - 67 Hz).[3] Therefore, it is necessary to design an F/A circuit to serve the expected frequency range. Calculations and considerations needed to design an F/A are presented in the following section.

The Design of a Modified F/A for the Modified V-S Controller

The first step in designing an F/A circuit is to make certain that the incoming signal contains nothing but frequency information. This is usually accomplished by providing some sort of signal limiting (or clipping) fluidic device as the first stage of the F/A. With this technique, all amplitude sensitivity is removed. The choice of fluidic elements which can best accomplish this clipping action reduces to two; a digital amplifier, or a flip-flop. The flip-flop was selected as the first stage of the F/A because tests showed it had superior switching characteristics and minimum loading sensitivity. Once a clipped (on-off) signal is obtained from the flip-flop (Figure 7), the signal is then sent to a digital amplifier for further amplification. This technique of AC limiting and amplification worked very well experimentally; only sudden changes in the throttle caused temporary loss of AC signal. For example, with no load on the engine, a step change from full throttle to idle caused momentary loss of AC switching. However, under all loaded conditions, and with gradual throttle changes, AC switching is always present.

---

[3] F/A circuitry is available for 50 - 1000 Hz.

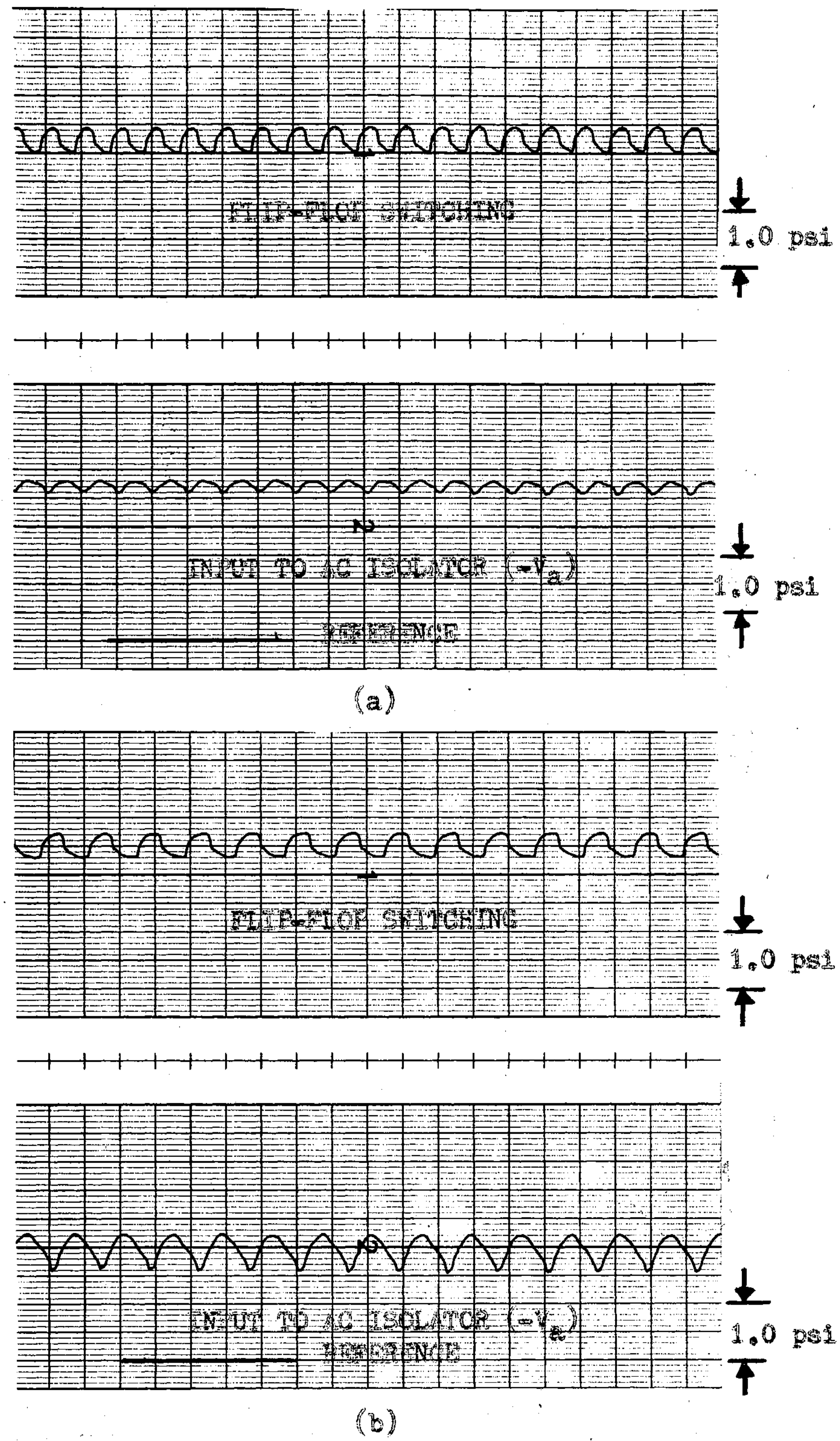


Figure 7. Signal Limiting for the AC Isolator, (a) Engine Lightly Loaded, (b) Engine Heavily Loaded

The next step in the design of an F/A requires that an RC network be added to the output of the digital amplifier to obtain the needed frequency sensitivity. The input resistance of the next element is used as the resistance of the RC combination and the capacitance is sized to provide a convenient break point on the Bode diagram. As an example of this calculation, the output of the digital amplifier is 1.0 psi in amplitude when loaded with a rectifier at three psig supply. Referring to the rectifier characteristics in Appendix A, the input resistance can be calculated

$$R_1 \triangleq \frac{\Delta P_c}{\Delta W_c}$$

and, at 3 psig $$R_1 = R_1 = 1.3 \times 10^7 \frac{1}{\text{in-sec}}$$

The capacitance takes advantage of the natural compressibility of air. For a rigid tank with one inlet and one outlet, the Continuity equation may be written as

$$W_{in} - W_{out} = \frac{d(\rho V)}{dt}$$

but, V = constant, so $$\Delta W = V \frac{d\rho}{dt} \qquad (2)$$

For the polytropic process, $P = c\rho^k$ and

$$\frac{1}{c}\frac{dP}{dt} = k\rho^{k-1}\frac{d\rho}{dt}$$

Reinserting the expression for P yields

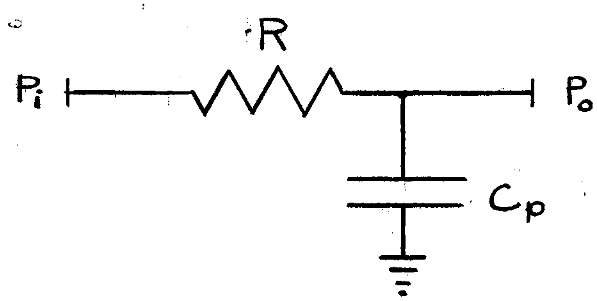
$$\frac{d\rho}{dt} = \frac{\rho}{kP}\frac{dP}{dt}$$

Furthermore, air must obey the equation of state

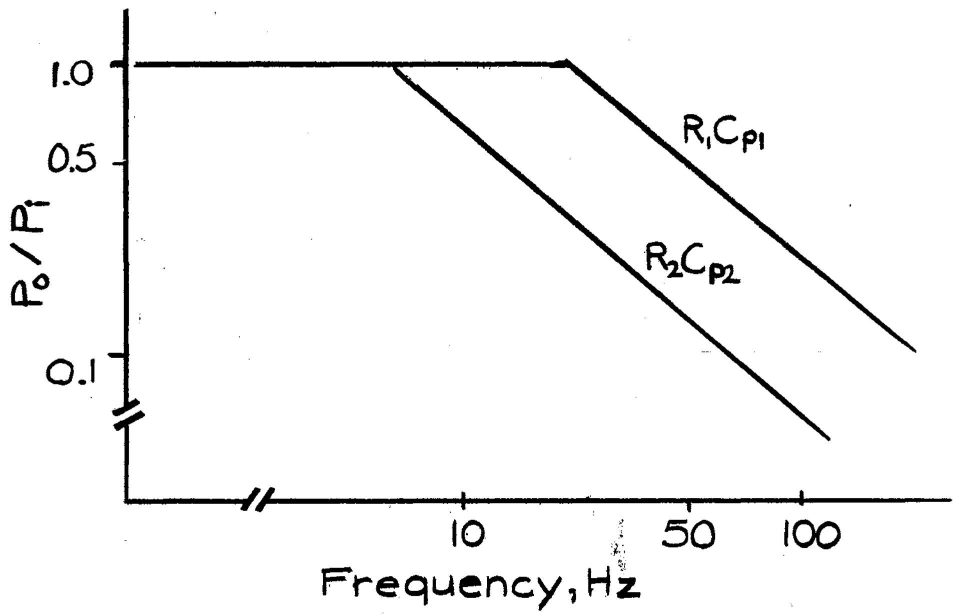
$$P = \rho RT$$

Combining the above relations with equation (2) yields

$$\Delta W = \frac{V}{kRT}\frac{dP}{dt} = C_p \frac{dP}{dt} \qquad (3)$$



(a)



(b)

Figure 8. The Frequency Sensitivity of an F/A Circuit. (a) Electrical Analog of the Pneumatic RC Network. (b) Bode Plots.

where C_p is the pneumatic capacitance

$k = 1.0$ for the isothermal process

$k = 1.4$ for the adiabatic process

Thus, for an adiabatic capacitance of 0.9 cu. in., the value of C_{p1} is 4.9×10^{-9} in sec^2. The Bode plot is based on the transfer function of

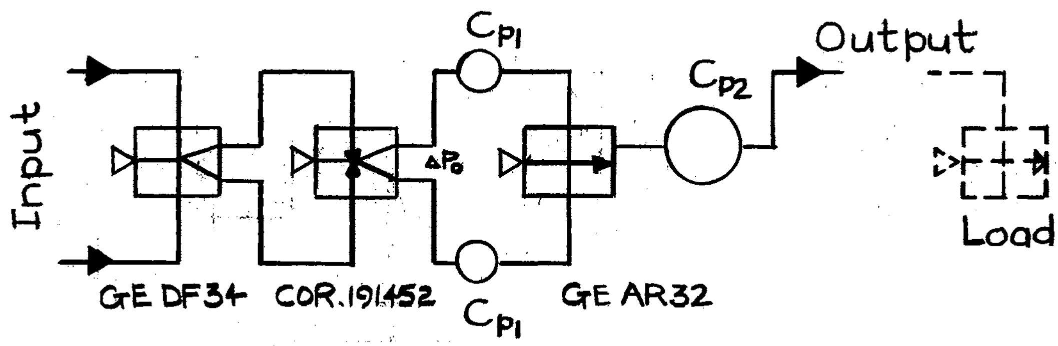


Figure 9. Schematic of an F/A

of the RC network as in Figure 8a.

$$\frac{P_o}{P_i} = \frac{1}{RCs + 1} \tag{4}$$

From (4) the Bode plot can be drawn, as in Figure 8b, for the R_1C_{p1} combination.

The final stage of an F/A requires yet another RC filter (whose resistance is that of the input resistance of the function generator) to filter out the high frequency AC signal, and leave only a DC signal. A schematic of a typical F/A circuit is presented in Figure 9. Two stages of digital devices provide signal limiting: capacitance to provide frequency sensitivity; a rectifier which translates the amplitude variation caused by the capacitance to a useful variation in average output level; and one final capacitor to filter out the residual AC signal and transmit the DC or average pressure to the function generator. However, before the last capacitor can be sized, more information must be known about the function generator.

Function Generation and Signal Summing

The function generator chosen for the original V-S controller was a biased proportional amplifier. However, the output characteristic of a rectifier is of the correct shape for a function generator (Figure 3) and could have been used. The rectifier offers one less output that will have to be captured when the conversion to hydraulics is made and was chosen for that reason alone.

Once the rectifier is specified, the last capacitor of the F/A can be sized. For example, if a rectifier supply pressure of two psig is selected to give proper function shape, the input resistance is calculated from performance characteristics (Appendix A). The capacitance is sized to offer a break point (1/RC) on the Bode diagram which reduces expected AC signals to negligible amplitude. For a capacitance of 2.75 cu. in. and the input resistance of the rectifier, the Bode diagram is that of R_2C_{p2} as shown in Figure 8b.

The entire Modified V-S controller circuit is illustrated schematically in Figure 10. In the summing amplifier, the signal proportional to the desired vacuum is subtracted from the signal from the DC isolator. Although the summing device is called an amplifier, its gain is only about two and, therefore, the summed signals must be again amplified to obtain a large enough signal for actuation.

Finally, the DC signal must be bias tuned at the summing amplifier (Figure 10). This adjustment is left for the user so that any tendency for the circuit to detune will be minimized.

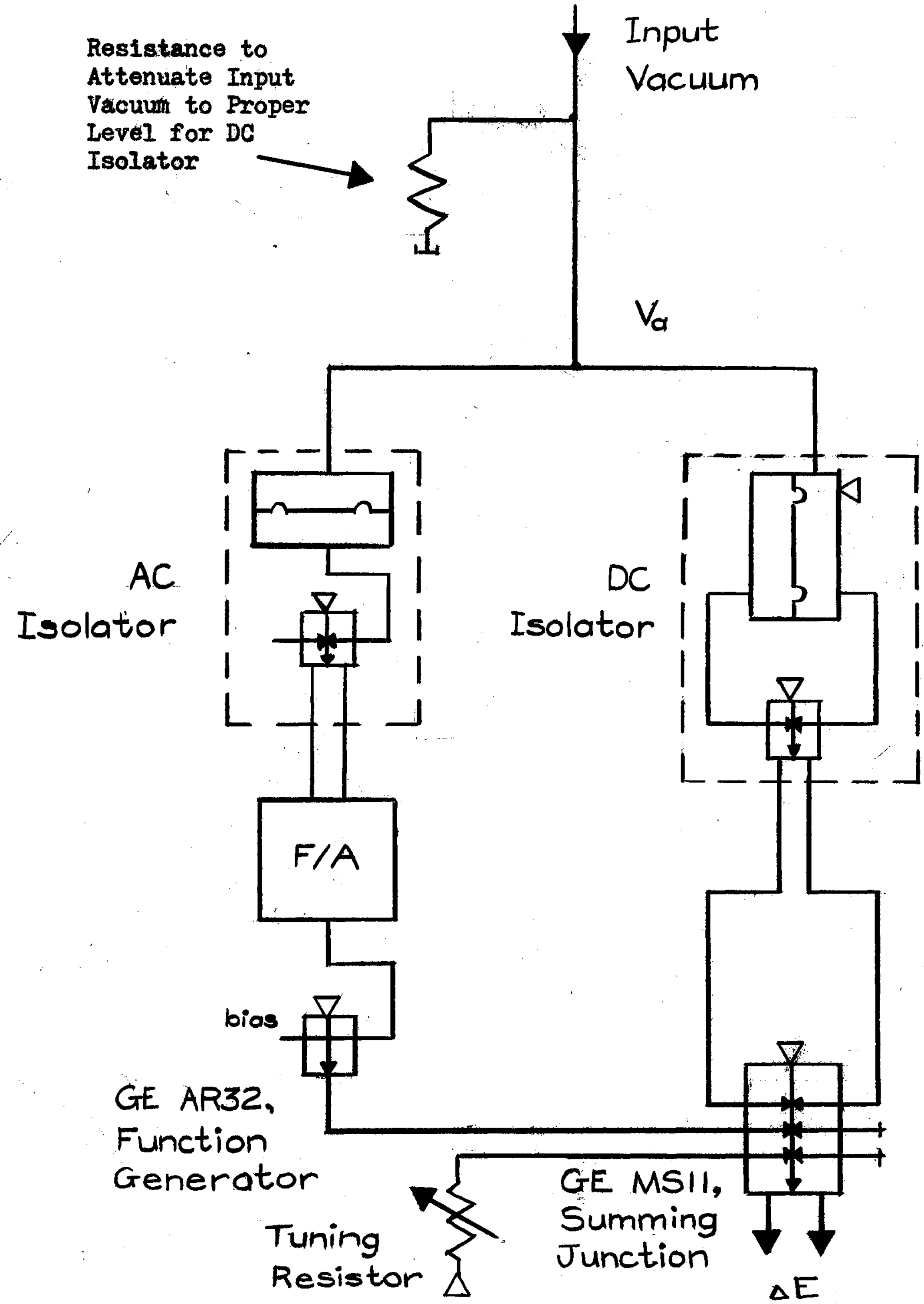


Figure 10. Schematic of Modified V-S Controller

CHAPTER IV

ALTERNATIVE METHODS FOR IMPLEMENTATION OF FREQUENCY-TO-ANALOG CONVERSION

The conclusion that implementation of the vacuum-speed controller is possible is partly based on the premise that the engine speed can be used to calculate the optimum vacuum. This task is accomplished in the Modified V-S controller in three steps: (1) the AC vacuum signal proportional to engine speed is isolated, (2) a DC analog of the frequency is obtained, and (3) a pressure signal representing optimum vacuum is generated in the function generator. Appendix C presents the development of the device needed to accomplish step (1). Step (3) is accomplished with a single element--the rectifier, after step (2) is complete. The modified F/A circuit presented in the previous chapter is one technique of accomplishing step (2). This chapter discusses the modified F/A circuit and three other techniques of implementing frequency-to-analog conversion fluidically.

Performance of the Modified F/A Circuit

The modified F/A developed in the previous chapter is the first F/A circuit examined (Figure 9). The capacitors, which were sized in the previous chapter (C_{p1}), were installed at the output legs of the digital amplifier. Output pressure of the digital amplifier, ΔP_o, was observed to have the behavior indicated in Figure 11. Although amplitude-versus-

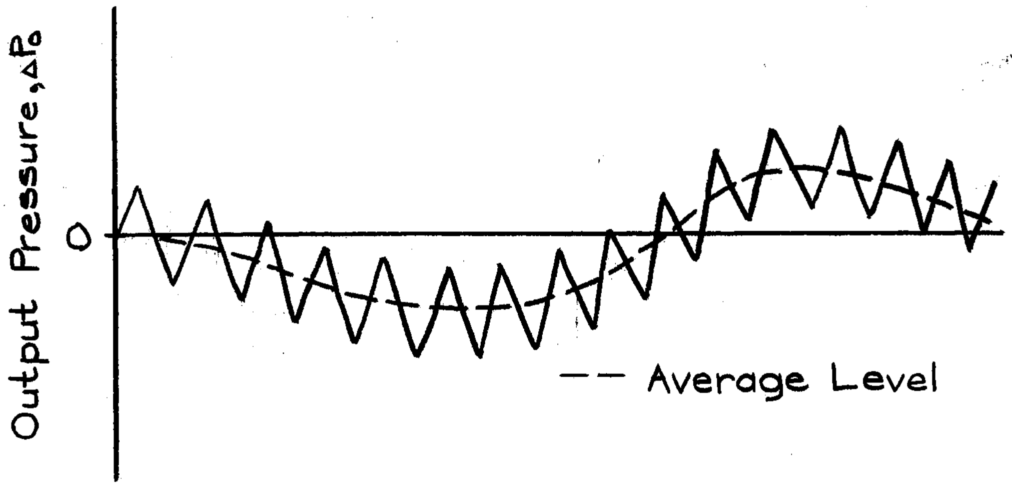


Figure 11. Dynamic Output Pressure of the Digital Amplifier in the Modified F/A (Qualitative)

frequency behavior was quite good, the constantly changing bias level made the signal unusable. The most likely cause of the fluctuation in bias level is the fact that the circuit is composed of elements which are not precisely matched. General Electric produces a modular F/A circuit which is composed of elements similar to those used in the modified F/A (Figure 17 in Appendix A). However, the elements, resistances, and capacitances in the GE device are precisely matched; even so, input signals must have a precise amplitude for the device to produce proper frequency-to-analog conversion.

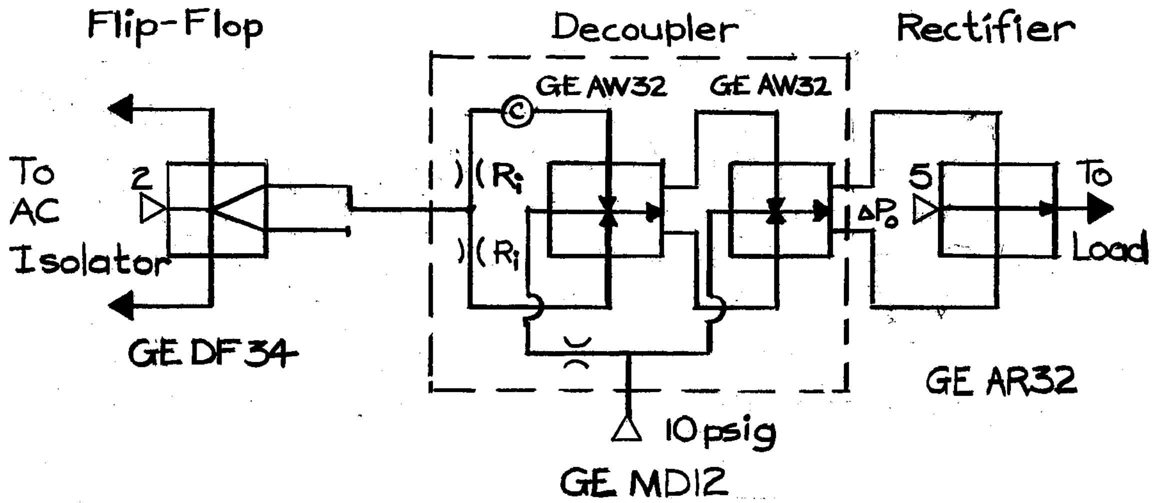
The result of the implementation of the modified F/A implies that a modular F/A be used. However, the frequency of the AC input signal is below the sensitivity range of modular circuitry available. Two approaches to the solution of this frequency problem may be taken; (1) the internal capacitances (Figure 9) may be modified to serve the frequency range, or (2) the AC signal may be rectified to increase the incoming frequency. An F/A circuit comprising one or both of these approaches should be implemented to determine the feasibility of its application in the Modified V-S controller.

An F/A Circuit Using a Decoupler and a Rectifier

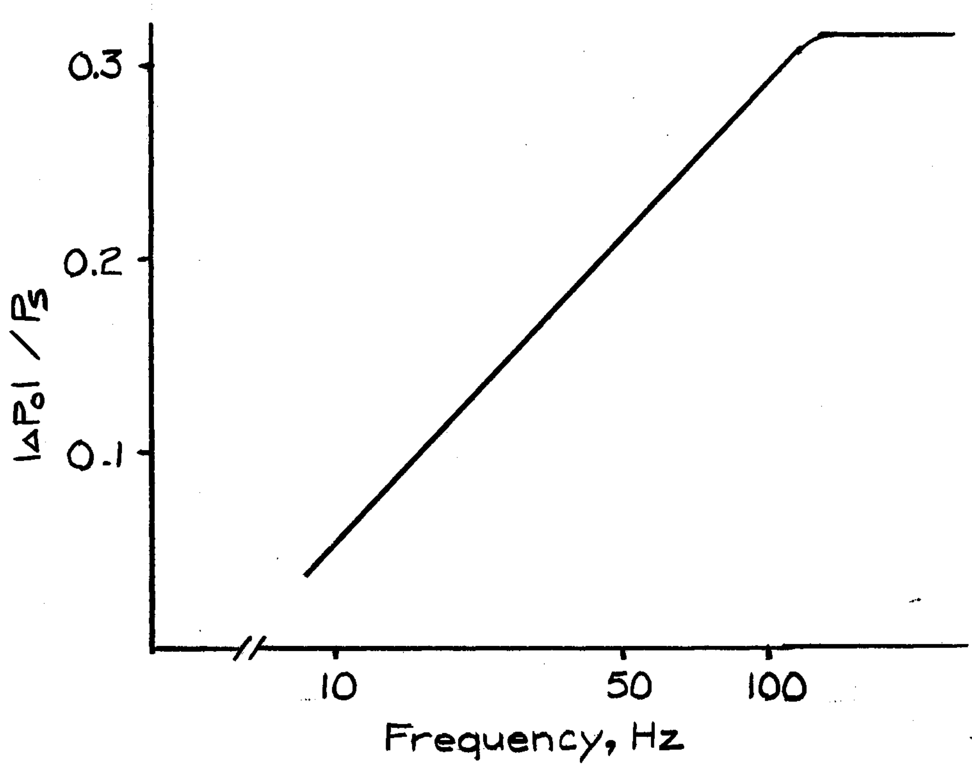
An F/A may also be constructed using a decoupler and rectifier as in Figure 12a. The decoupler is a device which takes a single-ended AC input with constant bias and produces a push-pull AC output pressure with zero bias. The important characteristic of the decoupler for the Modified V-S controller is its frequency sensitivity.

Shown in Figure 12b is the gain characteristic of a typical decoupler (GE MG11). The capacitance in one leg of the input provides frequency sensitivity and two stages of proportional amplification ensure sufficient output. The decoupler is input amplitude sensitive and, therefore, all input signals must be clipped. Thus, the decoupler should be placed immediately downstream of a flip-flop in the decoupler implementation.

The input resistances, R_1 of Figure 12a, are closely matched by GE and do not offer the problem of the previous implementation. Furthermore, a varying bias like that encountered in the modified F/A approach is eliminated at the input of the first proportional amplifier in the decoupler circuit. The problem with the decoupler implementation is lack of frequency sensitivity. This statement seems to be in contradiction with Figure 12b which was taken from the product literature. However, the load is not specified in the literature and was evidently quite low, thus giving a high output and large changes in output. Typical experi-



(a)



(b)

Figure 12. F/A Using a Decoupler (a) Circuitry, (b) Decoupler Frequency Response (After GE Product Literature)

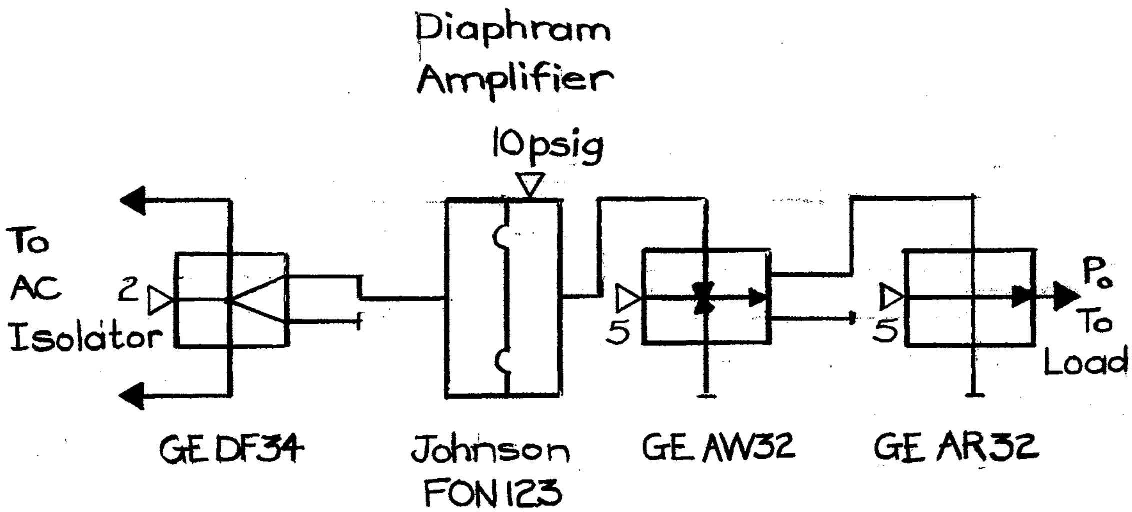


Figure 13. F/A Using a Diaphram Isolator

mental results for the circuit of Figure 12 were

at 25 Hz $\quad P_o = 0.6$ psi peak-to-peak

50 Hz $\quad P_o = 0.7$ psi peak-to-peak

with $P_s = 10$ psig.

The decoupler output signal needs to be amplified by at least two stages of properly biased proportional amplifiers. A stage of rectification (with RC filter) to translate the AC signal to a DC signal inversely proportional to the incoming frequency completes the decoupler F/A circuit.

An F/A Circuit Using a Diaphram Amplifier

This implementation takes advantage of the frequency response of a diaphram amplifier to form the frequency sensitive portion of the F/A "circuit" (Figure 13). A diaphram amplifier produced by Johnson Control was selected. This amplifier activates at a very low input pressure

(3 in. H_2O). Since the device only has one input, care must be taken to locate it at the proper point in the circuit. The single-ended output of a flip-flop connected to the AC isolator offers proper switching for the diaphram amplifier. Therefore, the diaphram amplifier was placed immediately downstream of the flip-flop in this implementation.

The built-in capacitance and input resistance of the diaphram amplifier form the passive, frequency-sensitive circuit. An example of the switching characteristics for the device is given in Figure 14a. Therefore, the frequency sensitivity is twofold--amplitude and bias level vary with frequency. If a proportional amplifier is placed downstream of the diaphram amplifier, good frequency sensitivity is obtained. Notice from Figure 13 that implementation causes the bias level change to accentuate the amplitude change. Since only one output of the proportional amplifier is used, this signal has a characteristic opposite to a rectified signal (Figure 14b). That is, the signal varies from ambient to some positive pressure such that the average pressure decreases as frequency increases. In order to accomplish function generation, the signal has to be inverted so that the average signal level increases as frequency is increased. A rectifier performs the task of signal inversion.

The problem with implementation is that most of the frequency sensitivity is attenuated in rectification. Figure 14 shows that although the input signal varies more than 50% in magnitude over approximately a 1500 rpm change in frequency (1500 - 3000 rpm), the corresponding rectified signal only varies on the order of 30%. For the frequency range of primary interest (1500 - 2500 rpm), the input signal varied 30% (a change of 0.5 psi peak-to-peak) with rectifier output

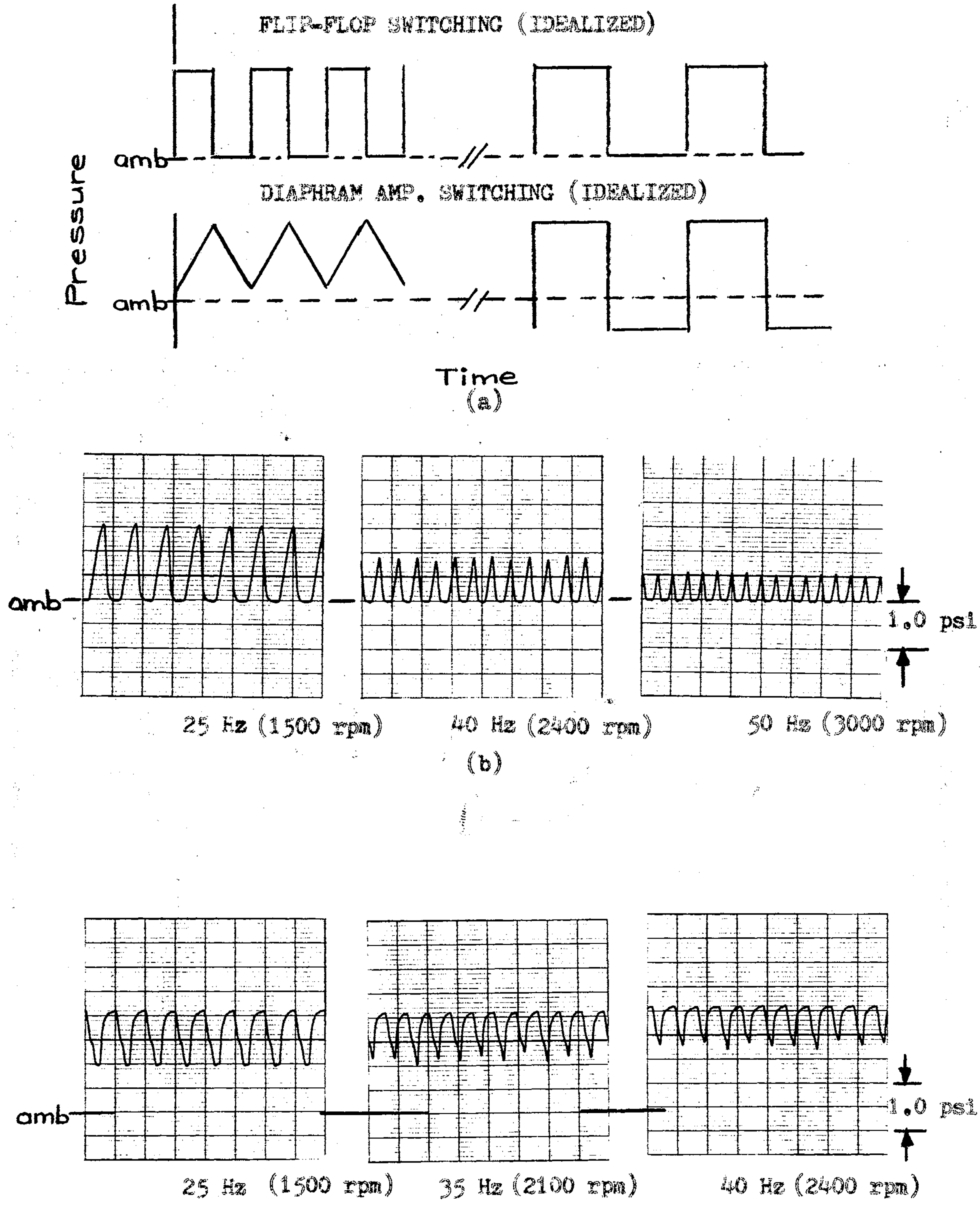


Figure 14. Diaphram Amplifier F/A Response, (a) Frequency Response of Diaphram Amplifier, (b) Response of Proportional Amplifier, (c) Response of Rectifier when Loaded with Another Rectifier at 10 psig

variations on the order of 15% (a change of 0.2 psi peak-to-peak). Therefore, once again at least two proportional amplifiers are necessary to boost the signal to a useful level following RC filtering.

CHAPTER V

HYDRAULIC OPERATION

Most of the major problems associated with the change from pneumatic operation to hydraulic operation can be attributed to two sources; change in density and change in compressibility. This chapter discusses some of the considerations which have to be observed when the working medium is changed from compressed air to hydraulic fluid.

Density and the Frequency Response

First, and perhaps most obvious, is that oil is much more dense than air. Consequently, if dynamic similarity is to be maintained, hydraulic supply pressures must be much greater than pneumatic supply pressures. Dynamic similarity is interpreted to mean that speed of response is comparable. For the same temperature, two amplifiers at the same Reynolds number (and spouting velocity) have the same speed of response. Boothe and Kelley (5) determined Figure 15 by experiment for the flow situation in a standard proportional amplifier. Figure 15a shows that a hydraulic supply pressure of 375 psig produces the same spouting velocity as a pneumatic supply of one psig.

Notice from Figure 15a that for hydraulic supply pressures above 10 psig, the spouting velocity is above 500 in./sec. The length of a proportional amplifier is of the order of one inch; therefore, the response time is of the order of 0.002 sec. The amplifier thus

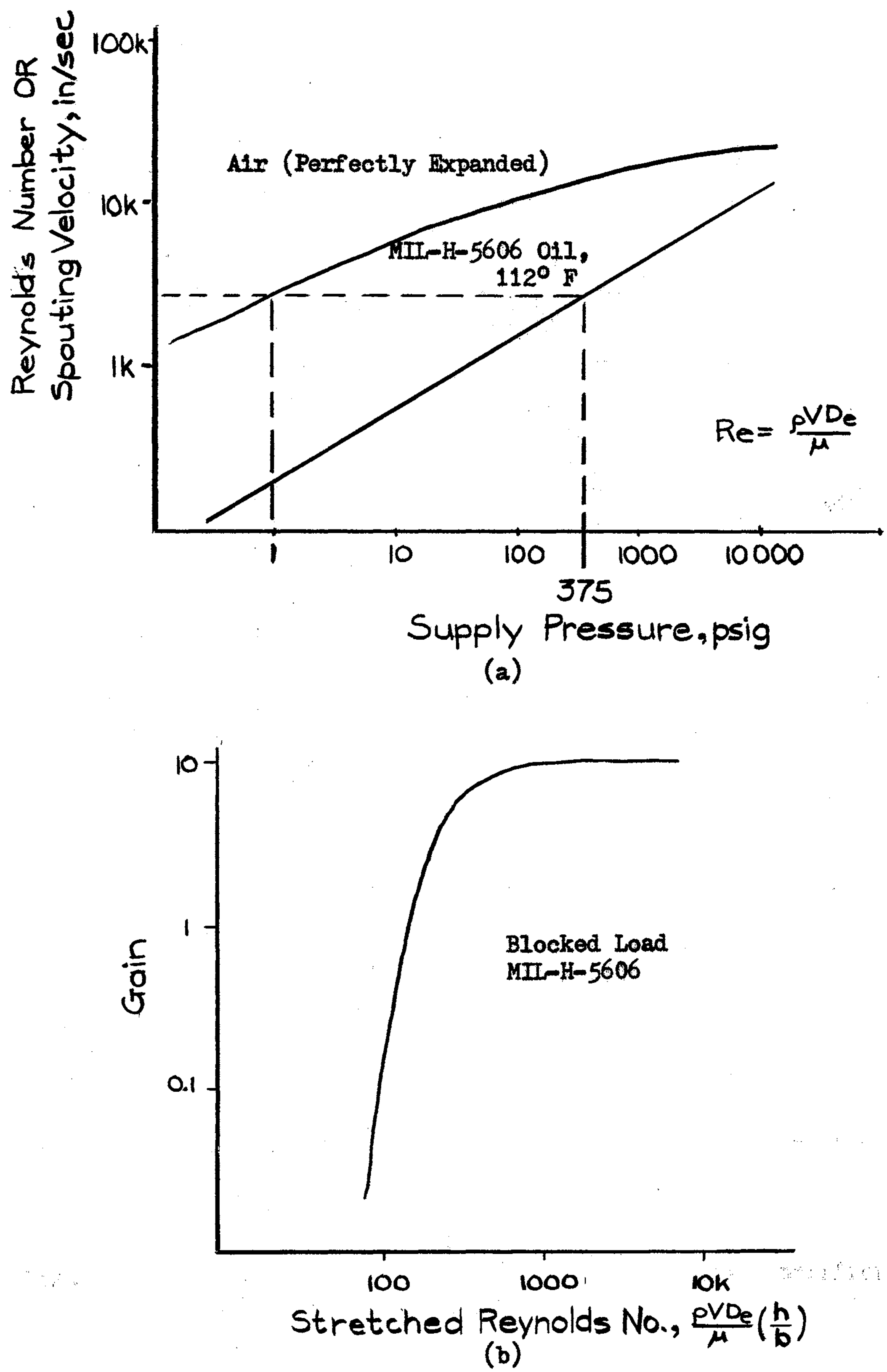


Figure 15. Hydraulic Fluid Response of a Proportional Amplifier (a) Dynamic, (b) Static

requires at least 0.004 sec. to respond to a cyclic input, which implies that any frequency greater than 250 Hz will have significant attenuation (if the supply pressure is less than 10 psig.). However, since the maximum expected frequency is less than 100 Hz, then any hydraulic supply above 10 psig. is satisfactory for the frequency response.

Density and the Gain Characteristic

Boothe and Kelley (5) also did studies on the effect of Reynolds number on the gain of proportional amplifiers; their results are presented in Figure 15b. The "Stretched Reynolds number," R_s, accounts for different aspect ratios (h/b) of the supply nozzle. The results indicate that gain is independent of R_s if that number is maintained above 1000. For $h/b = 1.0$, as is the case with the proportional amplifiers used in this study, the correlation is for Reynolds number directly. Returning to Figure 15a, this Reynolds number corresponds to supply pressures greater than 50 psig. Therefore, if the supply pressures to all devices are kept above 50 psig., the normalized curves obtained from pneumatic experiment (e.g., those presented in Appendix A) are accurate enough to proceed with the initial stages of the hydraulic circuit design.

Compressibility and Capacitance

The pneumatic capacitances of Chapter III were simply designed since they took advantage of the natural compressibility of air. However, hydraulic fluid is very nearly an incompressible fluid and, therefore, a compliant volume or bellows must be used. Choosing the control volume as shown in Figure 16 and permitting the rigid tank to move only in the x-direction, the continuity equation is written

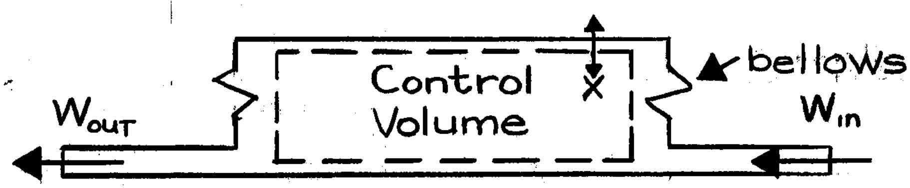


Figure 16. The Control Volume for the Theoretical Hydraulic Capacitance

$$W_{in} - W_{out} = \frac{d(\rho V)}{dt}$$

But, ρ = constant, so $$\Delta W = \rho \frac{dV}{dt}$$

where $V = V_0 + Ax$ and V_0 is the volume at time = zero.

Therefore, $$\Delta W = \rho A \frac{dx}{dt} \tag{5}$$

But, $$\frac{dx}{dt} = \frac{dx}{dP}\frac{dP}{dt} \tag{6}$$

Furthermore, the bellows possesses a spring-like action so

$$F = PA = Kx$$

or $$A\,dP = K\,dx$$

$$\frac{A}{K} = \frac{dx}{dP} \tag{7}$$

Inserting (6) and (7) into (5) yields

$$\Delta W = \frac{\rho A^2}{K}\frac{dP}{dt} = C_h \frac{dP}{dt}$$

where C_h is the theoretical capacitance of the bellows.

The values of the needed capacitances must be found as in Chapter III. That is, hydraulic supply pressures must be selected in order that input resistances may be determined. The Bode plot is determined from knowledge of the incoming AC signal frequency versus desired output amplitude. The break frequency thus determined gives the ratio $1/RC_h$. Since input resistances are known, values for hydraulic capacitances are calculated.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The feasibility of extracting AC and DC information from the total vacuum signal has been demonstrated. AC and DC isolators have been implemented such that they possess the capability of being supplied with either compressed air or hydraulic fluid. Furthermore, the first stages of design for the Modified V-S controller have been accomplished which utilizes the AC and DC isolators.

Studies on frequency-to-analog conversion of the AC signal have been conducted. Implemented F/A schemes have demonstrated frequency sensitivity at the expense of circuit simplicity. Further studies need to be accomplished to determine an F/A circuit which possesses the simplicity required to make the Modified V-S controller a practicality. Emphasis in this study has been placed on devices to accomplish assigned tasks and not on optimum configurations. Therefore, AC and DC isolators need to be redesigned such that optimum configurations are obtained.

V-S controllers have been presented which control the engine vacuum speed relationship to optimize system efficiency. An S-V controller was presented by Woods (4)[4] and offers possible simplification of implementation when AC and DC isolators are used. After implementation of the

---

[4]The speed-vacuum controller is presented in Appendix D.

Modified V-S controller is accomplished, the feasibility of an S-V controller utilizing AC and DC isolators should be determined.

SELECTED BIBLIOGRAPHY

(1) Heinrich, A. "Application of Mobile Hydrostatic Transmission." S.A.E. Paper No. 670696, Presented at the 1967 S.A.E. Meeting.

(2) Wilson, W. E. "Control Systems for Hydrostatic Transmissions." Machine Design. IV (March, 1968). 141-4.

(3) Howard, F.W.; Clark, S. J., and Turnquist, R. O. "Fluidic Control of Hydrostatic Tractor Transmissions." A.S.A.E. Paper No. 69-136, Presented at the 1969 Annual Meeting of the A.S.M.E.

(4) Woods, R. L.; Reid, K. N., and Gunda, R. "Application of Fluidics in Military Vehicle Propulsion Systems." Final Technical Report under Contract No. DAAE07-67-C-5639, to U.S. Army Tank-Automotive Command, Warren, Michigan. Technical Report No. 11401, April, 1971.

(5) Boothe, W. A. and Kelley, L. R. "Hydraulic Fluidics." A.S.M.E. Publication No. 68-WA/FE-26, Presented at the 1968 A.S.M.E. Winter Annual Meeting.

(6) General Electric. "Fluidic Speed Governing Controls." Specialty Fluidics Division, Schenectady, N.Y.

(7) Dummer, G. W. and Robertson, J. Mackenzie, eds. Fluidic Components and Equipment. Pergamon Press: N. Y. 1968.

(8) Katz, S. and Hastie, E. "Passive Lead Networks for Fluidic Systems." 1971. (Mimeographed.)

(9) Rexford, D. L. "Interconnecting Fluidic Devices." General Electric Specialty Fluidics Division, Schenectady, June, 1967.

(10) Schloesser, W. M. J. "Mathematical Model for Displacement Pumps and Motors." Hydraulic Power Transmission. April and May, 1971.

(11) Reid, KN. N. and Woods, R. L. "Fluidic Control of a Hydrostatic Transmission in a Vehicle Propulsion System." 1972. (Mimeographed.)

APPENDIX A

NOTES ON FLUIDIC ELEMENTS

In this appendix explanatory notes on the pneumatic behavior of selected fluidic elements are presented to enable the reader to follow implementation discussions more easily. These notes consist largely of a presentation of manufacturers' product sheets which display general performance behavior for the various elements. Fluidic devices are sensitive to the manner in which they are loaded and so the manufacturers' characteristics presented in this appendix must be used only in a general or qualitative fashion.

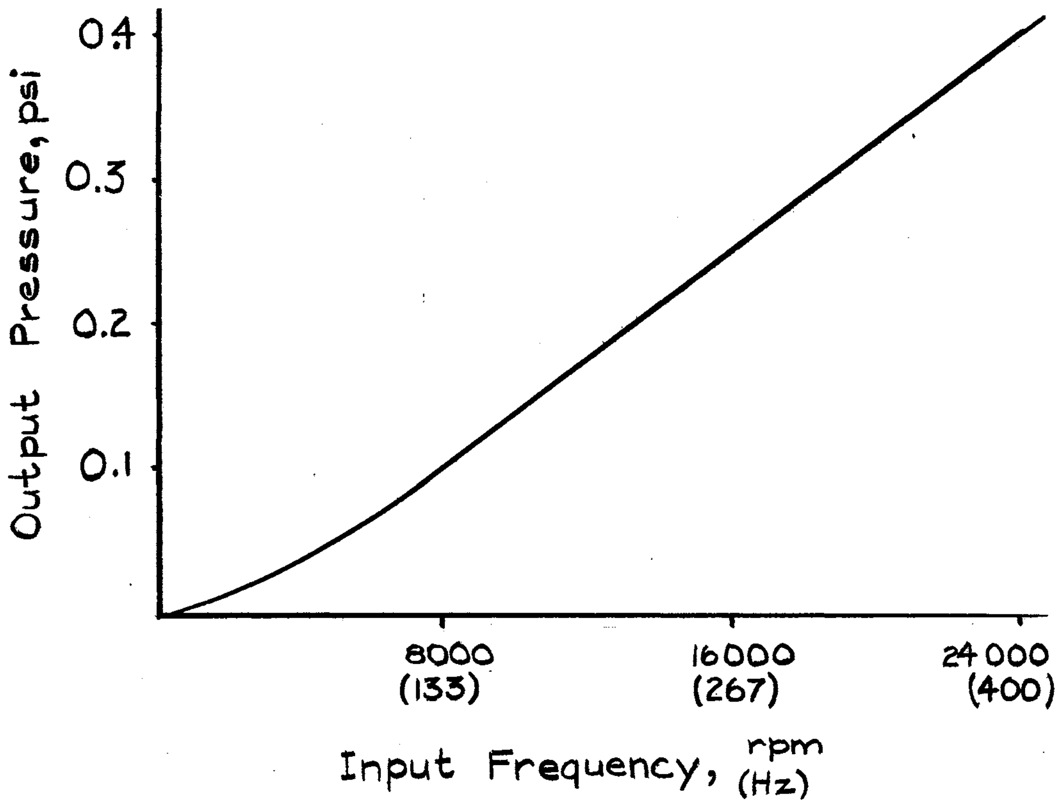


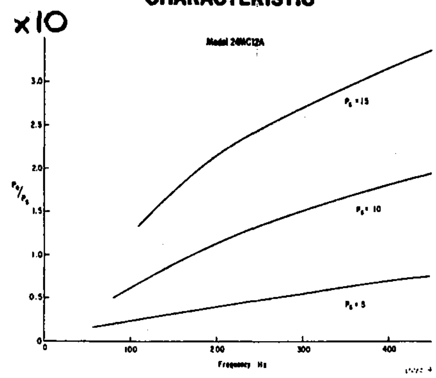
Figure 17. Modified GE MC12A Frequency-to-Analog Circuit (F/A) Characteristics

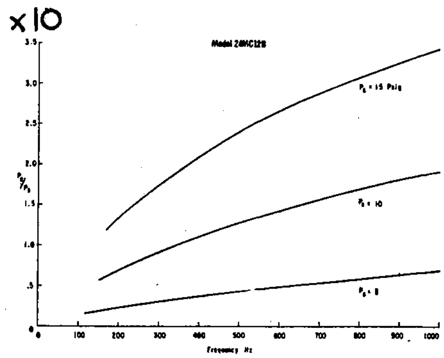
The V-S controller implementation required that the output capacitor of a standard GE F/A be modified to be consistent with the manner in which the device was loaded. The input-output characteristic for the modified device is presented in Figure 17 (compare to Figure 18), with the device loaded as it appears in the V-S controller.

PERFORMANCE CHARACTERISTICS

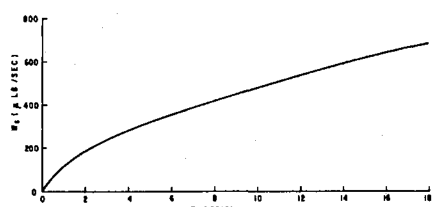
FREQUENCY TO ANALOG CIRCUIT
Models 24MC12A and B

OUTPUT PRESSURE vs. FREQUENCY CHARACTERISTIC

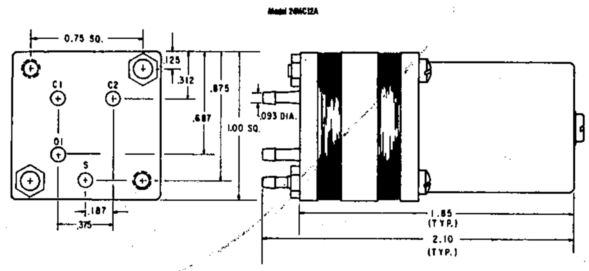


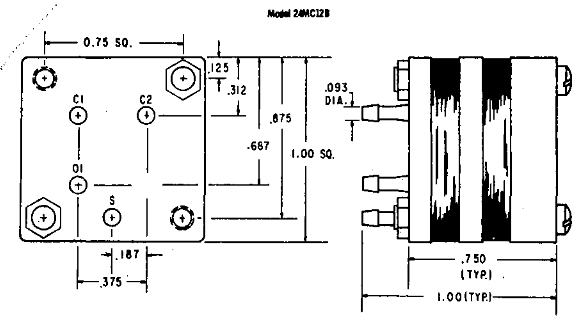


SUPPLY PRESSURE — FLOW CHARACTERISTIC



OUTLINE DIMENSIONS





CONSTRUCTION

Effective nozzle size: 0.020 in. square.

Materials:

- Lamination — stainless steel
- Cover and base — anodized aluminum
- Fittings — stainless steel

Also available without fittings for manifold mounting.

GET-3497A
7/69 (2M)

For more information, write Section 37-209

SPECIALTY FLUIDICS OPERATION
GENERAL ELECTRIC
NEW BUSINESSES DEVELOPMENT OPERATIONS
SCHENECTADY, NEW YORK

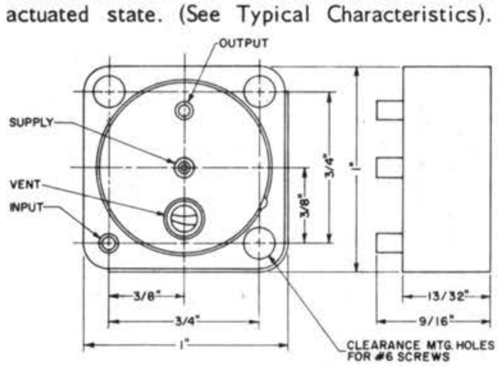
Figure 18. Performance Characteristics of the GE MC12

JOHNSON CONTROL FLUIDICS

Johnson Diaphragm Amplifiers

Diaphragm Amplifiers are miniature interface devices which perform the same function as a piloted three-way valve, but at low outlet flow rates. Fluidic signals of several inches water gage applied to the input will control the output pressure up to 35 psig in both digital and analog systems. Diaphragm Amplifiers are very suitable for providing pneumatic signals to air-piloted valves and for powering small cylinders. They are also used at fluidic signal levels for providing isolation and in timing circuits.

Johnson FON-Series Diaphragm Amplifiers are available in four models, with either 0.012" or 0.016" diameter supply orifice and with either 3" or 8" water gage actuating pressure. The larger supply orifice consumes more flow in the unactuated state and delivers more flow in the actuated state. (See Typical Characteristics).



Dimensions

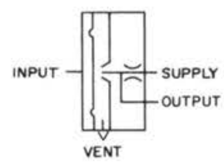
FON-Series Diaphragm Amplifier

Typical Turn-On Response Time

Supply Pressure * (psig)	FON-123 & FON-128 (milliseconds)	FON-163 & FON-168 (milliseconds)
1	14	24
5	30	54
10	43	75
20	61	107
30	74	129

* Output is 90% of supply pressure, with step input and zero volume on output. Turn-off times are always shorter.

The higher actuating pressure is desirable when the pilot chamber of the diaphragm amplifier is used in timing circuits at fluidic pressure levels; the lower actuating pressure is preferred when sensitivity is important.



Diaphragm Amplifier Symbol

Terminal connections are provided on the input, supply, and output ports for 1/16" I.D. flexible

Specifications

MODEL		FON-123	FON-128	FON-163	FON-168
SWITCHING PRESSURE		3" ±1" w.g.	8" ±2" w.g.	3" ±2" w.g.	8" ±2" w.g.
SUPPLY PRESSURE		0.012"	0.012"	0.016"	0.016"
SUPPLY FLOW		SEE TYPICAL SUPPLY CHARACTERISTICS			
MAXIMUM INPUT PRESSURE		5 psig			
INPUT LEAKAGE @ 1 psig		LESS THAN 0.003 SCFM			
TEMPERATURE LIMITS		0 TO 150F (-17 TO 65C)			
RECOMMENDED FILTRATION		10 MICRON			
MATERIALS	BODY	POLYSULFONE			
	DIAPHRAGM	POLYURETHANE			
	SPRING	BERRILIUM COPPER			

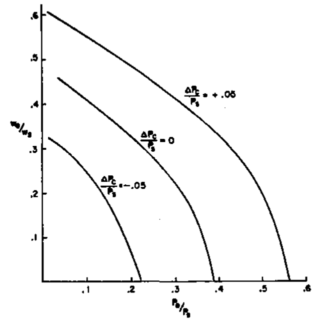
JOHNSON SERVICE COMPANY
Milwaukee, Wisconsin 53201

Figure 19. Performance Characteristics of the Johnson FON123 Diaphram Amplifier

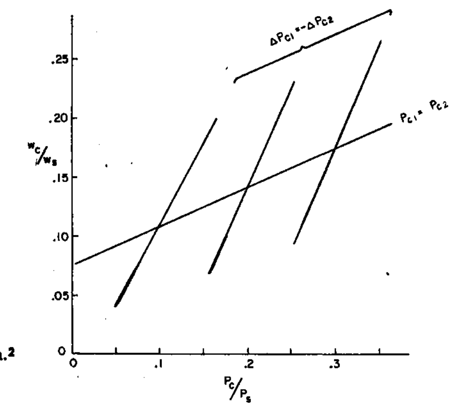
PERFORMANCE CHARACTERISTICS

PROPORTIONAL AMPLIFIER
MODEL AW32

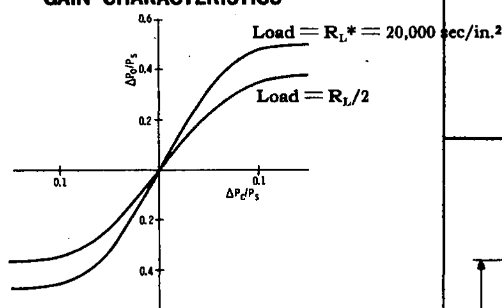
OUTPUT CHARACTERISTICS



INPUT CHARACTERISTICS

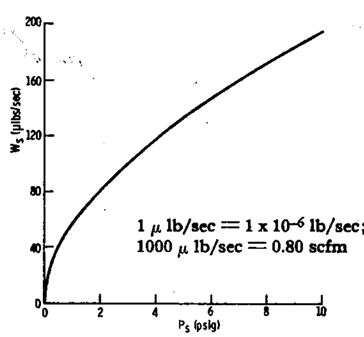


GAIN CHARACTERISTICS

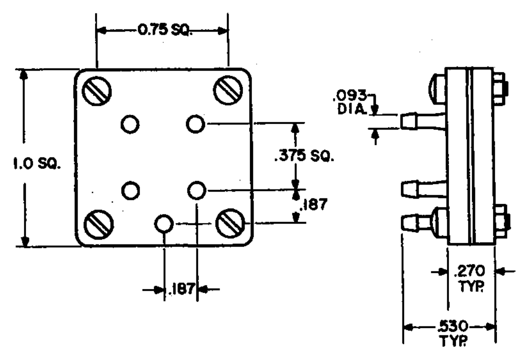


*flow impedance defined as $\frac{\Delta P}{\Delta w}\frac{\text{lb/in.}^2}{\text{lb/sec}}$

SUPPLY PRESSURE — FLOW CHARACTERISTICS



OUTLINE DIMENSIONS



Construction

The power nozzle is 0.020 in. square.
Element materials
- Laminations — stainless steel
- Cover and base — aluminum (anodized)
- Fittings — stainless steel

Also available without tubing fittings for manifold mounting.

For more information, write Section 37-365

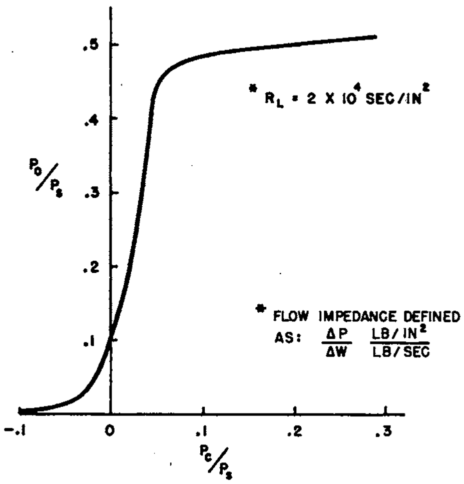
SPECIALTY FLUIDICS OPERATION
GENERAL ELECTRIC
SCHENECTADY, NEW YORK

Figure 20. Performance Characteristics of the GE AW32 Amplifier

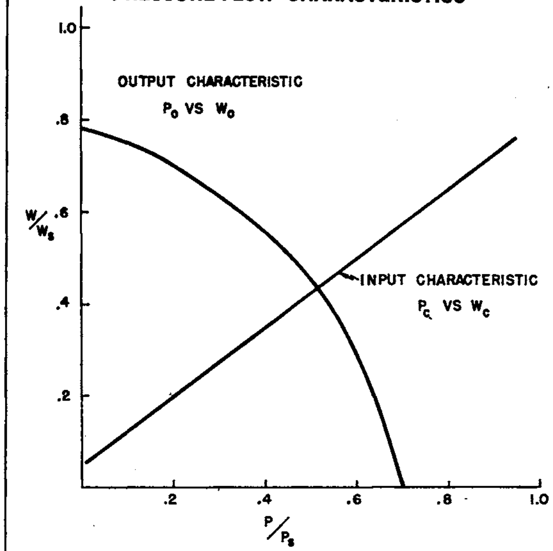
PERFORMANCE CHARACTERISTICS

**DIGITAL AMPLIFIER
MODEL DW32**

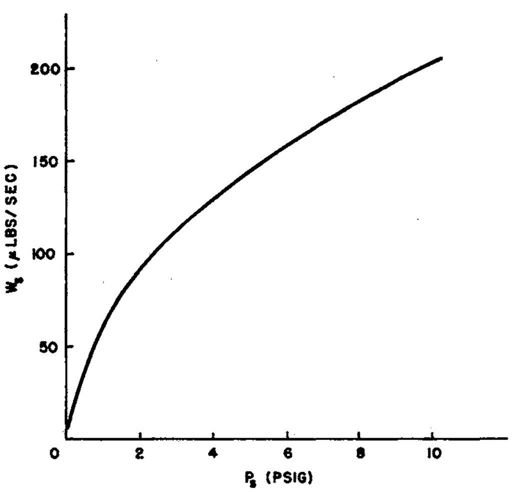
SWITCHING CHARACTERISTICS



INPUT AND OUTPUT PRESSURE-FLOW CHARACTERISTICS

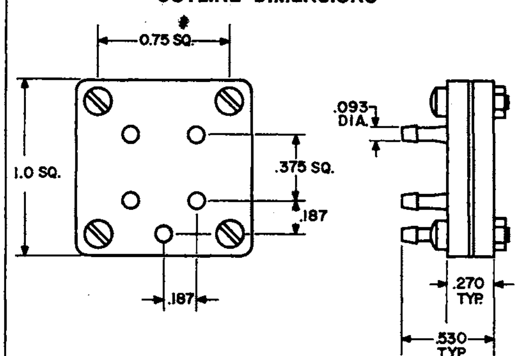


SUPPLY PRESSURE-FLOW CHARACTERISTICS



1 μ lb/sec = 1 x 10^{-6} lb/sec;
1000 μ lb/sec = 0.80 scfm

OUTLINE DIMENSIONS



Construction

Power nozzle — 0.020 in.

Element materials
- Laminations — stainless steel
- Cover and base — aluminum (anodized)
- Fittings — stainless steel

Also available without tubing fittings for manifold mounting.

For more information, write Section 37-365

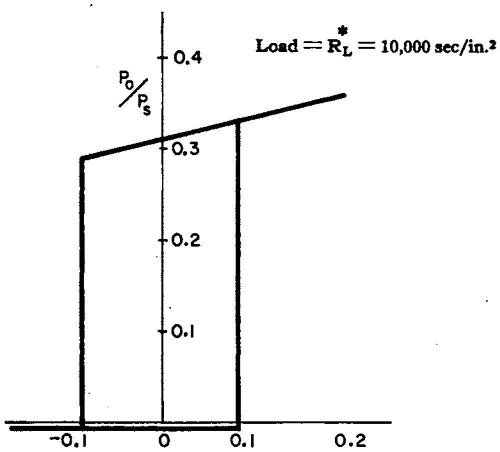
SPECIALTY FLUIDICS OPERATION
GENERAL ELECTRIC
SCHENECTADY, NEW YORK

Figure 21. Performance Characteristics of the GE DW 32 Amplifier

PERFORMANCE CHARACTERISTICS

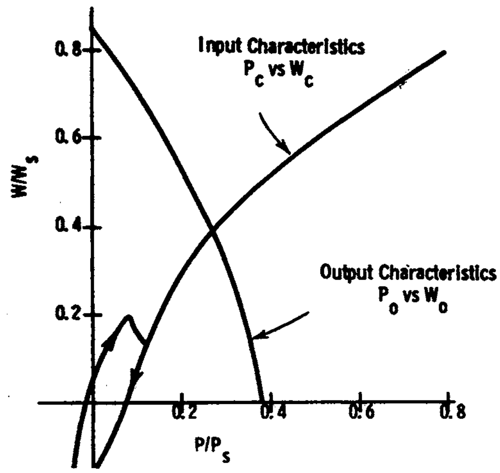
FLIP-FLOP
MODEL DF34

TYPICAL SWITCHING CHARACTERISTICS

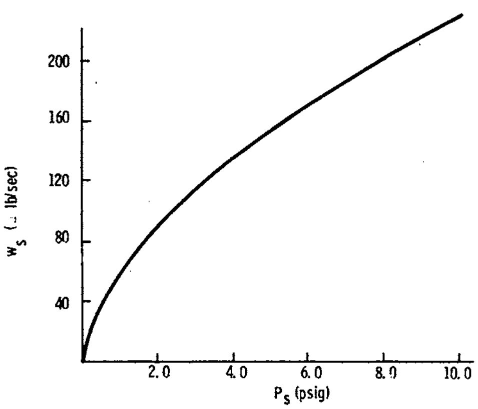


*flow impedance defined as $\frac{\Delta P \ \text{lb/in.}^2}{\Delta w \ \text{lb/sec}}$

INPUT AND OUTPUT PRESSURE-FLOW CHARACTERISTICS

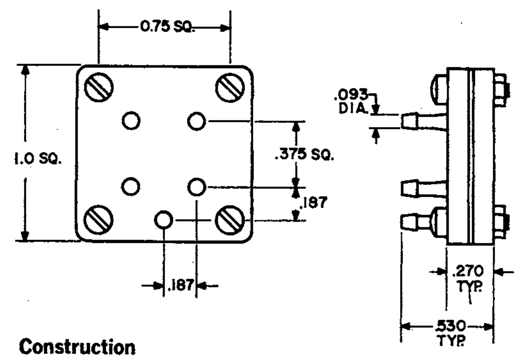


SUPPLY PRESSURE-FLOW CHARACTERISTICS



1 μ lb/sec = 1 x 10^{-6} lb/sec;
1000 μ lb/sec = 0.80 scfm

OUTLINE DIMENSIONS



Construction

Power nozzle — 0.020 in. square.
Element materials
- Laminations — stainless steel
- Cover and base — aluminum (anodized)
- Fittings — stainless steel

Also available without tubing fittings for manifold mounting.

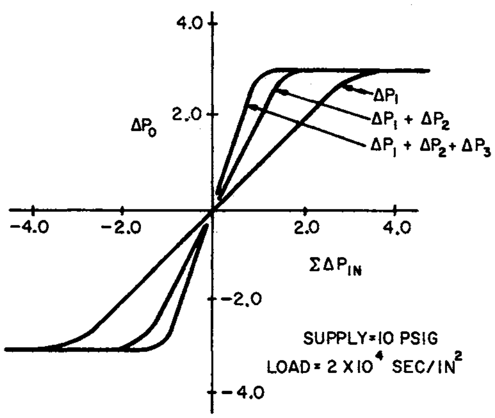
For more information, write Section 37-365

SPECIALTY FLUIDICS OPERATION
GENERAL ELECTRIC
SCHENECTADY, NEW YORK

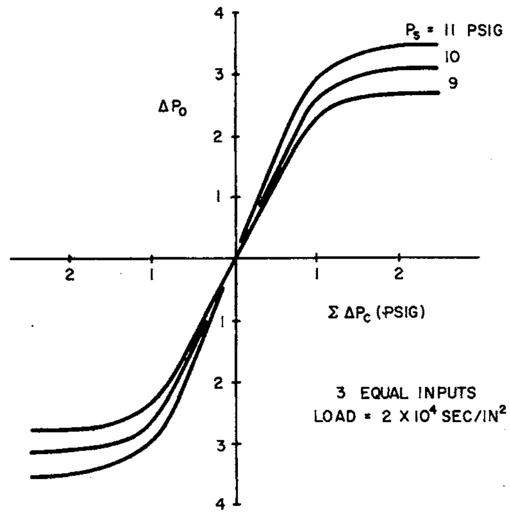
Figure 22. Performance Characteristics of the GE DF34

PERFORMANCE CHARACTERISTICS 3-INPUT SUMMING AMPLIFIER MODEL MS11

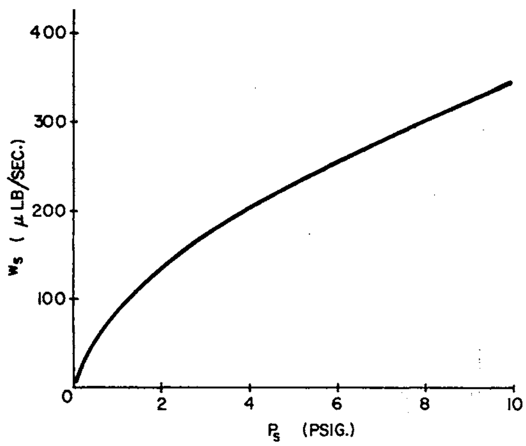
SUMMING CHARACTERISTIC



EFFECT OF SUPPLY PRESSURE ON GAIN

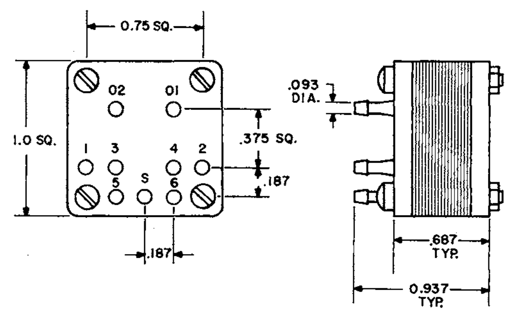


SUPPLY PRESSURE–FLOW CHARACTERISTIC



1 μ lb/sec = 1 x 10^{-6} lb/sec
1000 μ lb/sec = 0.80 scfm

OUTLINE DIMENSIONS



Construction

Effective nozzle size: 0.020 in. square

Materials:
- Lamination — stainless steel
- Cover and base — anodized aluminum
- Fittings — stainless steel

Also available without tubing fittings for manifold mounting.

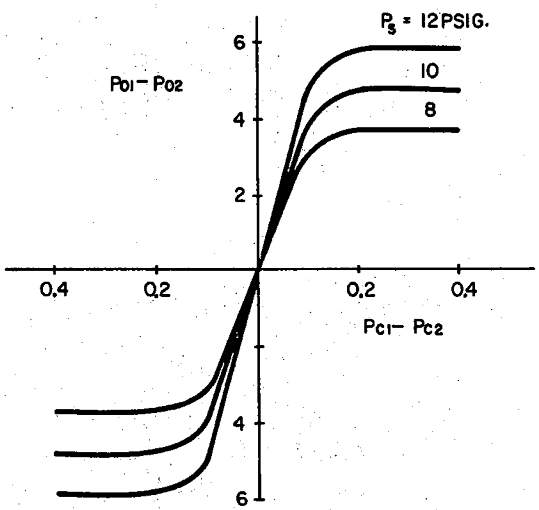
For more information, write Section 37-365

SPECIALTY FLUIDICS OPERATION
GENERAL ELECTRIC
SCHENECTADY, NEW YORK

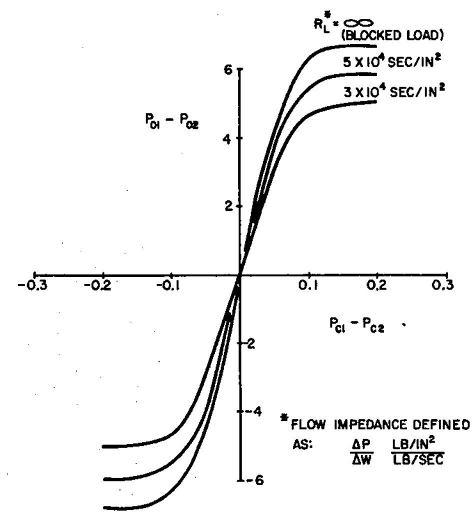
Figure 23. Performance Characteristics of the GE MS11

PERFORMANCE CHARACTERISTICS 3-STAGE PROPORTIONAL GAIN MODULE MODEL MG11

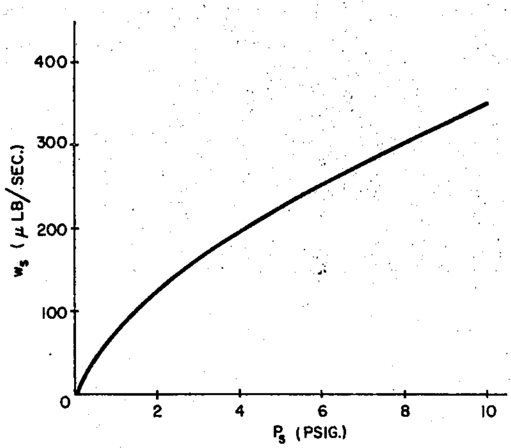
GAIN CHARACTERISTIC FOR VARIOUS SUPPLY PRESSURES



GAIN CHARACTERISTIC FOR VARIOUS LOADS

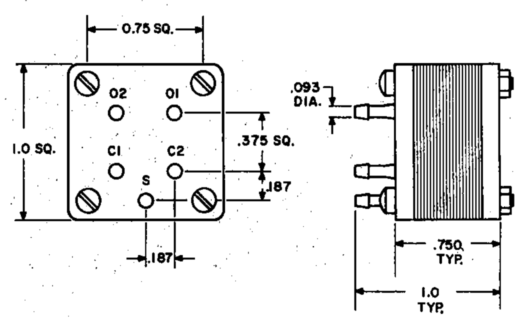


SUPPLY PRESSURE–FLOW CHARACTERISTIC



1 μ lb/sec = 1 x 10^{-6} lb/sec
1000 μ lb/sec = 0.80 scfm

OUTLINE DIMENSIONS



Construction

Effective nozzle size: 0.020 in. square

Materials:

- Lamination — stainless steel
- Cover and base — anodized aluminum
- Fittings — stainless steel

Also available without tubing fittings for manifold mounting.

For more information, write Section 37-365

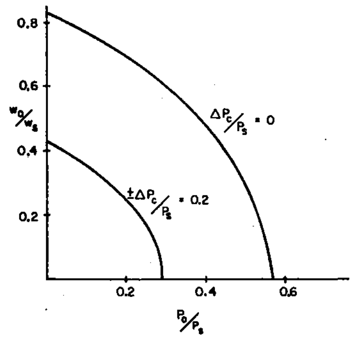
SPECIALTY FLUIDICS OPERATION
GENERAL ELECTRIC
SCHENECTADY, NEW YORK

Figure 24. Performance Characteristics of the GE MG11

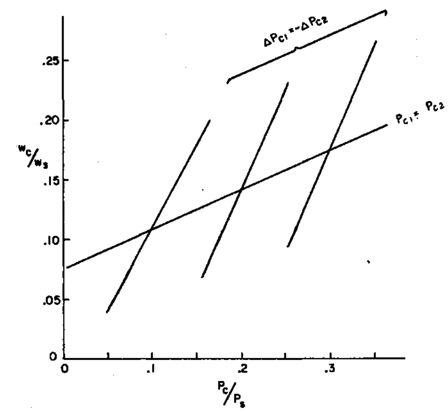
PERFORMANCE CHARACTERISTICS

RECTIFIER MODEL AR32

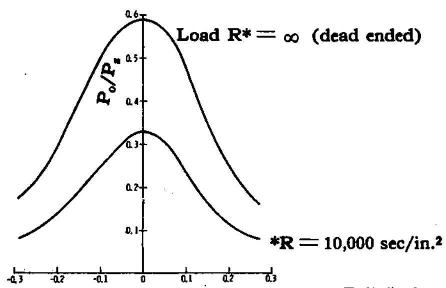
OUTPUT CHARACTERISTICS



INPUT CHARACTERISTICS

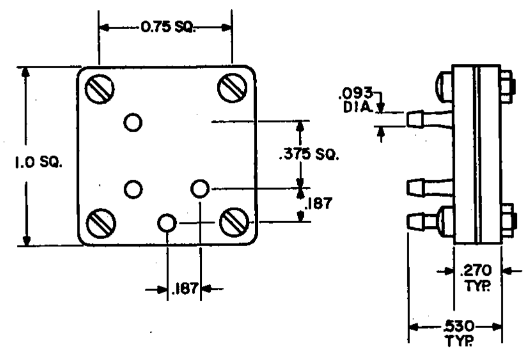


INPUT–OUTPUT CHARACTERISTICS

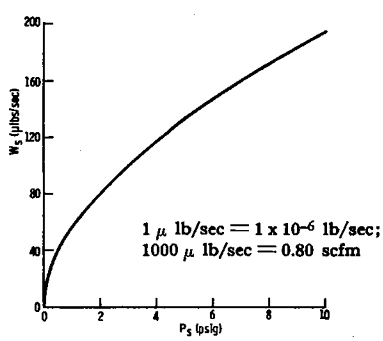


*flow impedance defined as $\frac{\Delta P}{\Delta w}\ \frac{\text{lb/in.}^2}{\text{lb/sec}}$

OUTLINE DIMENSIONS



SUPPLY PRESSURE — FLOW CHARACTERISTICS



1 µ lb/sec = 1 x 10⁻⁶ lb/sec;
1000 µ lb/sec = 0.80 scfm

Construction

The power nozzle is 0.020 in. square.
Element materials are:
- Laminations — stainless steel
- Cover and base — aluminum (anodized)
- Fittings — stainless steel

Also available without tubing fittings for manifold mounting.

For more information, write Section 37-365

SPECIALTY FLUIDICS OPERATION
GENERAL ELECTRIC
SCHENECTADY, NEW YORK

Figure 25. Performance Characteristics of the GE AR32

APPENDIX B

THE DC ISOLATOR

In order to implement the Modified V-S controller, a DC vacuum signal isolator is needed. This isolator must give an accurate reproduction of the DC vacuum signal while providing an interface between the incoming pneumatic vacuum signal and hydraulic controller circuitry. This appendix discusses the design and analysis of the DC isolator.

Design Criteria

A device which contributes as little additional complexity to the circuit as possible is highly desirable. This criteria can be best satisfied by a device which provides an output pressure which is a linear reproduction ($\pm$ 10%) of the vacuum DC signal. Any significant nonlinearities introduced by the isolator must be accounted for and only serve to complicate circuitry. Practically speaking, the DC isolator must take a maximum 1-7 psi pneumatic vacuum input and produce a corresponding maximum 1-5 psig output. The isolator must possess the ability to produce either a pneumatic or hydraulic output signal so that it is compatible with the purpose of this study.

Choosing the Configuration

A check with fluidics product literature (7) revealed that no interface element is commercially available to meet all the requirements

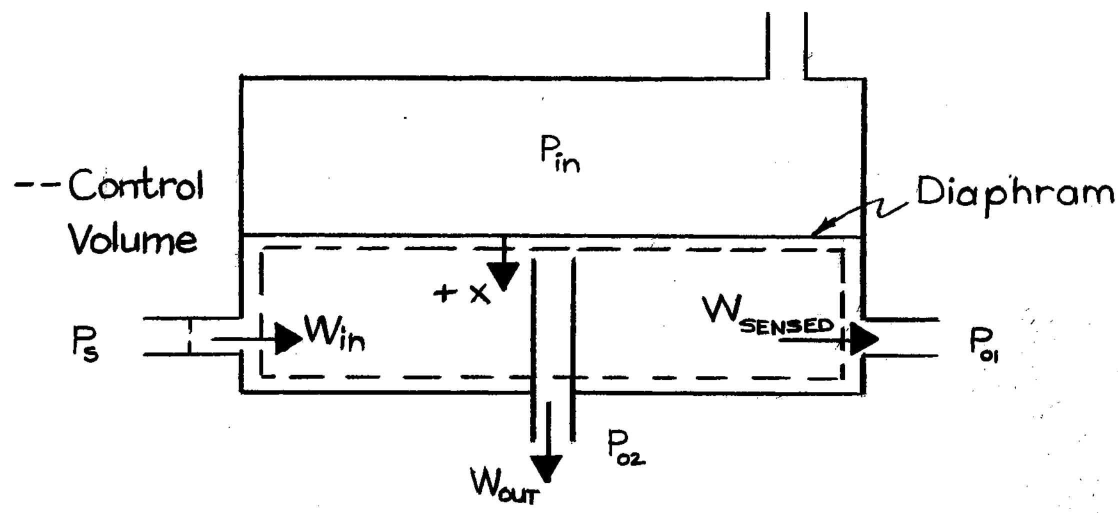


Figure 26. Cutaway View of the Corning Interface (Part No. 192695) Showing the Control Volume

of the circuit. Existing devices all function with a positive input and/or a high pressure output (about 100-500 psi hydraulic). Corning has recently developed a linear flapper-nozzle type interface element (part no. 192645) which is capable of producing the appropriate output pressure levels (either pneumatic or hydraulic). The only major drawback with this device is that it functions on a positive input. Therefore, it was decided to modify the Corning device so that it would accept the engine vacuum signal and still produce a linear input-output pressure characteristic.

A cutaway view of the Corning device is shown in Figure 26. A simplified analysis for all-pneumatic operation proceeds as follows.

Assumption 1: Pressure levels are assumed to be low enough so that compressibility effects can be ignored. This means that flow through restrictions obeys the general quadratic form,

$$W = k_1\sqrt{\Delta P} \tag{1}$$

A control volume is then chosen as in Figure 26 and the continuity equation written,

$$W_{in} = W_{out} + W_{sensed} \tag{2}$$

<u>Assumption 2</u>: W_{sensed} is loaded by an orifice discharging to atmosphere, P_a. If the flapper-nozzle spacing is X_o and $P_{in} = 0$, then Equation (2) becomes

$$k_1\sqrt{P_s - P_{o1}} = k_2(X_o - X)\sqrt{P_{o1} - P_a} + k_3\sqrt{P_{o1} - P_a} \tag{3}$$

Squaring both sides and rearranging Equation (3):

$$\frac{P_s - P_{o1}}{P_{o1} - P_a} = \frac{k_3^2}{k_1^2} + \frac{2k_3k_2}{k_1^2}X_o + \frac{k_2^2}{k_1^2}X_o^2 \tag{4}$$

$$-\left(\frac{2k_3k_2}{k_1^2} + \frac{2k_2^2}{k_1^2}X_o\right)X + \frac{k_2^2X^2}{k_1^2} \tag{5}$$

<u>Assumption 3</u>: If X is small, then $X^2 \rightarrow 0$ and (5) may be simplified to

$$\frac{P_s - P_{o1}}{P_{o1} - P_a} = k_4 - k_5X \tag{6}$$

where

$$k_4 \triangleq \frac{k_3^2}{k_1^2} + \frac{2k_3k_2}{k_1^2}X_o + \frac{k_2^2X_o^2}{k_1^2} \tag{7}$$

$$k_5 \triangleq \frac{2k_3k_2}{k_1^2} + \frac{2k_2^2}{k_1^2}X_o \tag{8}$$

To obtain a transfer characteristic, a description of diaphram stress-deflection is necessary, therefore

<u>Assumption 4</u>:

$$P_{in} - P_{o1} = KX \tag{9}$$

so that

$$\frac{P_s - P_{o1}}{P_{o1} - P_a} = k_4 - \frac{k_5}{K}\left(P_{in} - P_{o1}\right) \tag{10}$$

Rearranging $$K \frac{P_s - P_{o1}}{P_{o1} - P_a} - k_5 P_{o1} = k_4 K - k_5 P_{in} \qquad (11)$$

This equation can be greatly simplified if more is known about the relative sizes of the constants.

Assumption 5: The product $K \frac{P_s - P_{o1}}{P_{o1} - P_a}$ is very small with respect to the other terms in (11). Therefore, a linear form is obtained

$$P_{in} = P_{o1} - k_6 \qquad (12)$$

where $$k_6 \triangleq K \frac{k_3^2}{k_1^2} + \frac{2k_2k_3}{k_1^2} X_o + \frac{k_2^2}{k_1^2} X_o^2 \qquad (13)$$

One technique of assuring that the device does not violate assumption 5 is providing a very small spring constant, K, for the diaphram. Examination of the Corning diaphram verified that this approach was taken. However, the DC isolator must function with a P_{in} of 3-7 psi vacuum and a P_{o1} of 1-5 psi so that the net pressure differential across the diaphram is 4-12 psi at all times. With a small spring constant, the diaphram would simply deform until little, if any, sensitivity to input signal remained.

Therefore, the proposed Corning modification consists of finding a new diaphram material which gives the linear input-output characteristic desired, at the pressure levels expected.

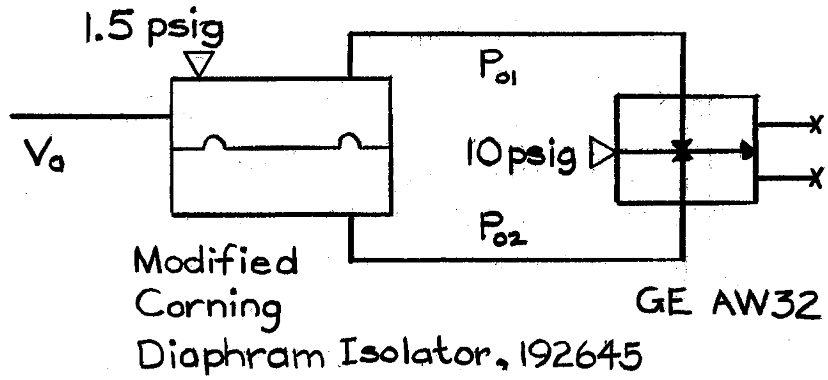
Design Method

The diaphram design method consisted primarily of trial-and-error experimentations. Equation (11) is the flow governing equation, but it does not lend much insight to the input-output relationship as K is varied. Furthermore, with exception of the metals, very little tabulated information exists for the static properties of possible diaphram materials; any calculation using K is very difficult. Even with metal diaphrams, the thickness and expected stresses can both be adjusted as design parameters so that the stress-deflection relationship becomes inconclusive at best. Therefore, a rigorous design procedure was considered to be beyond the purpose of this study and intuition and qualitative reasoning largely guided the selection of the diaphram material.

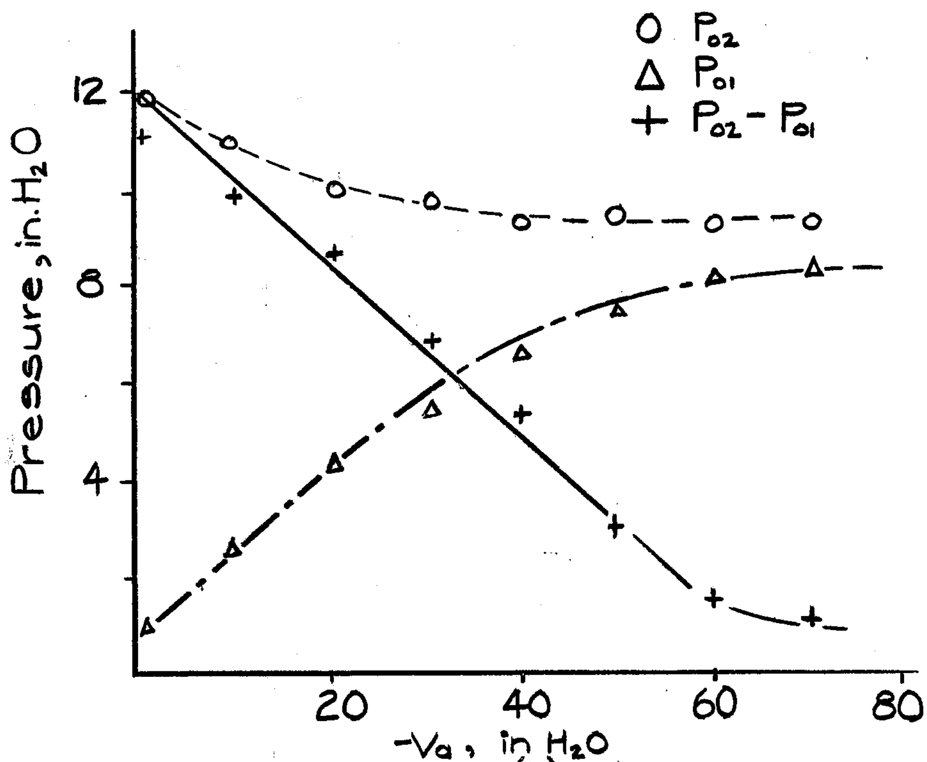
Selecting the Diaphram

The four general classes of diaphram materials considered for the isolator were; elastomers, plastics, composites, and metals. Each group had some predominate problem associated with its long-term use. The rubbers had unreliable physical properties when placed in contact with hydraulic fluid; the plastics had undesirable creep properties; composites had the bad characteristics of both plastics and rubbers; and metal diaphrams had extremely small deflections and must be mounted securely. Nevertheless, for feasibility purposes a variety of diaphram materials was tried; Neoprene, Butyl, and combinations of the two as well as brass and steel in various thicknesses.

The two diaphrams which offered desirable (e.g., linear) input-output characteristics were the Butyl and brass diaphrams. The Neoprene diaphram produced a highly nonlinear output and was therefore eliminated from consideration. It was felt that the Butyl diaphram material would be unreliable in the hydraulic fluid environment. Furthermore, tests indicated that the elastomers in general had a rather large hysteresis loop. A steel diaphram in the device did not give sufficient input-output sensitivity as compared to the brass, and consequently a brass diaphram of 0.005 inch thickness was selected. Construction of the



(a)



(b)

Figure 27. Modified Corning Interface Gain Characteristic with a Brass Diaphram 0.005 in. thick, (a) DC Isolator Schematic, (b) Gain Characteristic

Corning device offered a convenient solution to the mounting problem, since the mounting bolt holes pass through the diaphram at all four corners. Therefore, the problem of secure mounting was overcome by drilling the mounting bolt holes to within close tolerance of the size of the mounting bolts to assure no slipping.

Shown in Figure 27 are the gain characteristics of the Modified Corning Interface with brass diaphram of 0.005 inch thickness. Shown in a dashed line in Figure 27b is the single-ended output of the device. The nonlinearity was eliminated by capturing both P_{o1} and P_{o2} (see Figure 26) and letting the device function in a push-pull manner by loading it with a proportional amplifier. The amount of flow which passes out the P_{o1} tube is directly proportional to the area between the flapper and nozzle. If the diaphram deflects in a manner such that the input pressure and the deflection are directly related, then the area and, consequently, the flow are directly related to the input pressure. The input resistance to the amplifier is constant; therefore, the input pressure to the amplifier is directly related to the input flow (output flow of the isolator). Or, the input pressure to the amplifier is directly related to the input pressure to the isolator and the solid line of Figure 27 is established. However, if the diaphram does not deflect in a manner such that input pressure and deflection are directly related, then the entire argument collapses and a nonlinear characteristic is established.

In conclusion, a device has been developed (the DC isolator) which provides an output pressure directly proportional to input pressure and which performs this action such that input and output flow are isolated from each other.

APPENDIX C

THE AC ISOLATOR

This appendix presents the development of the AC isolator. Problems associated with AC signal isolation are presented and discussed.

The AC isolator must be the exact opposite of the DC isolator. That is, it must pass the AC signal while blocking the DC signal. A device introduced by Katz and Hastie (8) forms the basis of the AC isolator. It consists of a rubber diaphram stretched taut and separating two cavities; the experimental input-output relationship is shown in Figure 28.

Measurements made on the engine transmission system indicate that the amplitude of the AC vacuum signal is smallest when the DC vacuum signal is largest. This condition is designated as the worst case or minimum design condition for the AC isolator. That is, the AC isolator must be designed to transmit as much of the worst case AC signal as possible at the frequency involved (engine speed of 1000 rpm or 17 Hz). As a load condition, the signal is fed into a proportional amplifier. The incoming worst case AC vacuum signal is less than 0.2 psi in amplitude and some attenuation occurs across the isolator; therefore, some form of amplification is necessary. Experimentation showed that several stages of amplification are necessary. A GE three-stage amplifier was selected which gives a 1.0 psi amplitude signal at the worst case vacuum.

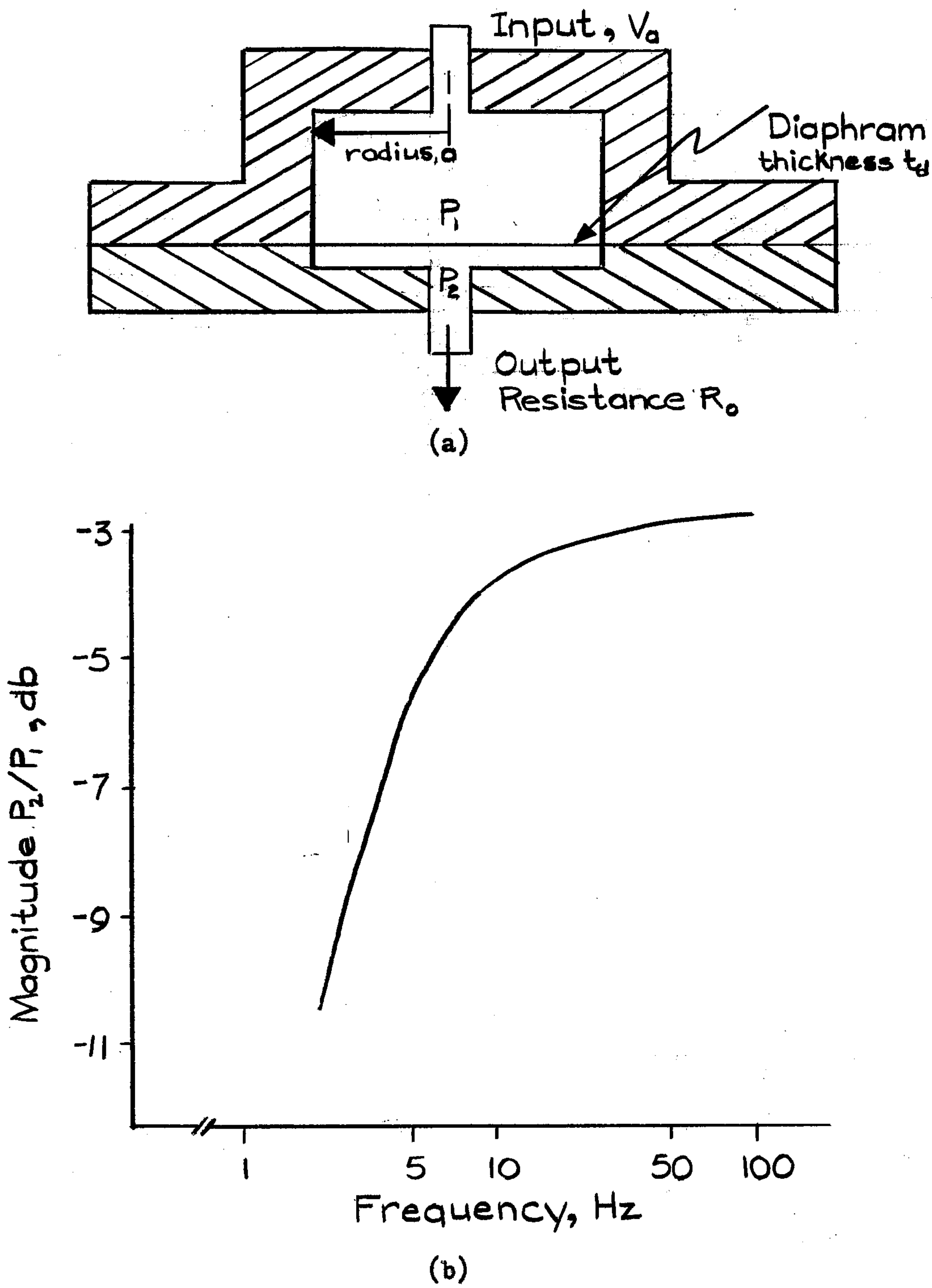


Figure 28. The Katz-Hastie Capacitor, (a) Cutaway View, (b) Experimental Gain

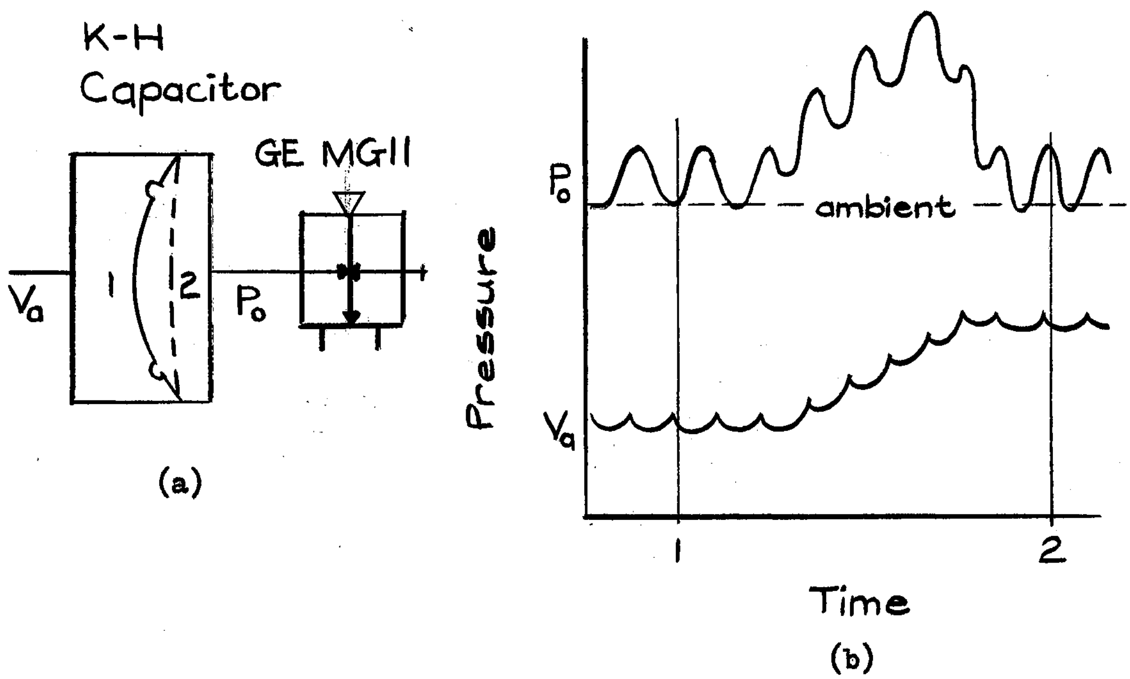
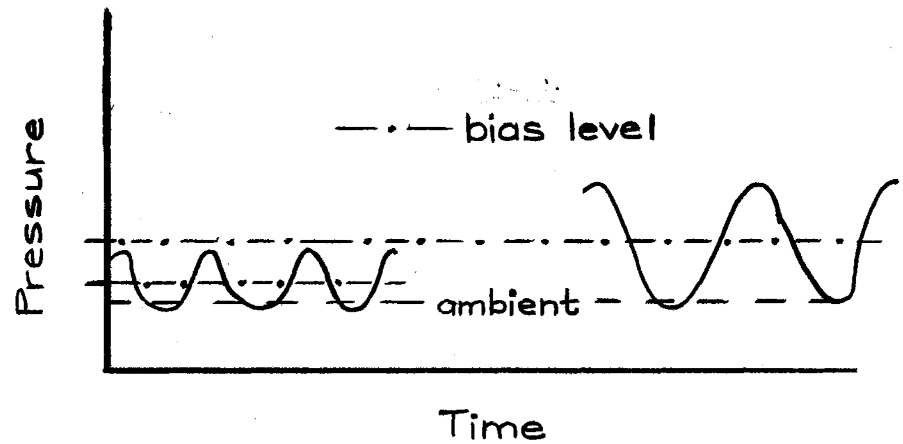


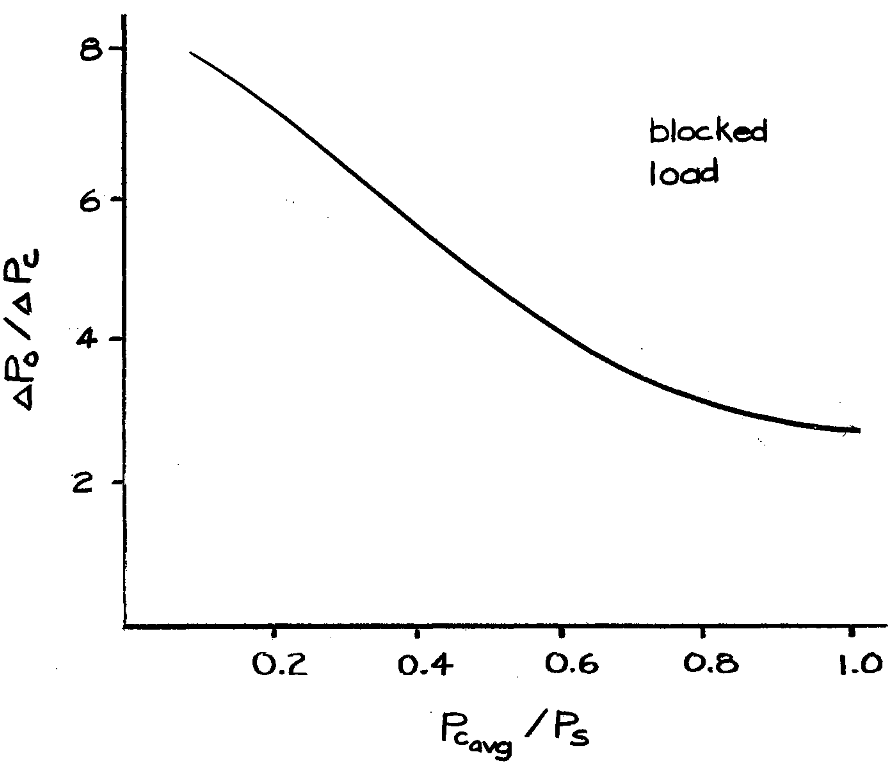
Figure 29. The Transient Response of the AC Isolator, (a) 1-2 Motion Due to Decrease in Vacuum, (b) Pressure Versus Time (Qualitative)

In the steady state, the diaphram of the isolator oscillates about some average position, which is a function of the DC vacuum input. As the load is varied, the DC vacuum signal varies and so does the average position of the diaphram. For example, referring to Figure 29, if the DC vacuum increases (e.g., gage value gets more positive) a volume of air is pushed to the amplifier causing a transient change in output pressure. This transient change appears to the multistage amplifier as a change in bias or mean level. Therefore, the supply pressure to the amplifier must be set high enough so that the transient response of the isolator does not saturate it (see Appendix A for amplifier characteristics). Experimental supply pressures less than 10 psig produced no AC signal as the transient vacuum occurred. Higher pressures provided good output for all incoming signals; therefore, 13 psig was arbitrarily selected.

Figure 30 shows how the AC input signal affects the proportional amplifier output by virtue of changing bias level. Load affects input signal bias and bias affects gain; therefore, load affects gain (in the steady state). The net result is that the steady-state output of the amplifier is a signal composed of load and frequency information. However, the AC isolator produces an AC signal which is of sufficient amplitude to be of use in related circuitry. Furthermore, the AC isolator provides a diaphram between input and output which functions as a convenient interface for potential hydraulic operation.



(a)



(b)

Figure 30. Bias Effect in the AC Isolator, (a) Steady-State Bias of the Katx-Hastie Device at Two Different Loads (Qualitative), (b) Gain Versus Bias (After Rexford (9))

APPENDIX D

THE SPEED-VACUUM CONTROLLER

The purpose of this appendix is twofold; (1) to offer background on the speed-vacuum controller concept, and (2) to briefly examine S-V controller implementation technique which offers potential reduction in circuit complexity. In particular, an S-V controller implementation requires that DC isolation and function generation both be done on the DC engine vacuum. For the Modified V-S controller, a primary role of the DC isolator was to provide an interface for proposed hydraulic circuitry. A configuration similar to the DC isolator can be designed with the shape of its input-output characteristic that of the optimum vacuum-speed function. Thus, the DC isolator can provide both interface and function generation tasks, and a combination of these two previously separate devices into one device reduces circuit complexity significantly. This appendix discusses the speed-vacuum controller concept as well as a design procedure to develop the needed isolator/function generator element.

The Speed-Vacuum Controller Concept

The S-V controller concept is the inverse of the V-S concept. That is, engine vacuum is used to determine optimum engine speed which is then compared to actual speed to determine the error. This concept if presented in block diagram form in Figure 31.

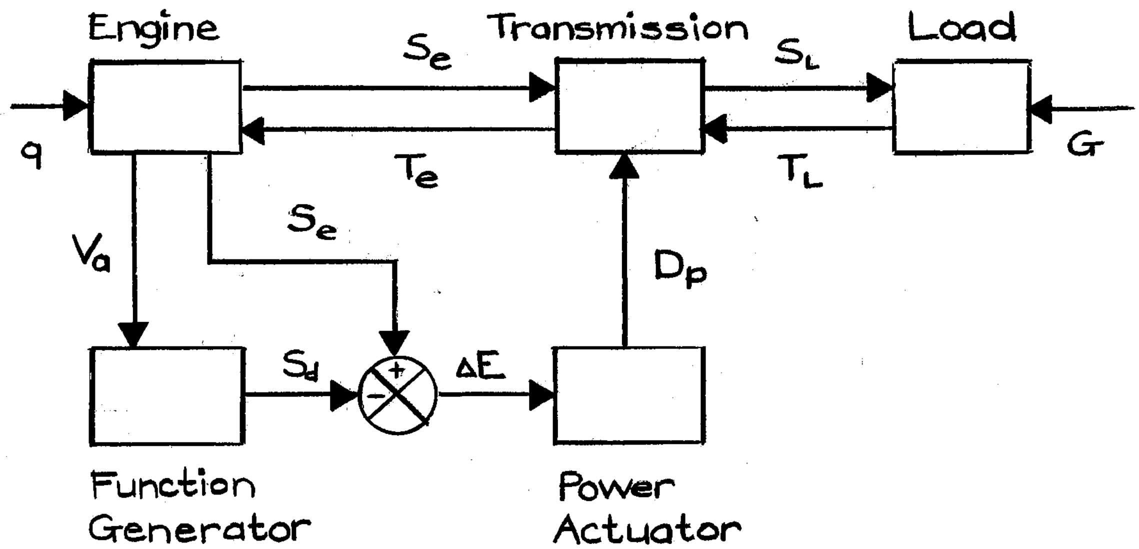


Figure 31. A Block Diagram of the Speed-Vacuum Controller Concept

The basic optimum vacuum-speed relationship is generated by the function generator to determine the desired engine speed, S_d. Therefore, as in the V-S controller, good off-nominal performance can be expected.

The Modified V-S controller called for a DC isolator with linear input-output characteristic. The S-V controller requires the device to have an input-output curve of particular shape; that is, the shape should be that of the optimum vacuum-speed relationship. This fact is an essential step in the general design procedure of the device.

The general design procedure requires:

1. The diaphram stress-deflection relationship be known;
2. The precise shape of the desired input-output relationship be known, and
3. The nature of the load on the device be known.

The design procedure is as follows;

1. The governing flow equations and diaphram stress-deflection relationship are written--the load must be known to write the complete set.
2. Design variables (e.g., geometric or mechanical properties) are searched until the input-output curve has the desired shape.

Step 2 may be accomplished with any of several optimization routines currently available for use on the digital computer (e.g., grid or gradient search techniques). The search is constrained by limits placed on diaphram deflection and geometric values. Some kind of a penalty function must be established so that geometrical or other design considerations are not violated in Step 2. This penalty function may be very difficult to derive and, consequently, places the most severe limitation on the use of the design procedure.

In summary, a design procedure has been presented which permits design of a DC isolator/function generator element. The use of this element in an S-V controller offers significant simplification in circuit hardware.

VITA

David Lee Smith

Candidate for the Degree of

Master of Science

Thesis: THE DESIGN AND IMPLEMENTATION OF A FLUIDIC HYDROSTATIC TRANSMISSION CONTROLLER

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Dayton, Ohio, November 27, 1945, the son of Mr. and Mrs. Milo D. Smith.

Education: Graduated from Central High School, St. Paul, Minnesota, in June, 1963; attended the University of Minnesota; received Bachelor of Science degree in Mechanical Engineering (Aerospace Option) from Oklahoma State University in 1971; completed requirements for the Master of Science degree at Oklahoma State University in July, 1972.

Professional Organizations: Member of the American Institute of Astronautics and Aeronautics, and Pi Tau Sigma.