THE FEASIBILITY OF APPLYING LIQUID JET AMPLIFIERS TO DIGITAL CONTROL SYSTEMS ON HIGH-POWER HYDRAULIC MACHINERY

By

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TO DIGITAL CONTROL SYSTEMS ON HIGH-POWER

HYDRAULIC MACHINERY

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CHAPTER I

INTRODUCTION

The fluid amplifier has created much excitement among both military and civilian researchers since it offers "no moving parts" control of fluid streams. A fluid amplifier is a fluid device whereby a high energy flow is controlled by a low energy flow. There are essentially two types of amplifiers -- proportional and bistable. In a proportional amplifier, the difference in energy of the fluid streams issuing from the two output ports is proportional to the difference in energy of the fluid streams issuing from the two control ports. The most successful proportional amplifiers are momentum controlled, i.e., the difference in energy of the fluid streams issuing from the two output ports is proportional to the difference in momentum of the fluid entering the two control ports. Most bistable amplifiers are pressure controlled. In a pressure controlled bistable amplifier, the majority of the output energy issues from one output port until switched to the opposite port by a sufficient pressure difference applied across the two control ports.

In 1959, the Army sponsored a research and development effort using the inventions of B. M. Horton, R. W. Warren, and R. E. Bowles (4)[1] as a starting point. Development work has spread to other government agencies, industries, and universities until at present there are some 100 projects

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[1] Numbers in parentheses refer to Selected Bibliography.

related to fluid amplifiers being carried out concurrently. The bulk of this work is being done on low-power pneumatic amplifiers to be used in quality control, guidance systems, and pneumatic computers.

The basic advantage of fluid amplifiers is the absence of any moving parts, which yields the desirable characteristics of greater reliability, high-density packaging, and lower cost. Another attractive feature is resistance to extreme environments of shock, vibration, and nuclear radiation. The prevalent feeling is that the successful development of the fluid amplifier could revolutionize the field of fluid power control.

In particular, the Fluid Power Controls Laboratory at Oklahoma State University is interested in the feasibility of adapting bistable fluid amplifiers for use in digital control systems on high-power hydraulic machinery using hydraulic fluid instead of gas as the working medium. If feasible, other advantages can be gained in addition to those already mentioned by using the same fluid in the control system as in the power system. For instance, the liquid amplifier control system could directly use input signals transmitted by the working fluid common to both systems without an interchange from one type energy to another. Likewise, the power system might directly use output signals from the control system without an energy exchange, e.g. electrohydraulic transducers.

The purpose of this study was to determine the feasibility of applying liquid jet amplifiers to digital control systems on high-power hydraulic machinery. The objectives were to devise a scheme for interconnecting currently available fluid amplifiers into a control system requiring logic, using hydraulic fluid as the working medium, and to demonstrate that the devised control system could be used to control high-power hydraulic machinery. Also of primary importance was the fact that, by an actual attempt to build such a control system, desired characteristics of a bistable amplifier specifically adapted for the purpose at hand could be more clearly defined for future investigations of basic amplifier design.

The success of meeting these objectives was contingent upon the definition of the optimum decision function of an amplifier for the development of an interconnection procedure. To define the decision function for each component amplifier of the control system, an experimental determination of all the operating characteristics of the amplifiers was required. In order to perform the proper decision function in each case, the interconnection procedure had to be adpated to match the control impedance of the driven amplifier to the output impedance of the driving amplifier successively backwards through the flow path.

CHAPTER II

THEORY OF BISTABLE FLUID AMPLIFIERS

Consider a free jet issuing from a nozzle adjacent to a flat plate as illustrated in Fig. 1. At some point downstream from the nozzle, the jet will become "attached" to the wall and will remain attached until the momentum of the jet is dissipated. In studies of boundary layer theory, this jet attachment phenomenon is known as the Coanda effect.

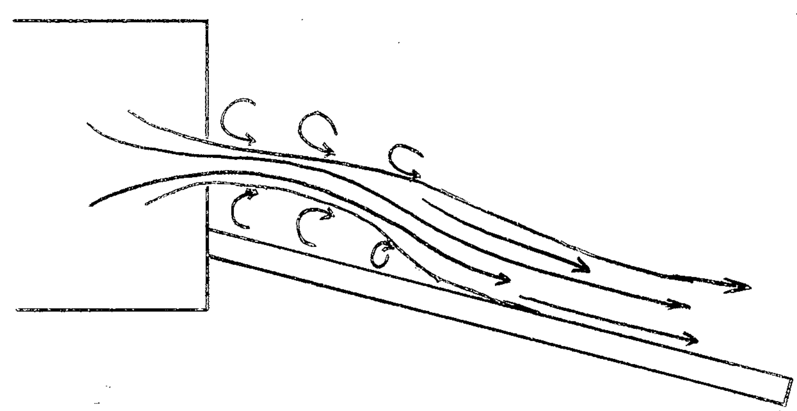

Fig. 1. Coanda Effect.

Consider next a two dimensional free jet issuing from a nozzle between two boundary walls as in Fig. 2. The jet entrains an equal amount of fluid on each side, thus the pressures on each side of the jet are equal. However, the jet is in a state of unstable equilibrium.

Suppose, due to some disturbance, the jet is slightly displaced to the right of center. The jet will still attempt to entrain the same amount of fluid on each side. Since the area on the right side is less, the velocity of entrained fluid is greater; and by Bernoulli's equation, the pressure must be proportionately decreased. The ambient pressure on the left side of the jet forces the jet to move even further to the right and creates a low-pressure bubble adjacent to the fluid attached wall.

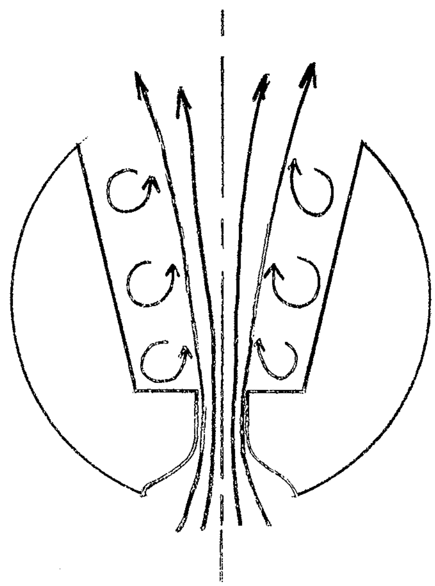

Fig. 2. Position of Unstable Equilibrium.

Thus, a regenerative action is initiated which rapidly forces the jet against the right wall (15). The Coanda effect then becomes predominant, and the jet is stable as shown in Fig. 3.

In order to switch the jet from one wall to the other, sufficient fluid must be injected into the region of the low-pressure bubble to cause the jet to move past the center line in the opposite direction.

If, in addition to the two control aperatures, a splitter is added above the reattachment point, the result is the bistable amplifier shown in Fig. 4.

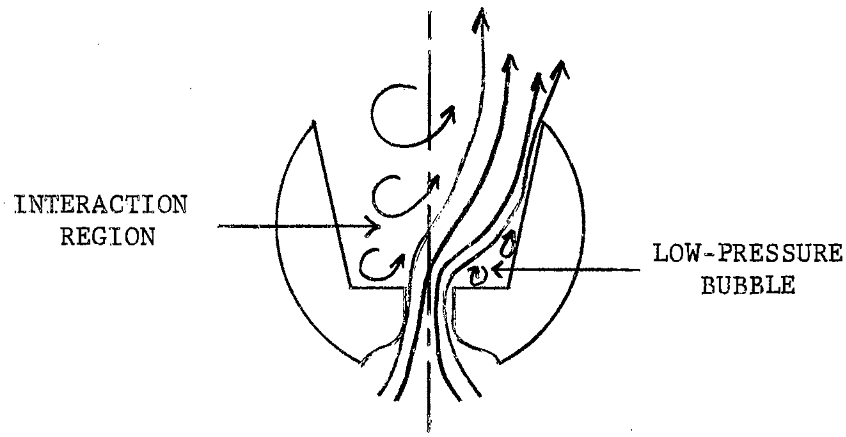

Fig. 3. Stable Position of Jet.

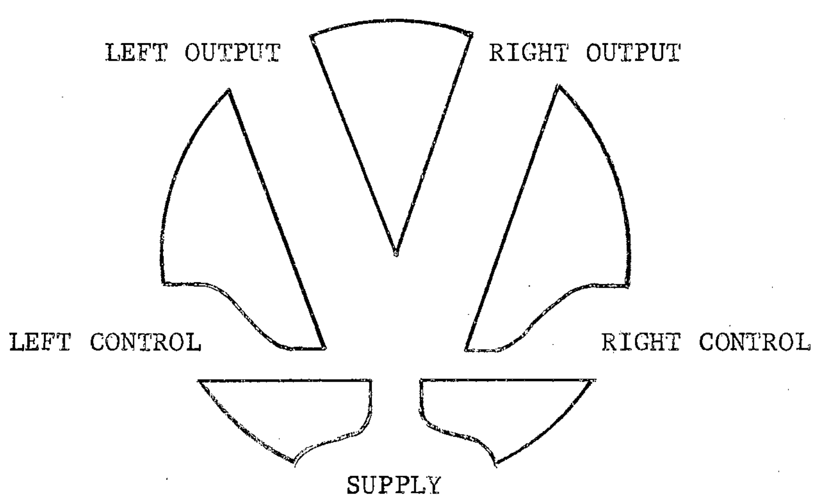

Fig. 4. Bistable Amplifier.

W. A. Boothe and Dr. J. N. Shinn (3) have suggested a system of symbols for fluid amplifiers. The basic symbol for the element shown in Fig. 4 seems to have been accepted by all writers in the field of fluid amplifiers, and is shown in Fig. 5.

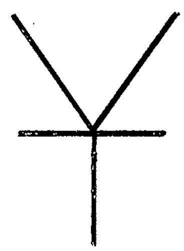

Fig. 5. Basic Symbol for Bistable Amplifier.

There are six different logic functions which can be performed using this one type of bistable fluid amplifier. These functions are the AND, NAND, OR, NOR, NOT and the S-R flip-flop. In Fig. 6, the bias flow is sufficient (or the impedance of the input restrictions is great enough) that both input signals are simultaneously required to switch the output from the right leg to the left leg. In this situation, the AND function is obtained from the left output port and the NAND function is obtained from the right output port.

If, on the other hand, the bias flow (or the input restrictions) is of the proper magnitude that only one of the input signals is required to switch the output from the right leg to the left leg, then the OR function is obtained at the left output port, and the NOR function is obtained at the right output port (see Fig. 7).

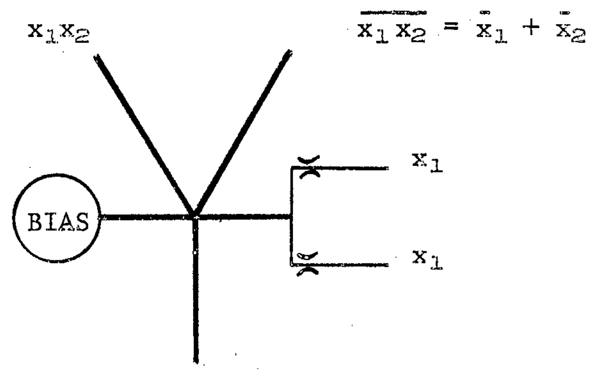

Fig. 6. AND, NAND Element.

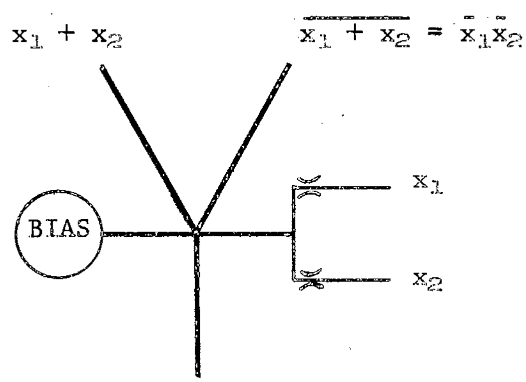

Fig. 7. OR, NOR Element.

If only one input signal is present at the right control port and bias flow is applied at the left control port as in Fig. 8, a simple inverter is obtained which performs the NOT function.

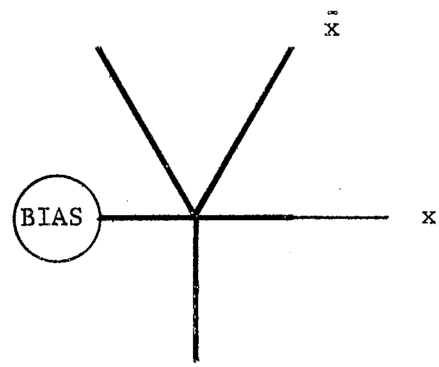

Fig. 8. Inverter.

Since the element under consideration is itself bistable, an S-R flip-flop can be made by connecting the SET signal to one control port and the RESET signal to the other control port (see Fig. 9). The output y is obtained from the output port opposite the SET control port, and $\bar{y}$ is obtained from the other output port.

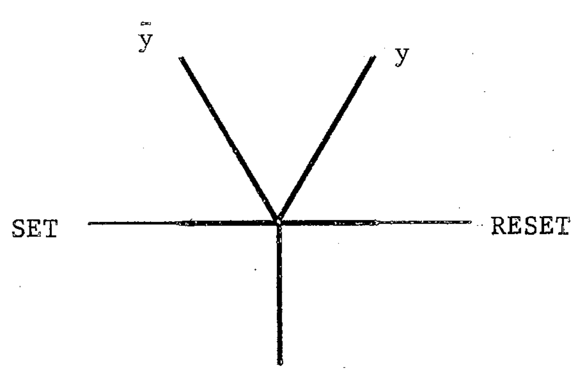

Fig. 9. S-R Flip-Flop.

There are an infinite number of ways in which these six logic functions can be used to build a digital control system. Any digital control system can be built using OR, AND, NOT, and the S-R flip-flop. Also, any logic equation can be transformed into NOR or NAND form and NOR or NAND elements used exclusively to implement the digital control system. Very often, however, some combination of the available logic elements will yield a control system with a minimum number of elements.

It would be proper, at this point, while discussing the theory of bistable fluid amplifiers, to explain their nomenclature and give a list of symbols used in the text. When a bias flow is used on a bistable amplifier, it is then called a "decision amplifier." The decision function being that the power jet will switch to the set position, if the proper signal is present at the control port, and will switch back to the reset position upon removal of the input signal. The set and reset positions of a decision amplifier, along with other nomenclature, are illustrated in Fig. 10.

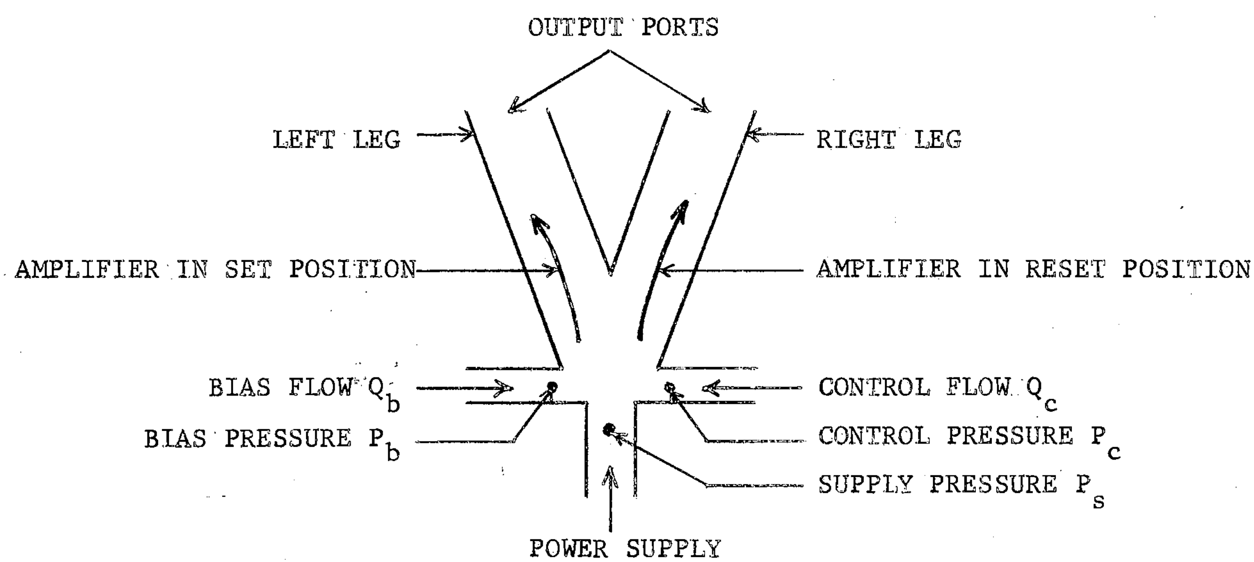

Fig. 10. Illustration of Amplifier Nomenclature.

The flow recovery of an amplifier is the quantity of flow out one of the legs (right leg if amplifier is in the reset position; left leg if amplifier is in the set position) divided by the supply flow. Similarly, the pressure recovery is the working pressure available at one of the legs divided by the supply pressure. The efficiency of an amplifier is determined by the power recovery, the product of flow recovery and pressure recovery. The flow gain of an amplifier is the output flow of one of the legs (right leg is amplifier is in the reset position) divided by the control flow required for shifting. Similarly, the pressure gain is the output pressure divided by the control pressure required for shifting. A list of the symbols used appears below:

Q_c	Control flow, gal/min
P_c	Control pressure, psig
Q_b	Bias flow, gal/min
P_b	Bias pressure, psig
P_{RR}	Output pressure of right leg, amplifier in reset position, psig
Q_{RR}	Output flow of right leg, amplifier in reset position, gal/min
P_{RS}	Output pressure or right leg, amplifier in set position, psig
ΔP_R	Control band $P_{RR}-P_{RS}$, psig
P_{LR}	Output pressure of left leg, amplifier in reset position, psig
Q_S	Supply flow, gal/min
P_S	Supply pressure, psig

CHAPTER III

OBJECTIVES OF THE STUDY

The need for this study arose directly from results of a larger research and development program sponsored by the Ford Tractor Division of Ford Motor Company entitled "The Synthesis of Fluid Circuits by Logic Methods," and performed by the Fluid Power Controls Laboratory at Oklahoma State University. During the first phase of the Ford project, mathematical procedures based on the science of Boolean Algebra were used to derive logic equations for hydraulic digital control systems (6). It was then demonstrated that these logic equations could be implemented in terms of existing stock spool valves, shuttle valves, check valves, pilot-operated check valves, etc., to automate (or partially automate) high-power hydraulic machinery where some basic cycle of operation existed (7).

Project personnel began to recognize the need for small, simple, fast responding, highly reliable logic elements, using hydraulic fluid as the working medium. Existing stock components were bulky, expensive, slow responding, and either single or double input devices. The quest for a hydraulic logic element more suitable for implementing logic equations brought about the invention of the billet valve. The billet valve is a small, inexpensive, multiple input device which operates on the same principle as an electronic diode gate. Still, one moving part is required for each input.

The feasibility of using fluid amplifiers was obviously the next thing to be investigated. The question was asked, "Can fluid amplifiers, with all the advantages they offer by having no moving parts, be specifically adapted to control high-power hydraulic machinery with system hydraulic fluid as the working medium?" The development of the billet valve opened the door for the fluid amplifier feasibility study. The billet valve could be used as a final stage amplifier to raise the relatively low pressure output of the fluid amplifier up to the pressure required to shift pilot-operated power valves.

Thus, the study reported herein was initiated with the following objectives:

1. Devise a scheme for interconnecting currently available fluid amplifiers into a control system requiring logic, using hydraulic fluid as the working medium.
2. If the first objective can be successfully achieved, demonstrate that the devised control system can be used to control a high-power hydraulic machine.
3. Regardless of the outcome of the first two objectives, make recommendations for future work on basic amplifier design which would make them specifically adaptable for high-power hydraulic machine control systems.

CHAPTER IV

PREVIOUS INVESTIGATIONS

Unfortunately, very little technical information has been published on successful applications of bistable fluid amplifiers to control systems. Much of the research and development in fluid amplifiers is either considered proprietary, or classified, or is simply undocumented, even after the devices are in commercial use. Some references can be found describing successful applications, but little elaboration is given. Most references refer to fluid devices such as counters and adders, shift registers, frequency detectors, and pneumatic gaging systems in the breadboard or prototype stages of development. Also, several feasibility studies are currently in progress to determine comparative production costs, packaging densities, life expectancies and power consumptions if presently existing electronic devices were to be replaced by fluid devices.

General Electric's Specialty Control Department is testing a conveyor type order filling system which uses a 7-digit pneumatic shift register to decode an order fed into the machine in the form of a punched card, and to signal the proper storage bins to release the required number of units. W. E. Gray and Hans Stern (8) presented a block diagram of the shift register but offered no technical information regarding the amplifier characteristics or interconnection procedures.

The Office of Naval Research is currently sponsoring a project to determine the applicability of using fluid amplifiers in turbine control.

A pneumatic circuit has been breadboarded which is a fluid amplifier hybrid speed control loop including the functions of speed reference, speed sensing, speed error detection, and steam flow control (8).

The only reference found concerning the use of liquids in fluid amplifiers was for a homing torpedo control system. In this system, water was used as the working medium. A sonar transducer provided the input signals to a system which made suitable logic decisions and provided the digital-to-analog conversion necessary to operate the rudder (8).

Gray and Stern also briefly described a combinational logic system using pneumatic amplifiers and air cylinders in an assembly fixture that operates in a repetitive manner. This system was of interest since it closely resembled the hydraulic system used in this feasibility study. However, as in most "state of the art" papers which have been published, no technical information was given which would be of assistance in the present study.

Concerning the basic design of fluid amplifiers to achieve desired operating characteristics, no method has yet been devised for calculating necessary dimensions and parameters. Due to the many different fluid properties and geometrical parameters that affect operating characteristics and the complexity of the Coanda effect itself, it is doubtful that any method will ever be devised for yielding a completely analytical design. Most researchers in the field of fluid amplifiers have been concerned with optimizing the efficiency of pneumatic elements. Several devices have been used to study the effects of various geometrical parameters in order to design fluid amplifiers by experimentation.

Some of the more comprehensive reports on experiments to determine geometric effects have been written by R. E. Olson (11, 12) of United

Aircraft Corporation Research Laboratories. Olson used an apparatus in which the wall angle and length of wall setback from the centerline could be varied. In addition, pressure taps were used along one wall to determine the jet reattachment point and the mean pressure in the separation bubble.

R. W. Warren (14) of Diamond Ordnance Fuze Laboratories used a water table to qualitatively determine how geometric parameters affected operating characteristics. From knowledge gained by use of the water table, two amplifiers were designed -- one a high-gain, low-stability type and the other a low-gain, high-stability type.

From papers written by Olson, Warren, and others, it could be seen that the design of a special fluid amplifier for the feasibility study would be a major undertaking in itself. Furthermore, with no prior experience or guiding literature, the desired operating characteristics of such a device could not even be well defined. Therefore, the decision was made to buy existing fluid amplifiers for the study, if possible.

Four technical papers have been found on the subject of interconnection of fluid amplifiers. Edwin M. Dexter (5) of Bowles Engineering Corporation describes how three flip-flops and two AND gates were interconnected to build a pneumatic shift register by representing the input pressure-flow characteristic as an equivalent square law orifice. The approximate control admittance Q_c^2/P_c was plotted for both modes of operation of the bistable amplifier. Then, by plotting the output admittance of the driving amplifier Q_o^2/P_o, it could be determined if the output pressure of the driver was sufficient to change the state of the driven. If a sufficient safety margin existed, i.e., P_o was sufficiently greater than P_c, the error introduced by a square law orifice assumption of control admittance could be neglected. For the amplifiers under study, the square law orifice assumption was sufficiently accurate; and Dexter's scheme was successful. However, this method was apparently restricted to the particular family of pneumatic elements described in the paper, and was not as suitable for a modular type iterconnection scheme as other methods to be discussed.

An interesting comparison between the performance of an amplifier when operated on air and when operated on water is given in a paper by W. A. Boothe (2) of the General Electric Company. The amplifier under consideration was a new bistable flip-flop with output legs properly vented to cause the device to be insensitive to output load but still maintain a high pressure recovery. The purpose of the paper was to discuss the manner in which the performance characteristics of the amplifier were obtained and to discuss some of the results. The output characteristics were shown in terms of output pressure versus output flow and power recovery (efficiency) versus pressure recovery. The input characteristics determined were the control flow rates and pressures required to switch the amplifier for different values of supply pressures and flow rates.

Boothe found that the output characteristic curves using water as the working medium were similar to those obtained in low pressure air tests. However, the control characteristics obtained in water tests varied considerably from those obtained in air tests. Boothe attributed this phenomena to the fact that turbulent shear in the interaction region (see Fig. 3) is the dominating factor in determining the volume of flow entrained by the jet. This may indeed be the proper explanation, for the author found that as much difference existed between control characteristics obtained in water tests and hydraulic oil tests as Boothe found between air and water tests. Boothe's description of his test apparatus was helpful in the author's study, and the data presented gave a qualitative insight into expected results of the feasibility study.

R. E. Norwood (10) of International Business Machines Corporation used the actual measured input impedance of a low-power bistable pneumatic amplifier as the performance criterion in order that elements could be properly designed and interconnected. Some experimental data was shown to illustrate the method. Norwood's paper served as the basis for a more comprehensive and detailed treatment of interconnection procedures written by C. P. Wright (16), also of IBM. Wright also used the input impedance as the performance criterion, but in addition, his technique involved the superposition of a bias on the amplifier which altered its switching characteristics.

The input impedance of an amplifier is the true relationship between pressure and flow rate at the control port. Wright gave an example of impedance curves similar to those shown in Fig. 11. Each member of the family of curves was obtained at constant bias flow, i.e., Q_b was the parameter of the impedance curves, and was obtained in the following manner. With the amplifier initially in the reset position, control flow was increased, developing the "reset line," until the power jet switched to the set position. The final pressure P_c and flow rate Q_c obtained before switching determined the "set point." The control flow was then decreased, developing the "set line," until the bias flow was sufficiently greater than the control flow to switch the power jet back to the reset position. The final data point obtained (point of discontinuity of data) determined the "reset point." In the case of the load insensitive IBM amplifier, the locus of reset points was coincident with the set line.

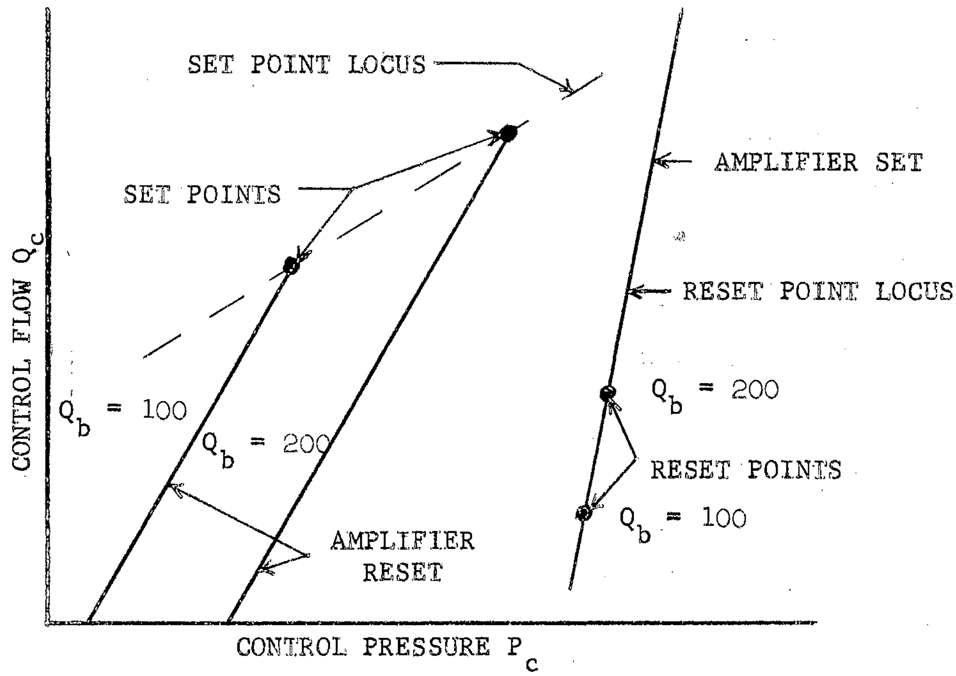

Fig. 11. Control Impedance.

The switching characteristics of an amplifier, with fixed bias flow Q_b, can be determined in the following manner. The control flow must pass through a fluid resistor before entering the control port. A schematic diagram of such an arrangement appears in Fig. 12. Fig. 12 shows the equation of the control resistor superimposed upon the control impedance curve with two different upstream pressures P_1 and P_2. Assuming a linear pressure-flow relationship, the equation of the left hand resistor line is

$$Q_c = K(P_1 - P_c) \tag{4-1}$$

where K is a positive number, and the equation of the right hand resistor line is

$$Q_c = K(P_2 - P_c) \tag{4-2}$$

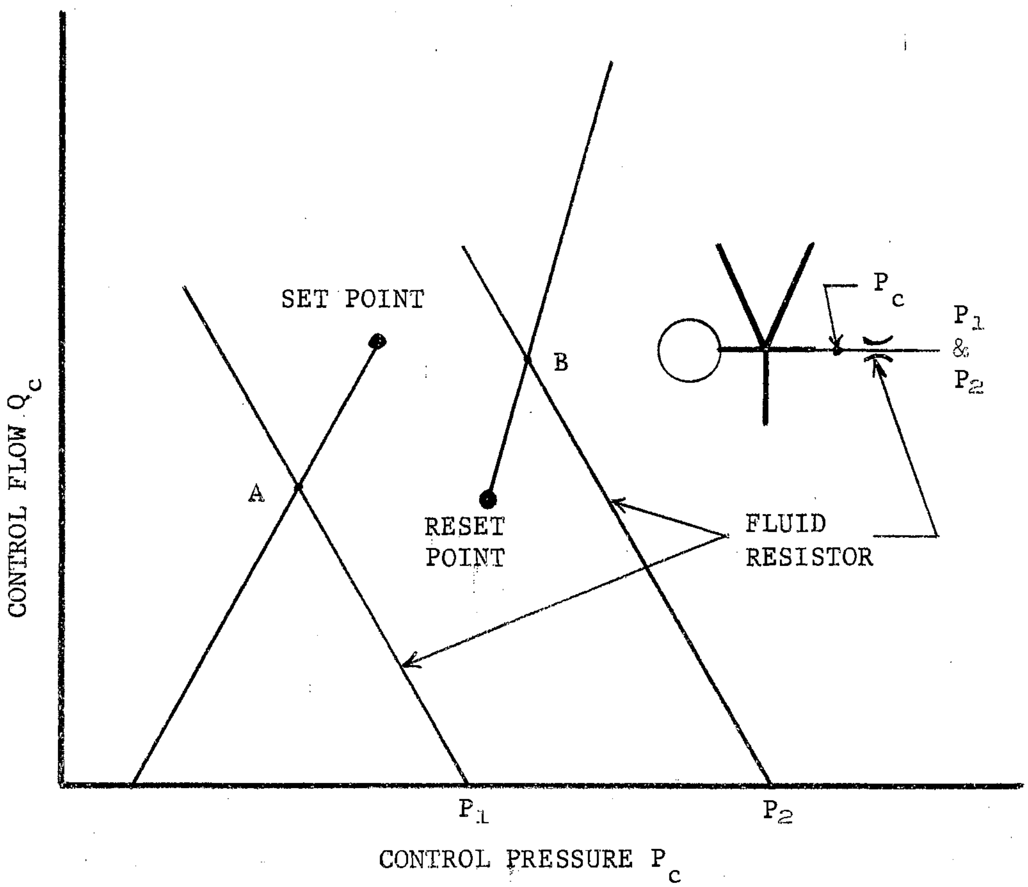

Fig. 12. Illustration of Decision Function.

Initially, with the upstream pressure equal to P_1, the operating point of the amplifier is at "A." If the upstream pressure is increased to P_2, the amplifier will shift to the set position; and the operating point will be at "B." Likewise, if the upstream pressure is reduced to P_1, the amplifier will shift to the reset position. Thus, the amplifier is a decision amplifier since it is set upon application of an input signal P_2 and reset upon its removal.

The illustration of the decision function shown in Fig. 12 was Wright's contribution to the problem of interconnecting decision amplifiers, and served as the basic principle underlying the interconnection procedure derived for this feasibility study.

This study was primarily concerned with digital control systems, and the selection of previous investigations reported in this chapter was biased in that direction. Several other successful applications of fluid amplifiers have been reported but were not discussed here because they are simple one-element devices such as a pneumatic eye to detect out-of tolerance pieces on a conveyor belt. At present, the "state of the art" of digital control systems and multi-element fluid devices is limited to the breadboard and prototype stages of development, undergoing various performance, endurance, and economic tests. However, most companies are naturally very careful about releasing technical information which might aid competitors in the same field.

To summarize basic research in the areas of amplifier design, most investigators are concerned with highly efficient, low-power units for applications in pneumatic computers. This is indeed an important endeavor, but such designs are not particularly well suited for use in hydraulic digital control systems on high-power hydraulic machinery.

CHAPTER V

THE THEORY OF INTERCONNECTION

This chapter discusses in general terms the interconnection procedure developed by the author during performance of the feasibility study. The successful interconnection of several decision amplifiers for the synthesis of a digital control system is contingent upon satisfaction of the proper decision function for the amplifiers. The work done at IBM by C. P. Wright, and reported in the previous chapter served as the starting point for the following development.

The performance criteria for determining the proper decision function of an amplifier are the experimentally determined static impedance curves found by measuring the actual control flow Q_c and the pressure P_c at the control port. These impedance curves will always have one or more parameters depending on the operating characteristics of the amplifier. The parameters might be bias flow, bias pressure, or output load. Regardless of the parameters involved, one of the family of impedance curves must finally be selected to satisfy the proper decision function. It is not the purpose of this chapter to develop methods of selecting the correct values of the parameters, but to define the optimum decision function and to show how this decision function is accomplished for various methods of driving the amplifier in question.

Assume that, by some method, one of the family of control impedance curves has been selected. In addition, the control flow must pass through a fluid resistor before it can enter the control port. The control pressure P_c is measured at a point between the input resistor and the control port. Since the system under discussion is a digital system, the pressure upstream of the resistor will have two values -- one value P_2 representing the "ON" condition of the driver and a lower value P_1 representing the "OFF" condition of the driver. One other restriction must be made in order to comply with theories of hydraulic digital control systems previously developed at the Oklahoma State University Fluid Power Controls Laboratory (7). The "OFF" condition cannot be accomplished by merely blocking the input line but must be accomplished either by a connection to tank or by connection to a low-pressure reference.

The impedance of the input resistor must be superimposed upon the control impedance curves for both upstream pressures P_1 and P_2 as shown in Fig. 13. Note that in this case, a linear relationship between flow rate and pressure drop through the resistor has been assumed. The theory developed herein is by no means limited to the linear case. On the contrary, these resistor lines should represent, as nearly as possible, the true impedance of the input restriction whether it is a square law orifice or an experimentally determined curve. For illustrative purposes, the equations describing the impedance of the input resistors shown in Fig. 13 have been assumed to be

$$Q_c = K(P_2 - P_c) \tag{5-1}$$

$$Q_c = K(P_1 - P_c) \tag{5-2}$$

where K is some positive constant representing the negative of the slope of the resistor lines.

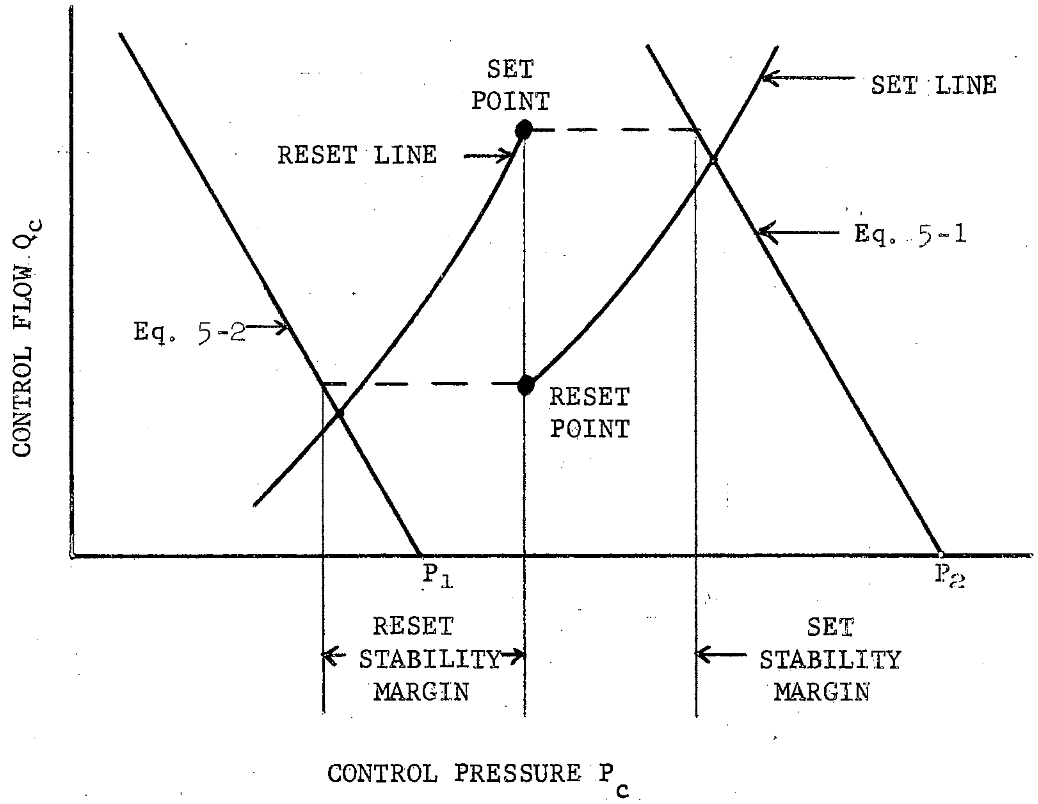

Fig. 13. Illustration of Stability Margins.

In order to define the switching characteristics of a decision amplifier, assume that the pressure upstream of the input resistor is P_1 and the amplifier is in an equilibrium condition in the reset position with the operating point defined by the point "A." If the input signal pressure is increased, the point "A" will move up the reset line until the point "A" and the set point coincide, at which point the amplifier will be forced to change state to the set position, thus accomplishing the set decision. The input signal pressure is further increased to the value P_2. At this point, the amplifier is again in a state of equilibrium with the operating condition defined by the point "B."

The relative stability of this state of equilibrium is determined by the length of a horizontal line drawn between the set point and the P_2 oriented resistor line (see upper dashed line in Fig. 13). The length of this dashed line is measured in psi and indicates the pressure available at the control port in excess of that required to perform the set decision. The magnitude of such an excess pressure is defined as the "set stability margin." Similarly, the length of the horizontal dashed line between the reset point and the P_1 oriented resistor line is defined as the "reset stability margin" (see lower dashed line in Fig. 13). This margin can also be measured in psi.

For a given control band (P_2-P_1) a proper decision function would be one in which the set and reset stability margins were of equal magnitude. This statement should be further qualified. In most instances, the designer will have a wide variety of choices for the "ON" pressure P_2, but may not have such control over the "OFF" pressure P_1. For example, P_1 might be zero gage pressure. In such cases, the reset stability margin might be quite large; and if an attempt is made to design for an equal set stability margin, sufficient pressure P_2 might be applied at the control port to cause adverse effects on the output characteristics of the amplifier. Another important fact is that switching time is inversely proportional to the magnitude of the stability margin.

In the eventuality of such a wide control band, the so-called "proper decision function" would not be a good engineering design. This problem is sometimes encountered when input signals to the control system are used directly to drive an amplifier. In the remainder of this chapter, it shall be assumed that such a case as described above is the exception rather than the rule and will be considered no further. Indeed, the problem most generally encountered is that of an insufficient control band for proper stability.

Regardless of exceptions to the rule, an "optimum decision function" will be defined which will stand alone as a theory and which will serve as the basis for the interconnection procedure. An engineering compromise between stability and switching time (or other adverse effects) can then be decided upon, but such a compromise can be achieved only if the two extremes are well defined.

In the optimum decision function, the magnitude of the stability margins are simultaneously maximized. If the two stability margins are of equal magnitude, and at the same time have the maximum value obtainable for a given control band width, then a straight line drawn through the two switching points must have the same slope as the two resistor lines and must intersect the P_c axis midway between the line segment P_2-P_1.

Note that in Fig. 13, vertical lines would be required to represent the impedance of the input resistor. Physically this would mean that the input resistor would have to have an infinite inside diameter. Neither can the straight line drawn through the two switching points have a positive slope, for this would require positive flow through the input resistor with a negative pressure drop. The slope of the resistor lines will always be negative regardless of the degree of polynomial used to describe the impedance of the input resistor. Thus, one further restriction has been placed upon the switching characteristics of the amplifier. The parameters of the control impedance curves must be properly chosen such that a straight line drawn through the two switching points has a negative slope.

In order to accommodate other polynomial representations of input resistor impedance, as well as straight lines and experimentally determined curves, the optimum decision function can be defined as follows: the optimum decision function is such that the input resistor curve, when superimposed upon the control impedance graph so that it passes through the two switching points, has a negative slope at all points along the curve and bisects the line segment P_2-P_1 on the P_c axis.

This definition of the optimum decision function (illustrated in Fig. 14) will stand alone as a theory regardless of the method used to obtain it. For example, if the two pressures P_1 and P_2 are chosen, or are otherwise specified, the parameters of the control impedance curves might be chosen so as to give two switching points which will satisfy the requirements of the optimum decision function.

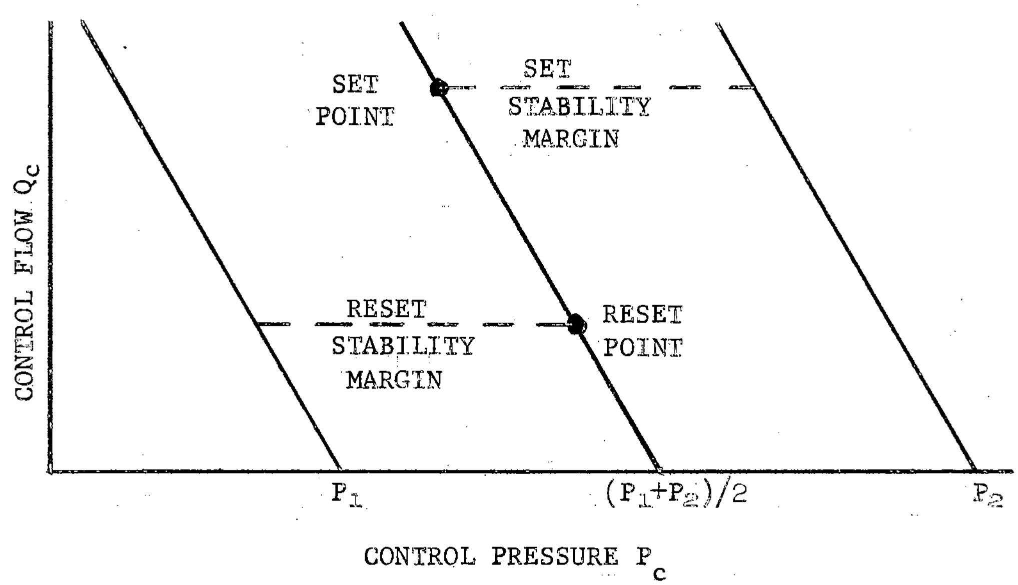

Fig. 14. Illustration of Optimum Decision Function.

From Fig. 14, it can be seen that satisfaction of the optimum decision function would yield maximum decision function stability but would also yield maximum response time (shifting time). The opposite extreme is illustrated in Fig. 15. If the same shifting points and control band are used, the minimum shifting time, and also minimum relative stability, would be obtained from switching characteristics in which the P_2 oriented resistor line passed through the set point and the P_1 oriented resistor line passed through the reset point.

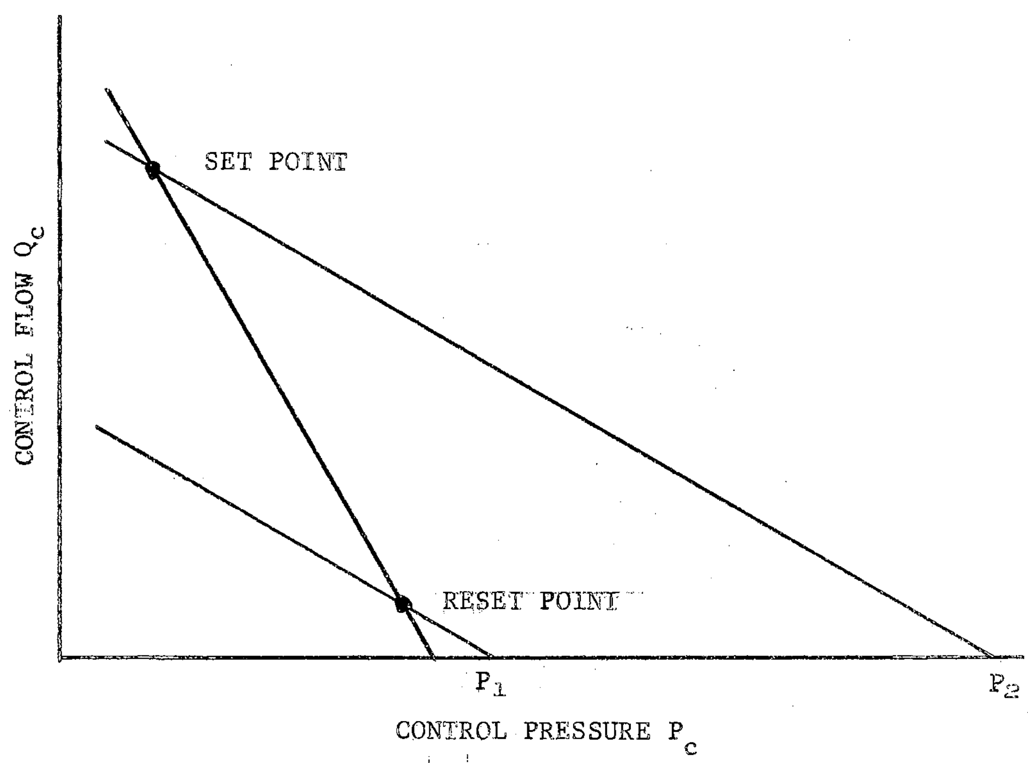

Fig. 15. Illustration of Minimum Switching Time Decision Function

In cases where only one input resistor is necessary, such as in the case of an inverter, the slope of the resistor lines illustrated in Fig. 14

can be used to calculate the dimensions of the input restriction. If two or more input signals are applied to an amplifier, such as in the cases of OR, NOR, AND, and NAND units, the resistor line on the control impedance graph represents some imaginary resistor which is equivalent to the several resistors actually used. Fig. 16 is a schematic diagram of a NOR unit with two input signals x_1 and x_2. In a NOR unit, the amplifier must be set upon application of either or both input signals and reset upon their removal. Assume that x_1 is "ON" and x_2 is "OFF." The pressure upstream of the x_1 signal resistor is P_2, the pressure upstream of the x_2 signal resistor is P_1, and the pressure downstream of both resistors is P_c.

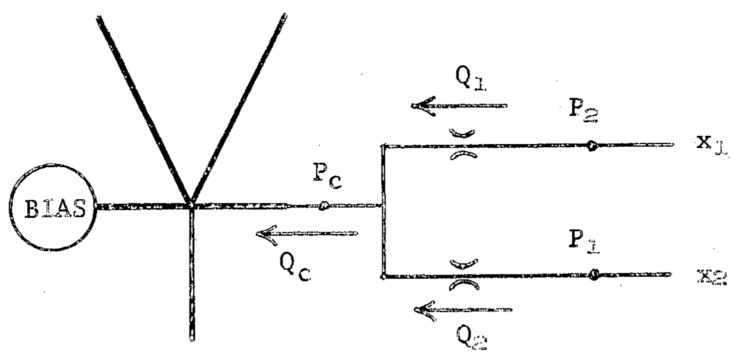

Fig. 16. Interconnection Diagram for a NOR Unit.

If the flow through the x_1 resistor is denoted by Q_1, and the flow through the x_2 resistor is denoted by Q_2, the following nodal equation can be written for the system:

$$Q_c = Q_1 + Q_2 \tag{5-3}$$

By assuming a linear relationship between flow and pressure drop through the resistors and by assuming that the impedance of both resistors are the same, the flows Q_1 and Q_2 can be written as

$$Q_1 = K(P_2 - P_c) \tag{5-4}$$

$$Q_2 = K(P_1 - P_c) \tag{5-5}$$

where K is some positive constant. Substitution of Equations 5-4 and 5-5 into Equation 5-3 yields

$$Q_c = K(P_2 + P_1 - 2P_c) \tag{5-6}$$

Equation 5-6 is the equation representing some imaginary resistor which is the equivalent of the two resistors shown in Fig. 16. To obtain the reset decision, both input signals must be "OFF." Therefore, the pressures upstream of both input resistors are P_1. In this case, Equation 5-3 becomes

$$Q_c = K(2P_1 - 2P_c) \tag{5-7}$$

Fig. 17 illustrates the superposition of Equations 5-6 and 5-7 upon the control impedance graph in such a manner as to obtain the optimum decision function.

Note that the slope of the imaginary resistor lines in Fig. 17 has a value of 2K; for from Equation 5-7

$$Q_c = 2K(P_1 - P_c) \tag{5-8}$$

But, the equation for the flow through the x_2 input resistor is

$$Q_2 = K(P_1 - P_c) \tag{5-5}$$

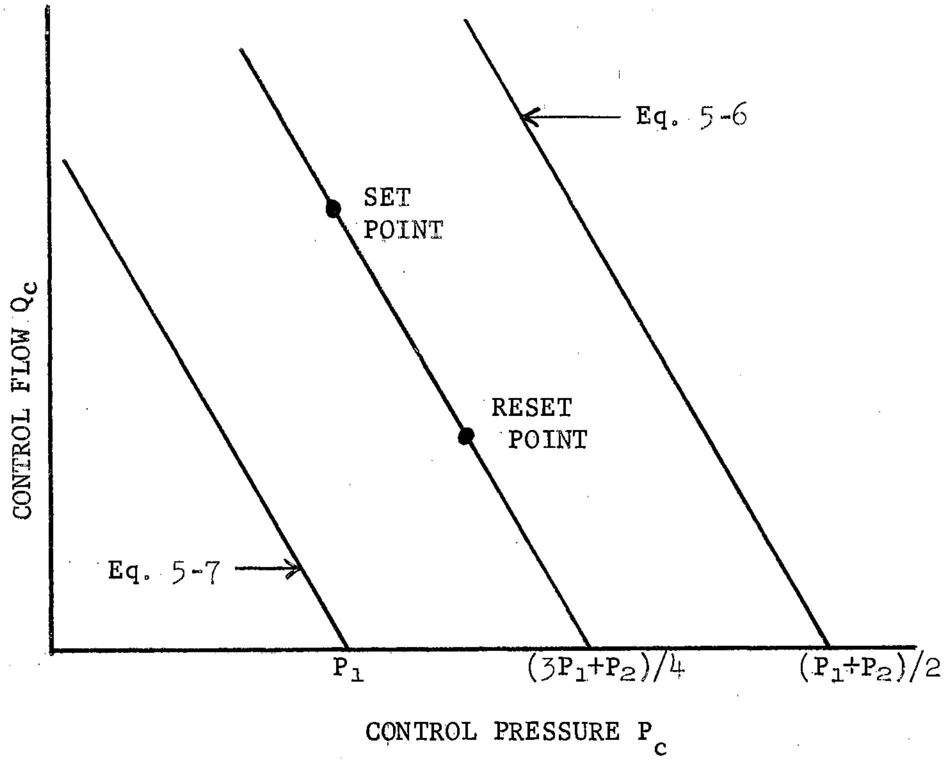

Fig. 17. Illustration of Optimum Decision Function for a Double Input NOR unit.

Therefore, the value of K for use in calculating the dimensions of the two input resistors is found by measuring the slope of the resistor lines shown in Fig. 17 and using half that value in Equation 5-5.

In a similar manner, the equation of the equivalent resistor can be found for any number of input signal resistors. Let "N" be the number of input signals to a NOR unit. The equation representing the flow required to set the amplifier if one input signal were "ON" and (N-1) input signals were "OFF," would be

$$Q_c = K[P_2 + (N-1)P_1 - NP_c] \tag{5-9}$$

and the equation representing the control flow necessary to reset the amplifier with all input signals off would be

$$Q_c = NK(P_1 - P_c) \tag{5-10}$$

The value of K to use in calculating the dimensions of the input resistors would be 1/N times the measured slope of the imaginary resistor line shown on the control impedance graph.

A similar set of equations can be developed for an AND or NAND unit. In order to set a NAND unit, all input signals must be "ON" simultaneously. Thus, the equation for the flow required to set the unit would be

$$Q_c = NK(P_2 - P_c) \tag{5-11}$$

The amplifier is to be reset if any one of the input signals is "OFF." Therefore, the equation for the flow required to reset the unit would be

$$Q_c = K[P_1 + (N-1)P_2 - NP_c] \tag{5-12}$$

One other situation arises during the interconnection of amplifiers which is illustrated in Fig. 18. In this case, the two input signals to a NOR element originate from another NOR element and a system input signal. This situation is unique since the "OFF" pressures of the two input signals differ from each other; and generally, the two "ON" pressures will differ.

Assume that the minimum and maximum output pressure of the driving amplifier are P_{RS} and P_{RR}, respectively; and minimum and maximum pressures

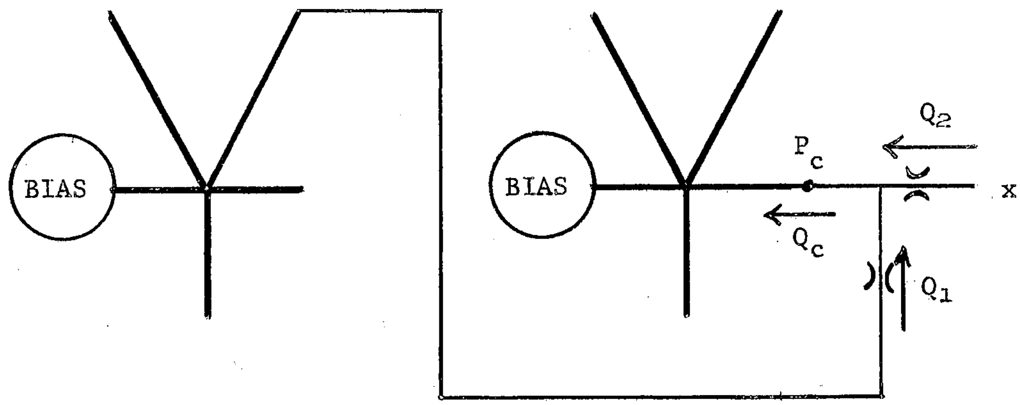

Fig. 18. Interconnection Diagram for Two Dissimilar Input Signals.

of the x input signal are P_1 and P_2, respectively. The assumption will also be made that the impedance of the two input resistors are different, but that one can be expressed as a ratio of the other. Two situations must be satisfied simultaneously. The driven amplifier must be set when the driving amplifier is reset and the x signal is "OFF," and it must also be set when the driving amplifier is set and the x signal is "ON."

In the former case, the flow rates Q_1 and Q_2 can be expressed as

$$Q_1 = \alpha K(P_{RR} - P_c) \tag{5-13}$$

$$Q_2 = K(P_1 - P_c) \tag{5-14}$$

Substitution of Equations 5-13 and 5-14 into Equation 5-3 yields

$$Q_c = K[\alpha P_{RR} + P_1 - P_c(1 + \alpha)] \tag{5-15}$$

In the latter case, the flow rates Q_1 and Q_2 can be expressed as

$$Q_1 = \alpha K(P_{RS} - P_c) \qquad (5\text{-}16)$$

$$Q_2 = K(P_2 - P_c) \qquad (5\text{-}17)$$

Substitution of Equations 5-16 and 5-17 into Equation 5-3 yields

$$Q_c = K[\alpha P_{RS} + P_2 - P_c (1 + \alpha)] \qquad (5\text{-}18)$$

Since Q_c must be the same in both cases, Equations 5-15 and 5-18 can be equated. Rearranging terms and solving for P_2 yields

$$P_2 = \alpha (P_{RR} - P_{RS}) + P_1$$

or (5-19)

$$P_2 = \alpha \Delta P_R + P_1$$

In order to reset the driven amplifier, the driving amplifier must be in the set position and the x signal must be "OFF." Thus, the control flow required to reset the driven amplifier would be

$$Q_c = K[\alpha P_{RS} + P_1 - P_c (1 + \alpha)] \qquad (5\text{-}20)$$

Fig. 19 illustrates the optimum decision function for the interconnection diagram of Fig. 18. It should be noted that the slope of the resistor lines in Fig. 19 is $K(1 + \alpha)$. Thus, the value of K can be found by measuring the slope of the resistor lines and used to calculate the dimensions of the input resistors.

The selection of the proper decision function by use of Equations 5-15 through 5-20 is done by a combination graphical and iterative procedure. An example of such a graphical solution, by assuming various values for α, appears in the last section of Chapter VI.

A similar derivation could be made for multiple input signals in combination with multiple driving amplifiers by following the procedure previously used.

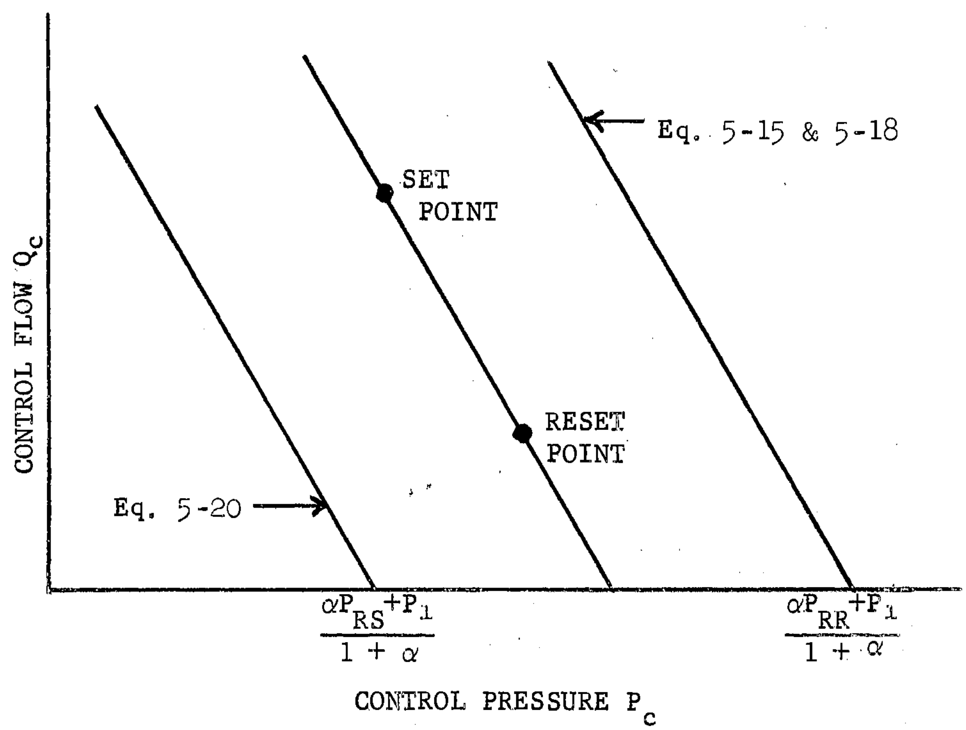

Fig. 19. Illustration of Optimum Decision Function for Two Dissimilar Input Signals.

CHAPTER VI

EXECUTION OF THE FEASIBILITY STUDY

Development of the theory of interconnection propagated the synthesis of an experimental control system for the execution of the proposed feasibility study. Necessarily, the first step had to be the development of a hypothetical control problem in order to obtain a set of switching circuit equations with which to illustrate the interconnection procedure, and in order to have some operative machine with which to demonstrate the pure fluid control system if successful. The hydraulic machine to be controlled was made up to two hydraulic cylinders which were to be operated in a repetitive sequence requiring a combinational switching circuit.

During the literature survey phase of the study, the decision was made to buy existing "on-the-market" type amplifiers if available. At the time the investigation was started, only two bistable fluid amplifiers were commercially available. Both were of similar design and were obtained from Bowles Engineering Corporation, Silver Spring, Maryland. One (catalog No. 0247) was a high-gain, low-stability type, and the other (catalog No. 0246) was a low-gain, high-stability type. These two amplifiers are shown in Figs. 20 and 21, respectively. They are approximately 1 5/8" long, 1 9/16" wide, 3/8" thick, and are provided with sockets for 1/4" O.D. plastic tubing.

The low-gain, high-stability type was selected since it could be operated at higher pressures. Operation at higher pressures gave greater

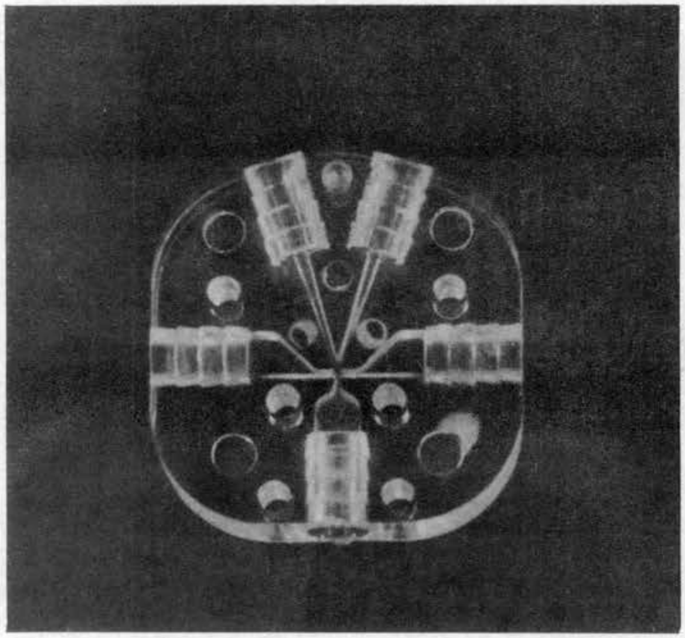

Fig. 20. **High-Gain Low-Stability Bistable Fluid Amplifier, Bowles Engineering.**

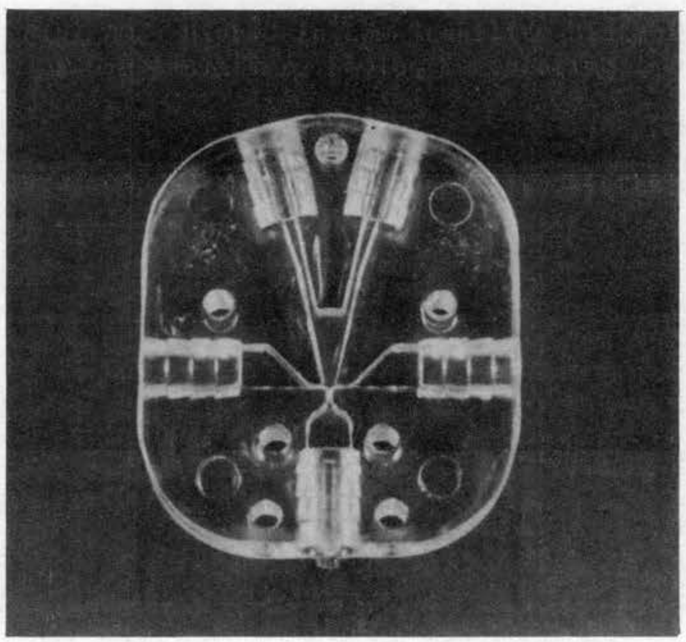

Fig. 21. **Low-Gain High-Stability Bistable Fluid Amplifier, Bowles Engineering.**

maximum output pressure P_{RR} and a greater ΔP_R for increased decision function stability.

The next step in the study was to determine the operating characteristics of the amplifier. It was necessary to determine the output characteristics as well as all parameters of the control impedance curves and their interrelations in order to apply the interconnection theory developed in the previous chapter. Once the operating characteristics were clearly defined, the theory developed in Chapter V was used to design the proper fluid resistors for interconnection of the amplifiers into a pure fluid control system. These fluid resistors had to be designed from an experimental nondimensional graph describing the flow rate and pressure drop through a small capillary tube.

In general, the chronological plan of attack was as follows:

1. Derivation of switching circuit equation for the hypothetical control problem.
2. Experimental determination of the operating characteristics for use in the systematic search for the proper decision function.
3. Interconnection of the several fluid amplifiers by use of the theory developed in Chapter V.

The Hypothetical Control Problem

The first step in the feasibility study was to set up a hypothetical control problem. The hydraulic machine to be controlled was made up of two single-rod-end cylinders -- one controlled by a spring-centered, block-center, pilot-operated, 1 1/8" power valve, and the other controlled by a spring-offset, pilot-operated 1 1/8" power valve. Input signals were developed through cam-operated, center-bypass, 3/4" valves driven by cams attached to the end of each cylinder rod. These cylinders were to be operated in a repeated cycle which required a combinational digital control system to switch the power valves in the proper sequence.

Fig. 22 shows the power system and input signal generating devices for the hydraulic machine to be controlled. The cam valves are so arranged that when cylinder A is fully retracted, $x_1 = 1$; and the x_2 line is open to tank. When the cylinder is fully extended, $x_2 = 1$; and the x_1 line is open to tank. Both the x_1 and x_2 lines are open to tank for any position of the cylinder rod between fully extended and fully retracted. Note that signals $\bar{x}_1$ and $\bar{x}_2$ are not generated. In the synthesis procedure for the derivation of logic equations, it was assumed that $\bar{x}_1$ and $\bar{x}_2$ were available; therefore, x_1 and x_2 were to be inverted where necessary for the implementation of the control system. The arrangement for generating signals x_3 and x_4, which monitor the position of cylinder B, is exactly the same as that of cylinder A.

To obtain a combinational control system requiring no memory, the sequence of operations for the two cylinders was selected as -- cylinder A extends, cylinder B extends, cylinder A retracts, cylinder B retracts. In shorthand notation, this sequence is A B $\underline{A}$ $\underline{B}$. The machine was to perform this sequence of operations repeatedly. The output signals of the control system used to pilot the power valves were denoted as Z_1, Z_2, and Z_3 (see Fig. 22).

The primitive flow table for the desired sequence of operations is shown in Fig. 23 (9). The primitive flow table will merge to one row proving that the problem is combinational and requires no memory. The output map can be completed directly from the primitive flow table and appears in Fig. 24. The output equations for the control system can be

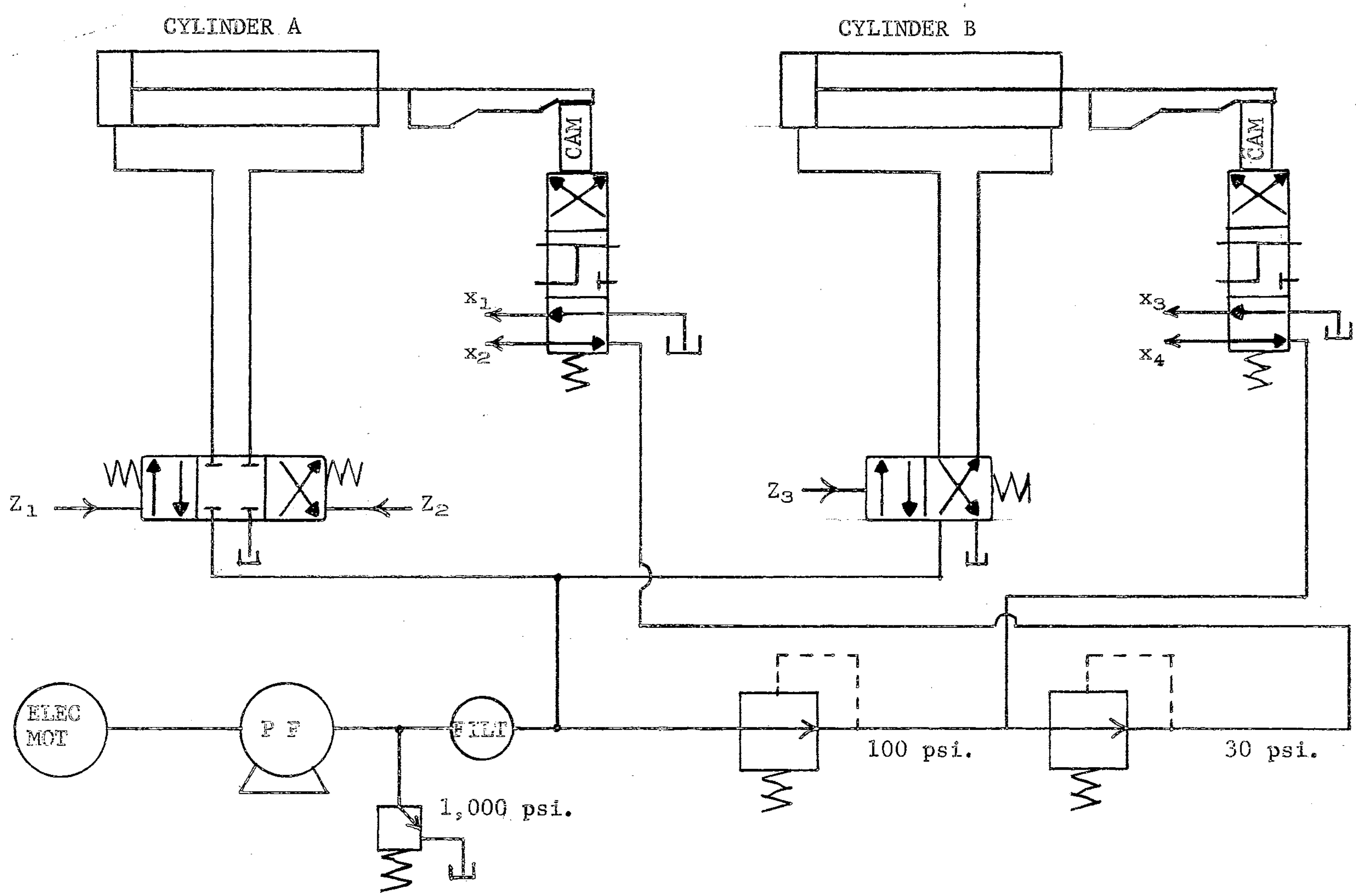

Fig. 22. Hydraulic Power System.

read from the output map as

$$Z_1 = X_3 \tag{6-1}$$

$$Z_2 = X_4 \tag{6-2}$$

$$Z_3 = \bar{X}_1\bar{X}_3 + X_2 \tag{6-3}$$

Note that Z_1 and Z_2 can be obtained directly from the signal generating cam valves. However, a digital switching system must be used to obtain the output Z_3.

X_1X_2	00				01				11				10						
X_3X_4	00	01	11	10	00	01	11	10	00	01	11	10	00	01	11	10	Z_1	Z_2	Z_3
				2												1	1	0	0
				2				3									1	0	0
					4			3									-	0	1
					4	5											-	0	1
		6				5											0	1	1
		6												7			0	1	1
													8	7			0	-	0
													8			1	0	-	0

Fig. 23. Primitive Flow Table.

x_1x_2	00				01				11				10			
x_3x_4	00	01	11	10	00	01	11	10	00	01	11	10	00	01	11	10
z_1		0		1	—	0		—					0	0		1
z_2		1		0	0	1		0					—	—		0
z_3		1		0	1	1		1					0	0		0

Fig. 24. Output Map.

The Proposed Control System

The next decision to be made was what type of logic functions to use. Several possibilities existed. The system could have been built with one AND element and an OR element, one NOR element and an OR element, two NAND elements, three NOR elements, and many other combinations. However, some preliminary investigation into the operating characteristics of the Bowles amplifier revealed that the pressure gain (output pressure divided by pressure required for switching) of the amplifier was less than unity when operated as an OR element. This eliminated OR units from consideration. To use the amplifiers as AND or NAND elements required very accurate metering of the control flow through the interconnecting restrictors. Later investigation into the flow through a small capillary tube proved the accuracy requirement to be impractical.

It was also learned that each different logic function would require an entire set of operating characteristic curves. This fact was an incentive to use only one type of logic function in the control system. Therefore, the decision was made to use three NOR elements.

To put Z_3 into NOR form, double inversion is used.

$$Z_3 = \bar{x}_1\bar{x}_3 + x_2$$

$$= \overline{\overline{\overline{\overline{\bar{x}_1 x_3}} + \overline{\overline{x_2}}}} \qquad (6\text{-}4)$$

$$Z_3 = \overline{\overline{\overline{(x_1 + x_3)} + x_2}}$$

A schematic diagram of the switching circuit proposed to obtain Z_3 is shown in Fig. 25.

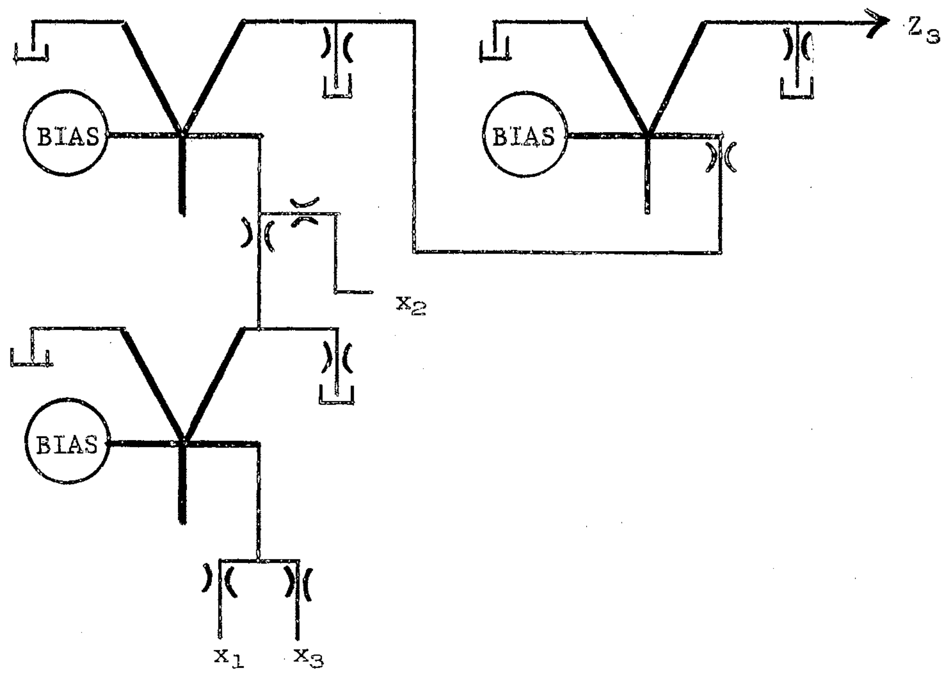

Fig. 25. Proposed Z_3 Switching Circuit.

Determination of Operating Characteristics

As was mentioned in Chapter IV, an extensive preliminary investigation was necessary to determine some of the more general characteristics of the Bowles amplifier and to set up procedures for obtaining required data. Fig. 26 is a schematic diagram of the test apparatus used to obtain all data for the operating characteristics.

The first operating parameter to be decided upon was the supply pressure. It was found that P_{RR}, ΔP_R, and the pressure recovery all increased as the supply pressure was increased. However, at about 35 psi, the amplifier exhibited some unstable tendencies. The final supply pressure selected was 30 psi, which also corresponded with manufacturers specifications. All subsequent tests were run at this supply pressure.

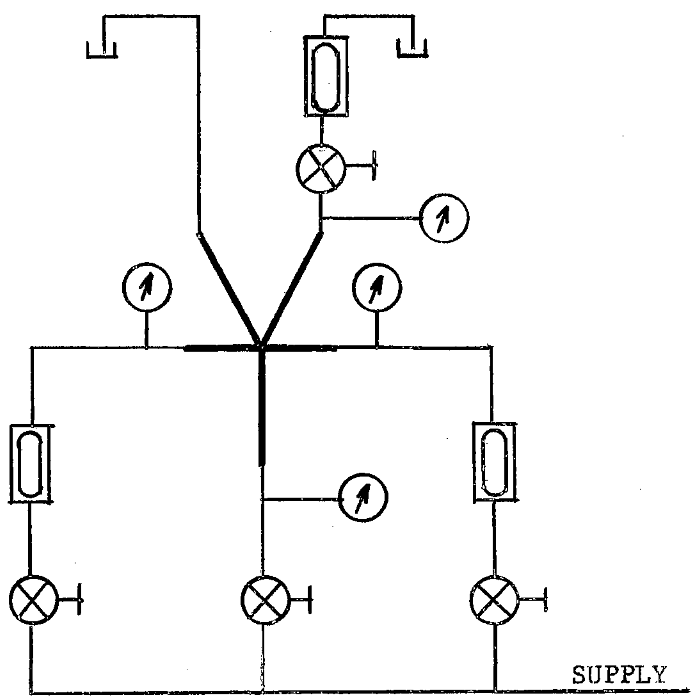

Fig. 26. Diagram of Test Apparatus.

The amplifier was found to be load sensitive, i.e., the switching points and minimum amount of bias flow required for operation as a NOR unit were affected by the working load seen by the right leg. It was also determined that ΔP_R was not constant nor a linear function of the load imposed on the right leg. Also, the switching points, required bias, P_{RR}, and ΔP_R were all affected by the load imposed on the left leg.

The effect of one parameter upon another is summarized by the chart in Fig. 27. For example, an increase in the bias flow Q_b will increase P_{RR}, decrease ΔP_R, and increase both Q_c and P_c at the shifting point.

	P_{RR}	ΔP_R	Min Q_b required for biased operation	Q_c at shift pt.	P_c at shift pt.
Increase load on right leg	increase	depends on magnitude	increase	depends on magnitude	increase
Increase load on left leg	increase	decrease	decrease	depends on magnitude	increase
Increase Q_b	increase	decrease		increase	increase

Fig. 27. Parameter Coupling Chart.

In order to make final stage amplification easier and increase operating stability, ΔP_R was held at or near maximum for all output loads on the right leg. To help increase ΔP_R, the output load on the left leg was held constant at a minimum by using as short a piece of tubing as possible to connect the left output port to tank.

By studing the coupling chart, it could be seen that the control impedance curves would have two parameters -- output load and bias flow. Another curve was necessary to relate P_{RR} to Q_b and thereby eliminate the parameter Q_b from the control impedance curves. In order to keep ΔP_R at a maximum, the minimum bias flow required for operation as a NOR unit was found at each value of P_{RR} used as data points. This curve is shown in Fig. 28.

To obtain the minimum bias flow for the curve shown in Fig. 28, a specified load was imposed upon the right output leg; and bias flow was applied in excess of that required to reset the amplifier. While holding the bias flow constant, the control flow was increased until the amplifier switched to the set position and then was decreased until the bias flow was sufficiently greater than the control flow to reset the amplifier. The bias flow was decreased by small increments, and the procedure repeated until the amplifier failed to reset itself.

In instances where a NOR element is used to control another, the pressures P_1 and P_2 discussed in Chapters IV and V become P_{RS} and P_{RR}, respectively, i.e., the maximum and minimum output pressures of the driving amplifier depending on whether it is set or reset. It was therefore necessary to know what pressure P_{RS} could be expected for each value of P_{RR}. This information can be found from Fig. 29 which is a curve of P_{RR} versus ΔP_R.

The curve shown in Fig. 29 was found in the following manner. A specified load was imposed upon the right output leg with the amplifier in the reset position. The correct amount of bias flow, found from Fig. 28, was applied at the bias port. The control flow was then slowly applied until it was just sufficient to set the amplifier. At that point

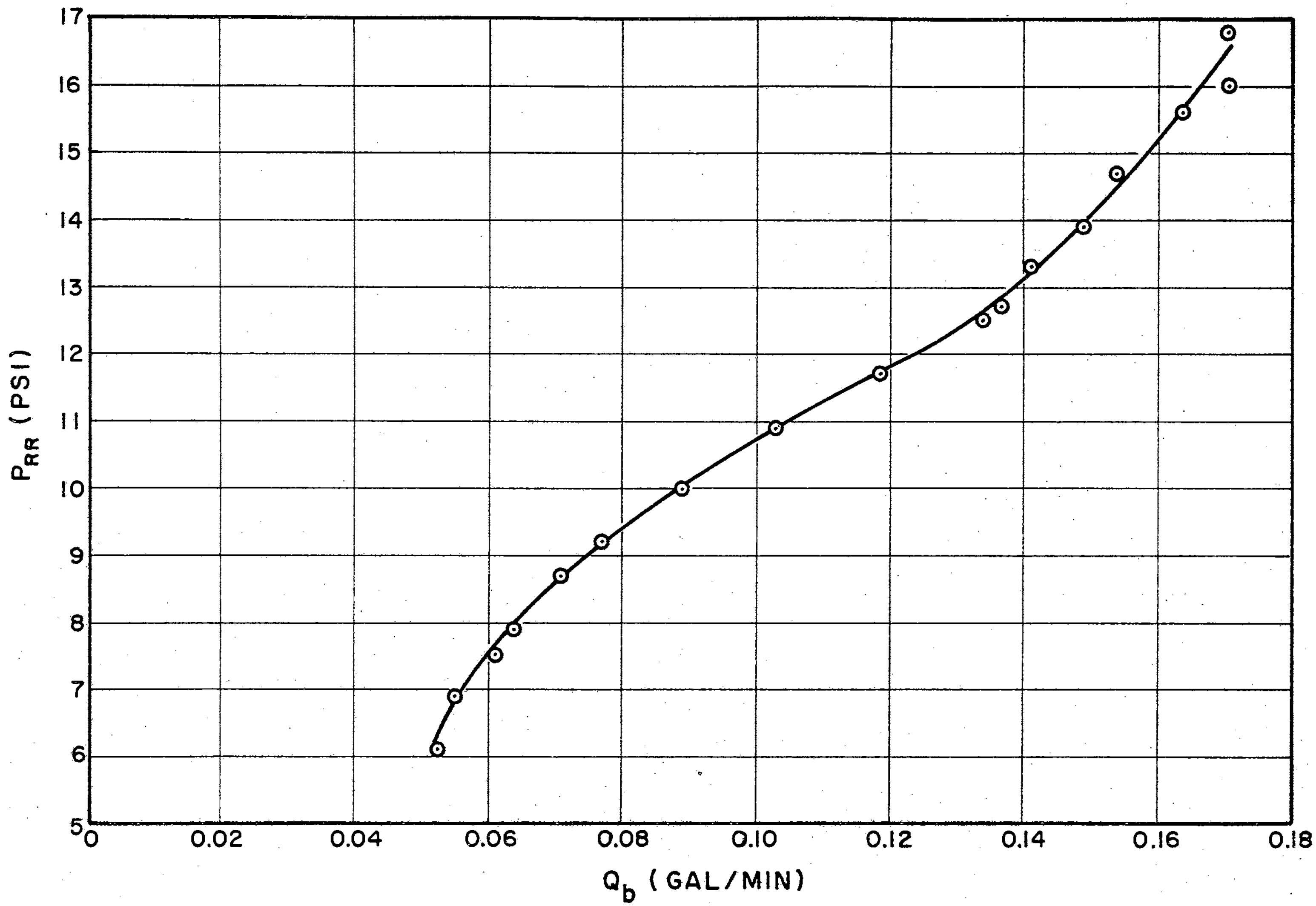

Fig. 28. Minimum Bias Flow Required to Reset a NOR Unit.

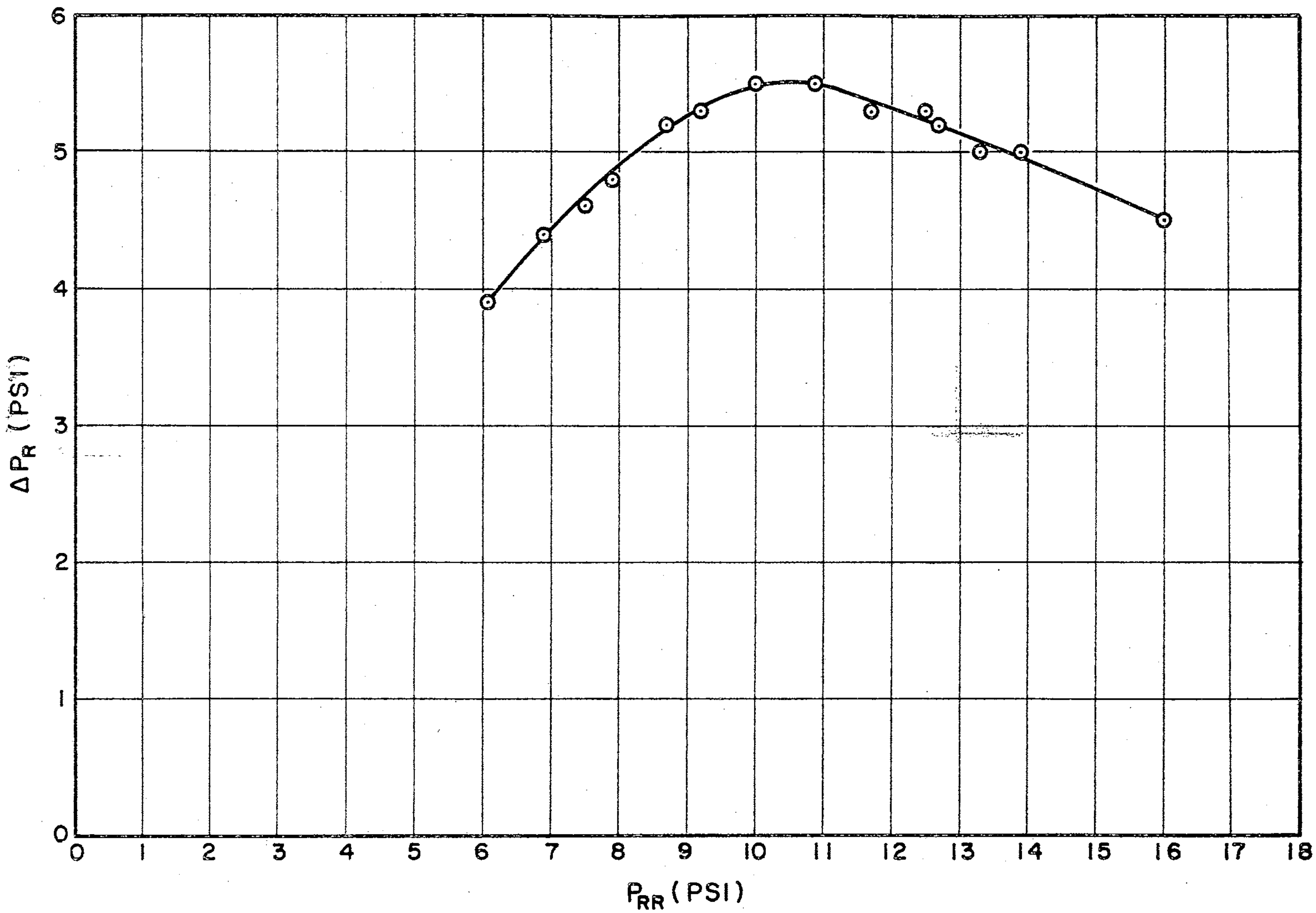

Fig. 29. ΔP_R Versus P_{RR} at Minimum Q_b.

the value of P_{RS} was measured, and ΔP_R calculated by $\Delta P_R = P_{RR} - P_{RS}$. It was found that P_{RS} could be decreased (thereby increasing ΔP_R) by applying somewhat more control flow than was actually needed for shifting. The values of ΔP_R in Fig. 29 are the minimum values that can be expected for each value of P_{RR}, i.e., the ΔP_R found by applying the least possible control flow. The minimum value of ΔP_R was used in calculations for the interconnecting fluid resistors. Any greater value of ΔP_R that might be obtained during operation added a factor of safety to the decision function.

For the purpose of interconnection, it was not necessary to obtain the entire control impedance curves but only the switching point loci as shown in Fig. 30. The parameter for the family of switching points was the output load P_{RR}. The necessary bias flow corresponding to each value of P_{RR} is found by consulting Fig. 28. However, the bias flow was not held constant during determination of the shifting points for the reason to be discussed.

If the bias flow is held constant at a specified output load, the orientation of the two shifting points with respect to each other when shown on the control impedance graph would appear as in Fig. 31. When the input resistor equation is superimposed upon the figure with a maximum upstream pressure of P_{RR} and a minimum upstream pressure of P_{RS}, it can be seen that an excessively wide control band ΔP_R might be required to perform the decision function. In this feasibility study, the control system was to be designed for maximum stability; therefore, P_{RR} and P_{RS} should be selected so that the set stability margin is equal to the reset stability margin. In addition, the switching points should be so arranged that a straight line drawn through them has a negative slope.

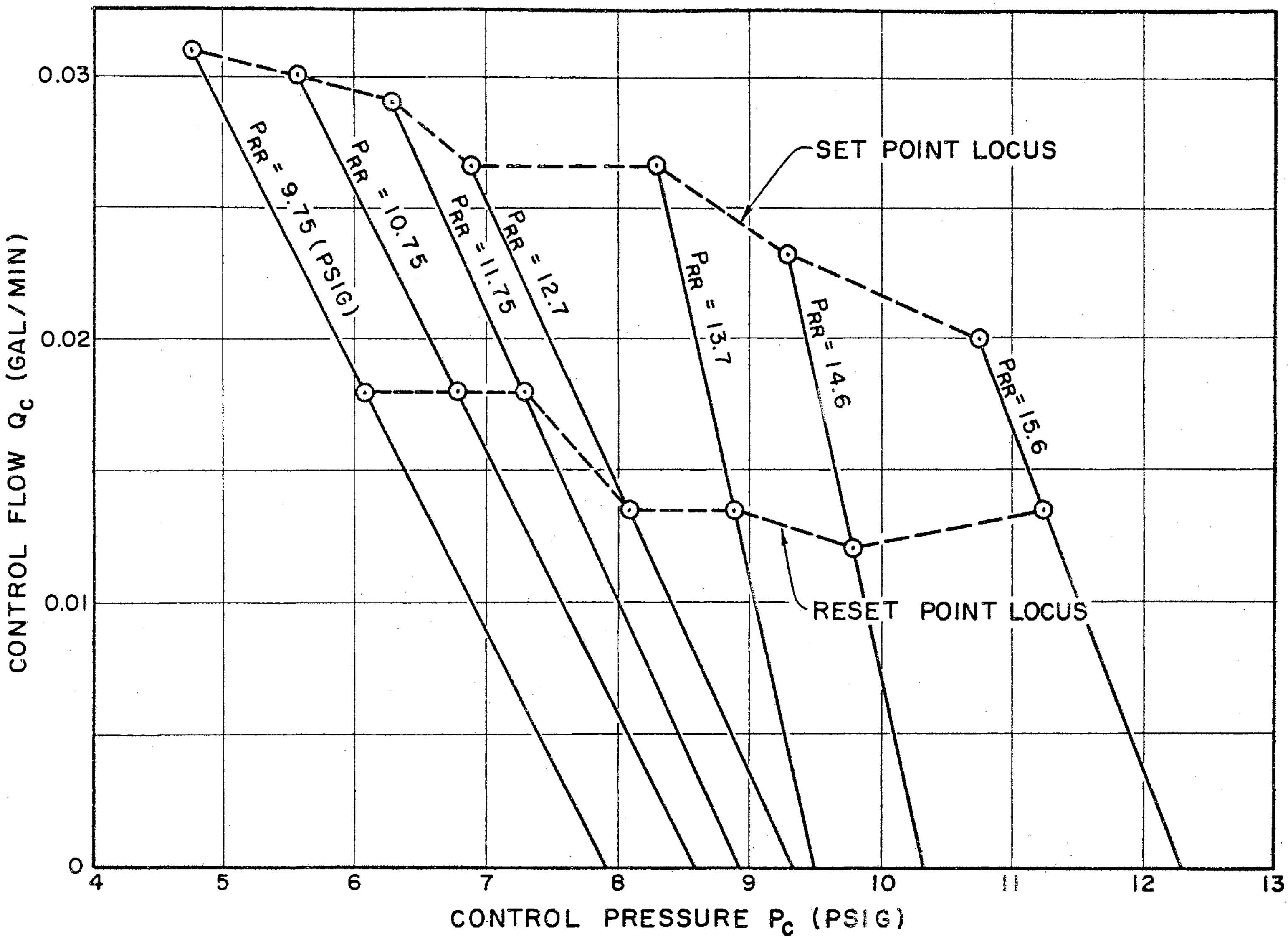

Fig. 30. Switching Point Loci.

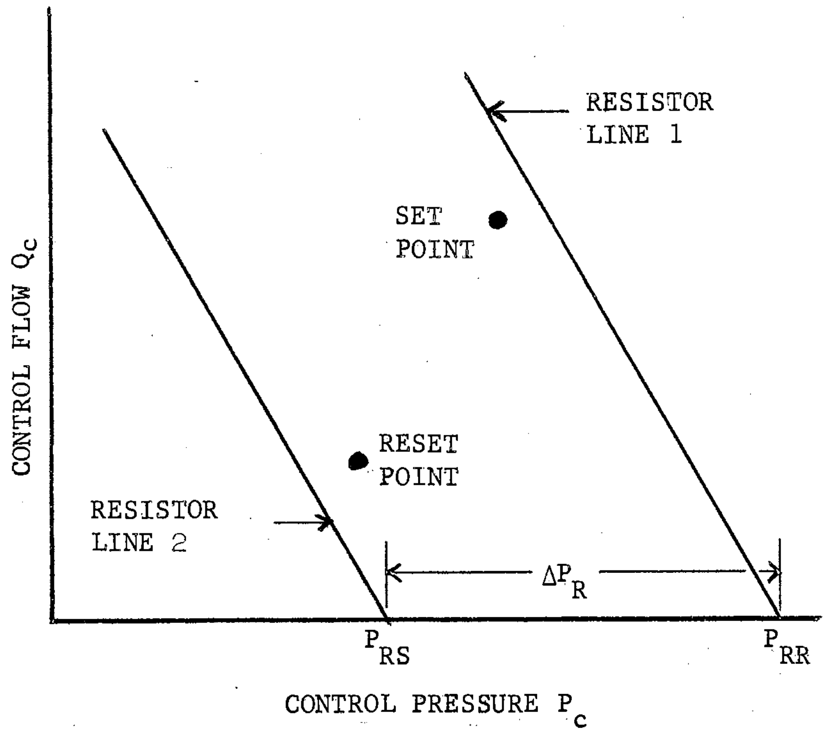

Fig. 31. Control Impedance for Constant Bias Flow.

The use of constant bias flow does not approach the optimum switching characteristics. A better bias would be one that supplied a smaller Q_b when the amplifier was reset than when it was set. This would offer less resistance to the control flow when attempting to set the amplifier, thus decreasing P_c at the set point, and would give assistance when switching back to the reset position thus increasing P_c at the reset point.

The characteristics of a bistable amplifier are such that the bias pressure P_b is greater when the amplifier is reset than when set (recall that a low-pressure bubble exists on the side to which the power jet is attached). This suggested the use of a fluid resistor with a relatively small upstream pressure to provide the bias. When the amplifier was in the reset position, the downstream pressure P_b was high, giving a small flow rate Q_b. When the amplifier was in the set position, the downstream pressure P_b was low which increased the flow rate Q_b.

It was found by experiment that a supply pressure of 30 psi upstream of the bias resistor was sufficient to cause the positions of the switching points to move so that a straight line drawn through them had a negative slope.

To design a bias resistor for an amplifier operating at a specified load, the minimum amount of bias flow required to reset the amplifier at the specified value of P_{RR} was read from Fig. 28. The proper value of the bias pressure P_b downstream of the bias resistor had to be measured with the amplifier in the set position. This bias impedance curve is shown in Fig. 32.

The Interconnection Procedure

In this section, the interconnection theory developed in Chapter V will be used to design input resistors for the synthesis of the experimental switching circuit. The procedure was complicated by the fact that the amplifiers were load sensitive. Since the switching characteristics were affected by the magnitude of the output load, it was necessary to start with the amplifier from which the output signal was taken and match the output load of the driving amplifier to the control impedance of the driven element successively backwards through the flow path. For this feasibility study, the interconnection procedure was biased toward obtaining maximum decision function stability.

The first problems that had to be solved were those of selecting the type of input resistor to be used in the interconnection procedure, and of accurately predicting the flow rate and pressure drop through the

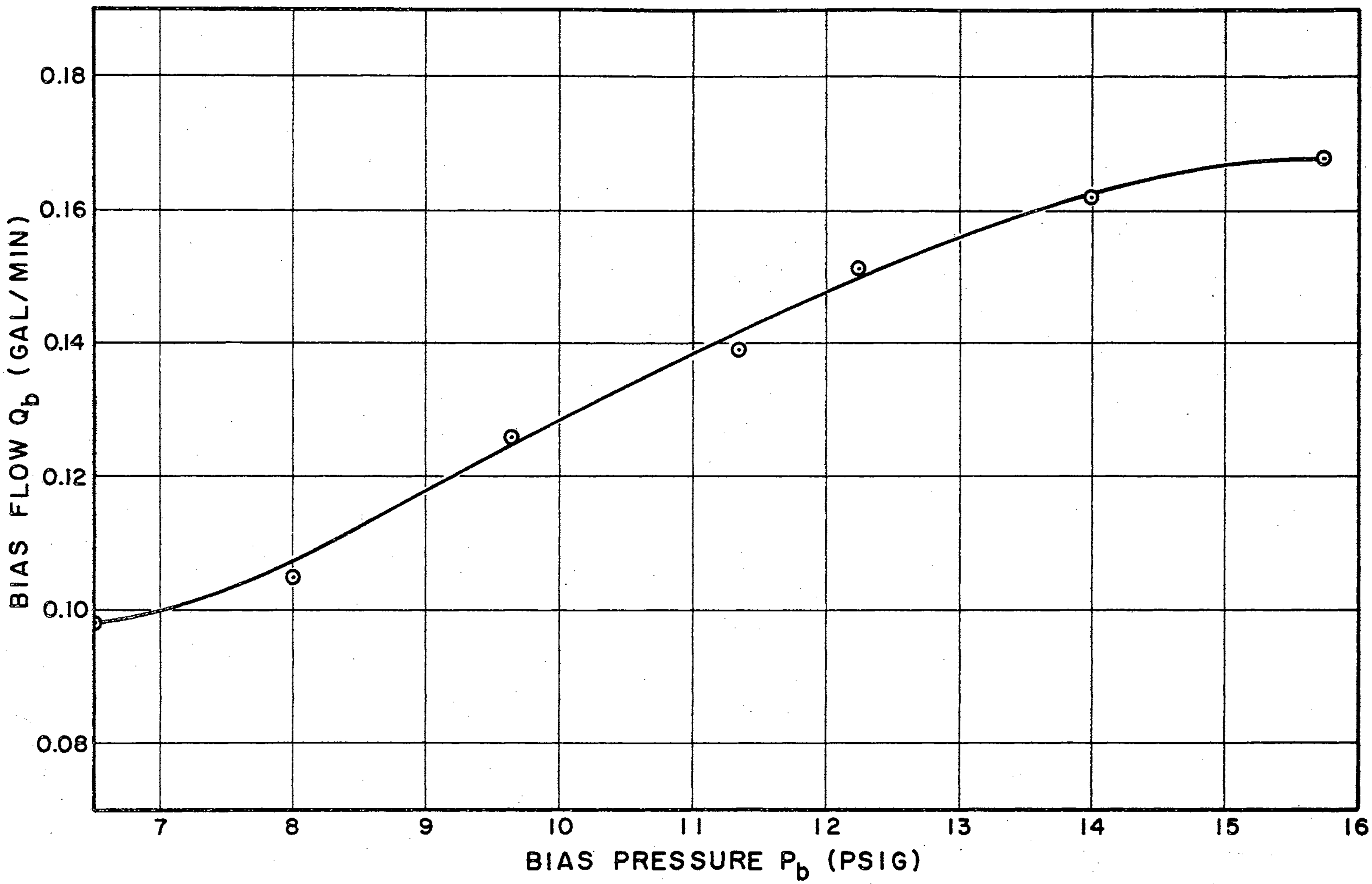

Fig. 32. Bias Impedance, Amplifier in Set Position.

resistor. There are two different types of fluid resistors which could have been used for interconnection -- the sharp-edged orifice and the small tube. The small tube was decided upon because of the ease of construction and the ease of use. The small tube could be made by drilling a hole in a small slug of soft material which would slip inside a 1/4" brass tube union. However, some difficulty was experienced trying to predict the amount of flow and pressure drop through a small tube. The well known equation for viscous laminar flow through a pipe (Equation 6-5) was useless. The measured flow through a tube designed by Equation 6-5

$$Q = \frac{\pi D^4 \Delta P}{128 \mu L} \qquad (6\text{-}5)$$

was only about half that predicted. This can be attributed in part to the capillary action within the tube. Some work is currently being done on the problem of flow through small tubes and orifices at the Massachusetts Institute of Technology. In a progress report, D. J. Tapporo (10) of M. I. T. presented a dimensional analysis and experimental data of flow through a capillary tube. The data scatter was so pronounced that no conclusions could be reached.

The flow Q through a capillary tube is a function of ΔP, ρ, μ, D, and L where

ΔP = pressure drop across the tube

ρ = fluid density

μ = fluid viscosity

D = inside diameter of tube

L = length of tube.

These parameters can be arranged into three dimensionless groups:

$$\frac{\rho Q}{D\mu}, \qquad \frac{\rho \Delta P D^2}{\mu^2}, \qquad L/D \tag{6-6}$$

The fluid used for the feasibility study was MIL-O-5606 hydraulic oil which has a specific gravity of 0.86 and a viscosity of 1.86×10^{-6} Reyn at 100°F. Substitution of these values into the dimensionless groups yields

$$1.66Q/D, \qquad 234\Delta PD^2 \qquad L/D \tag{6-7}$$

Q - gal/min

P - psig

L - inches

D - inches

The flow and pressure drop through a capillary tube made of teflon with an inside diameter of 0.040 inches and a length-to-diameter ratio of 6.1 were measured and the results used to obtain the graph of Fig. 33. To use Fig. 33, a diameter D is assumed, either the ordinate or abscissa value is calculated, the plot is used to find the value on the remaining axis, and a new diameter calculated. A trial-and-error procedure is followed until the assumed and calculated values of D converge. Even this method was not accurate enough for the close flow control required by the interconnection procedure. The predicted diameters were fairly accurate, but it became necessary to make the tubes longer than required and then shorten the tube until the desired flow rate or pressure drop was obtained.

For convenience, Fig. 25 is repeated here as Fig. 34 with the amplifiers designated as A, B, and C and the resistors numbered from one to eight.

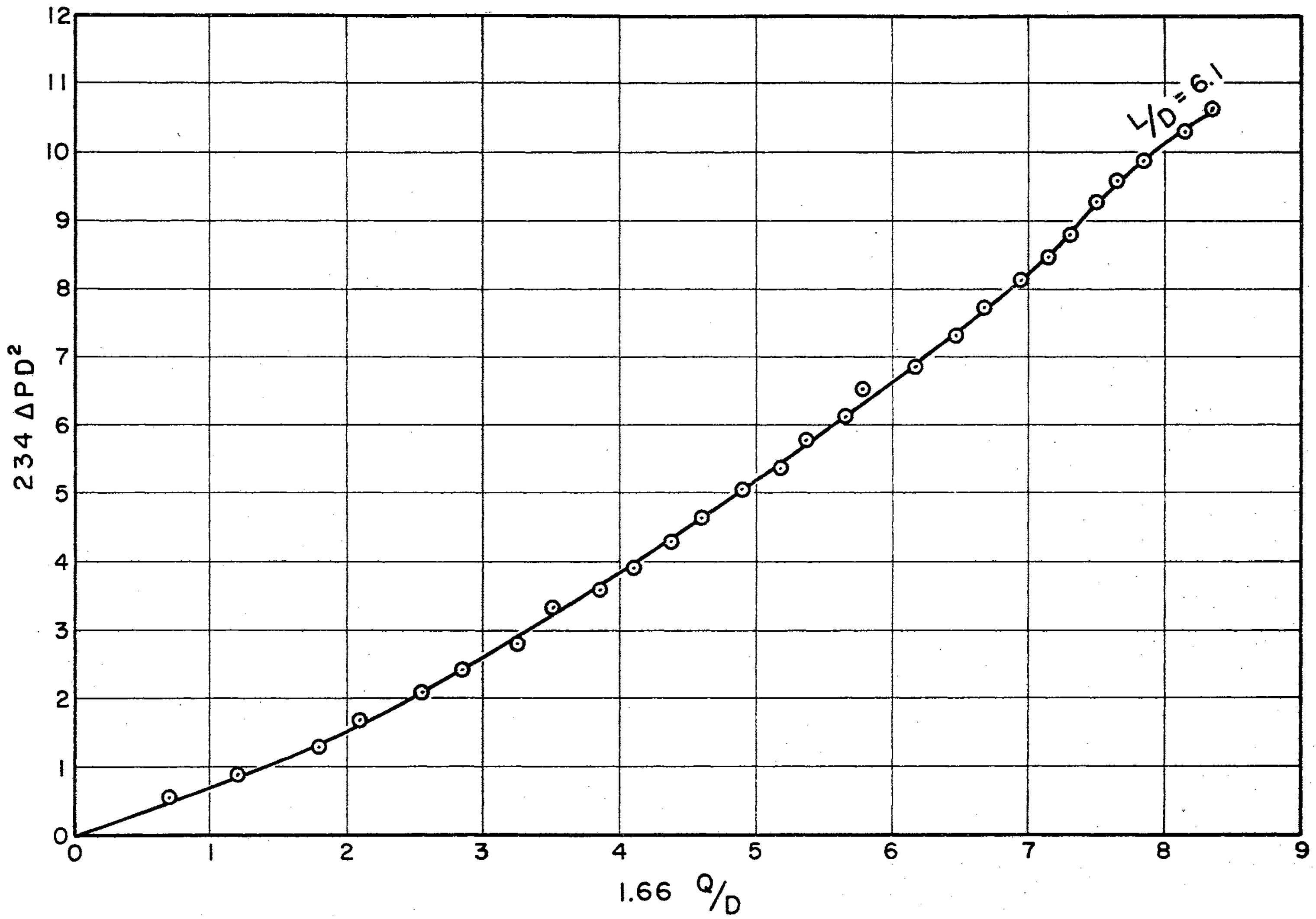

Fig. 33. Flow Through a Small Tube.

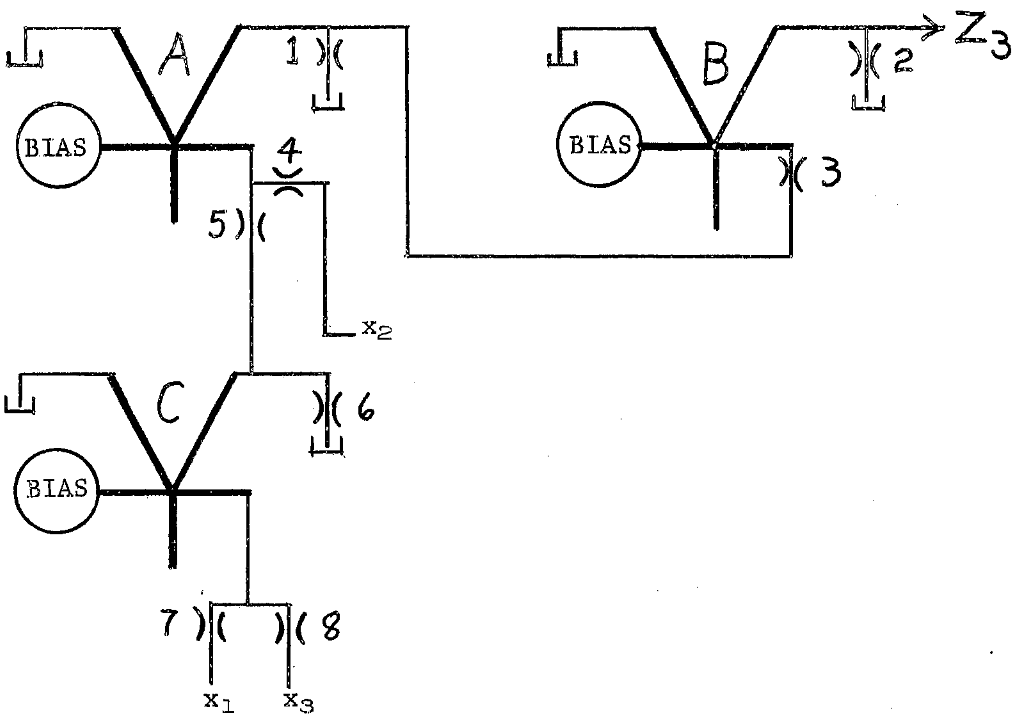

Fig. 34. Z_3 Switching Circuit with Elements Identified.

Since a specified output was required of amplifier B, the interconnection procedure had to begin with amplifier B and proceed backwards through the flow path from driven to driver. An output pressure as great as practical was required of amplifier B. From Fig. 30, it can be seen that the maximum output pressure obtainable from any amplifier is 15.6 psi. The two switching points corresponding to the output load parameter $P_{RR} = 15.6$ are transferred to the control impedance graph in Fig. 35. The problem is to select an output load for the driving amplifier (amplifier A) that will match the control impedance of the

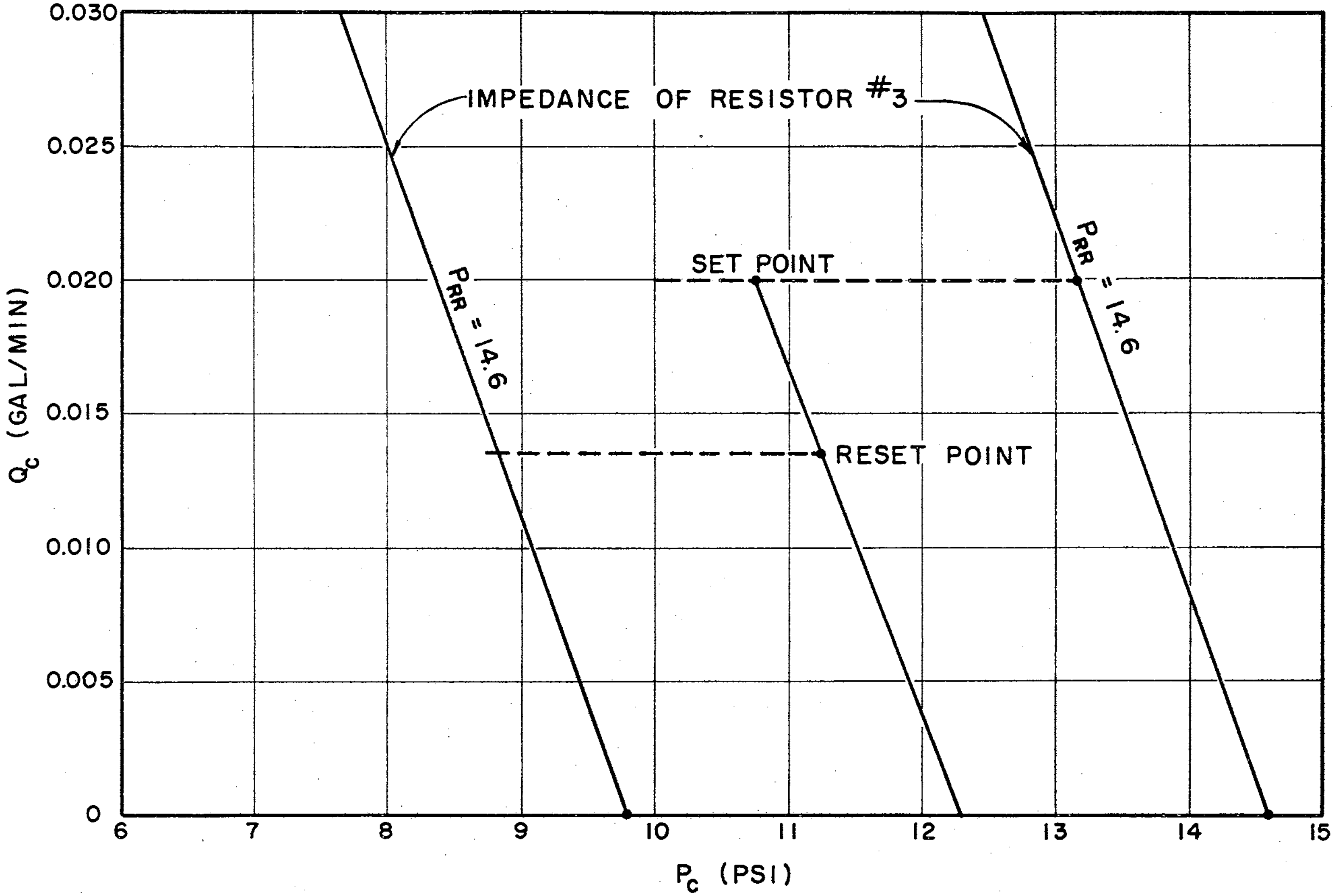

Fig. 35. Proposed Decision Function for Amplifier B.

driven amplifier (amplifier B). In addition to the impedance matching, it is desired to approach the optimum decision function as closely as possible. Note from Fig. 30 or Fig. 35 that a straight line drawn through the two switching points intersects the abscissa at $P_c = 12.3$ psi. If possible, amplifier A should be operated at an output load so that its ΔP_R for that load is bisected by the point $P_c = 12.3$ when superimposed upon the P_c axis of the amplifier B control impedance graph.

An infinite number of different values of P_{RR} and ΔP_R are not available -- only those values of P_{RR} shown in Fig. 30 and corresponding values of ΔP_R found from Fig. 29. It would only be coincidental if the optimum characteristics derived in the previous chapter were obtained. The method used to approach the optimum characteristics as nearly as possible is explained below.

The first step involves superimposing upon the amplifier B control impedance graph two lines -- one with a P_c intercept at P_{RS} and one with a P_c intercept at P_{RR} -- which represent by a straight-line approximation the impedance of the input signal resistor, e.g., resistor 3 for amplifier B. The slope of the two lines must be the same. The optimum characteristics are such that the set stability margin is the same as the reset stability margin. Several different values of P_{RR} are tried in an effort to find the one whose corresponding ΔP_R is nearest bisected by the P_c intersection point of a straight line drawn through the two switching points. Fig. 35 illustrates the above procedure for amplifier B. The value of P_{RR} finally selected was 14.6, giving equal stability margins of 2.4 psi.

The equation of the resistor line is

$$Q_c = K(P_{RR} - P_c) \tag{6-8}$$

where K is some positive constant. The proper value of $\bar{P}_c$ for use in Equation 1 is found at the intersection of a horizontal straight line passing through the set point and the P_{RR} oriented resistor line (see upper dashed line in Fig. 35). The inside diameter of the input resistor is found by a trial-and-error procedure with the aid of Fig. 33 using the value of Q_c at the set point for calculating 1.66 Q/D and $P_{RR} - P_c$ for the ΔP in $234 \Delta PD^2$. Using this procedure, the diameter of resistor number 3 was found to be 0.042 inches and its length, 0.256 inches.

The output load on amplifier A has now been fixed at 14.6 psi. In this case, one amplifier and one input signal are used to drive amplifier A; and the procedure for selecting the output load of the driving amplifier is different. A schematic flow diagram of this situation would appear as in Fig. 36. The optimum decision function for this situation was discussed and the proper equations were derived in Chapter V.

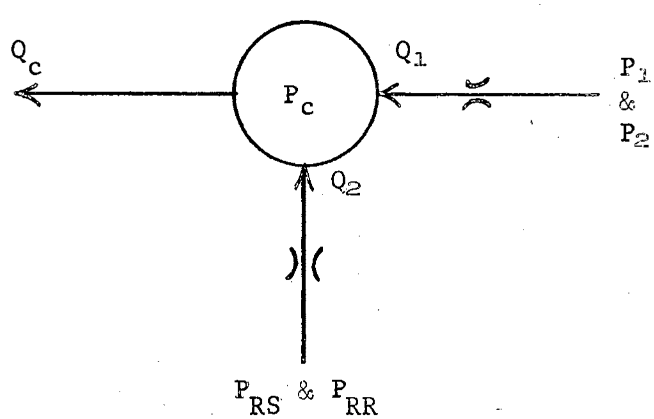

Fig. 36. Schematic Flow Diagram of Amplifier A Input Signals.

In order to design the input resistors, the following development is necessary. If $234\Delta PD^2$ is less than approximately 2.5, it can be seen from Fig. 33 that the relationship between $234\Delta PD^2$ and $1.66Q/D$ is almost linear with the straight line intersecting the origin. Thus,

$$234\Delta PD^2 = K'(1.66Q/D) \tag{6-9}$$

where K' is some positive constant. Rearranging Equation 6-9,

$$Q = 234\Delta PD^3/1.66K'$$

$$Q = K''\Delta P \tag{6-10}$$

where $K'' = 234D^3/1.66K'$. The value of K' can be found from Fig. 33

$$\begin{aligned} K' &= 0.8 \\ K'' &= 176D^3 \end{aligned} \tag{6-11}$$

In the linear region (with zero intercept) of the pressure-flow curve (Fig. 33) the following flow equations taken from Chapter V are valid.

$$Q_c = K''[\alpha\, P_{RR} + P_1 - P_c(1 + \alpha)] \tag{6-12}$$

$$Q_c = K''[\alpha\, P_{RS} + P_2 - P_c(1 + \alpha)] \tag{6-13}$$

$$Q_c = K''[\alpha\, P_{RS} + P_1 - P_c(1 + \alpha)] \tag{6-14}$$

The next step involves superimposing Equations 6-12 and 6-14 upon the control impedance graph of amplifier A. It was known that P_1 was approximately 0.5 psi. In order to plot the equations, a value of α

had to be assumed. The procedure was to plot Equations 6-12 and 6-14 for several values of P_{RR} and their related values of P_{RS}, beginning with $P_{RR} = 15.6$ and trying each permissible value (those values shown as parameters in Fig. 30) until the slope of the resistor lines became positive. The results of this systematic search, with an assumed value of $\alpha = 3$, is shown in Fig. 37. As in the previous case, both resistor lines corresponding to a value of P_{RR} have the same slope; and the slope was adjusted by trial and error to obtain equal stability margins. For $\alpha = 3$, only the resistor lines corresponding to $P_{RR} = 15.6$ have a negative slope. The magnitude of the stability margins can be measured on Fig. 37 and is 1.76 psi.

Fig. 38 shows the results of the same procedure except α was assumed to be four. The stability margin corresponding to $P_{RR} = 15.6$ is 1.67 psi and that corresponding to $P_{RR} = 14.6$ is 2.06 psi. From these results, it was decided to operate amplifier C at 14.6 psi with $\alpha = 4$. The pressure P_2 could then be calculated from Equation 5-19 to be 19.7 psi.

As discussed in Chapter V, the slope of the resistor lines is $K''(1 + \alpha)$. From Fig. 38, the value of the slope of the resistor line corresponding to $P_{RR} = 14.6$ is 0.05. Therefore,

$$K'' = \frac{0.05}{1 + \alpha} = 0.01 \tag{6-15}$$

The inside diameter of resistor number 4 can be calculated from Equation 6-11 to be 0.0385 inches. Since the length-to-diameter ratio is 6.1, the length of resistor number 4 is 0.235 inches. For resistor number 5, the equation for the diameter would be a variation of Equation 6-11 as shown in Equation 6-16.

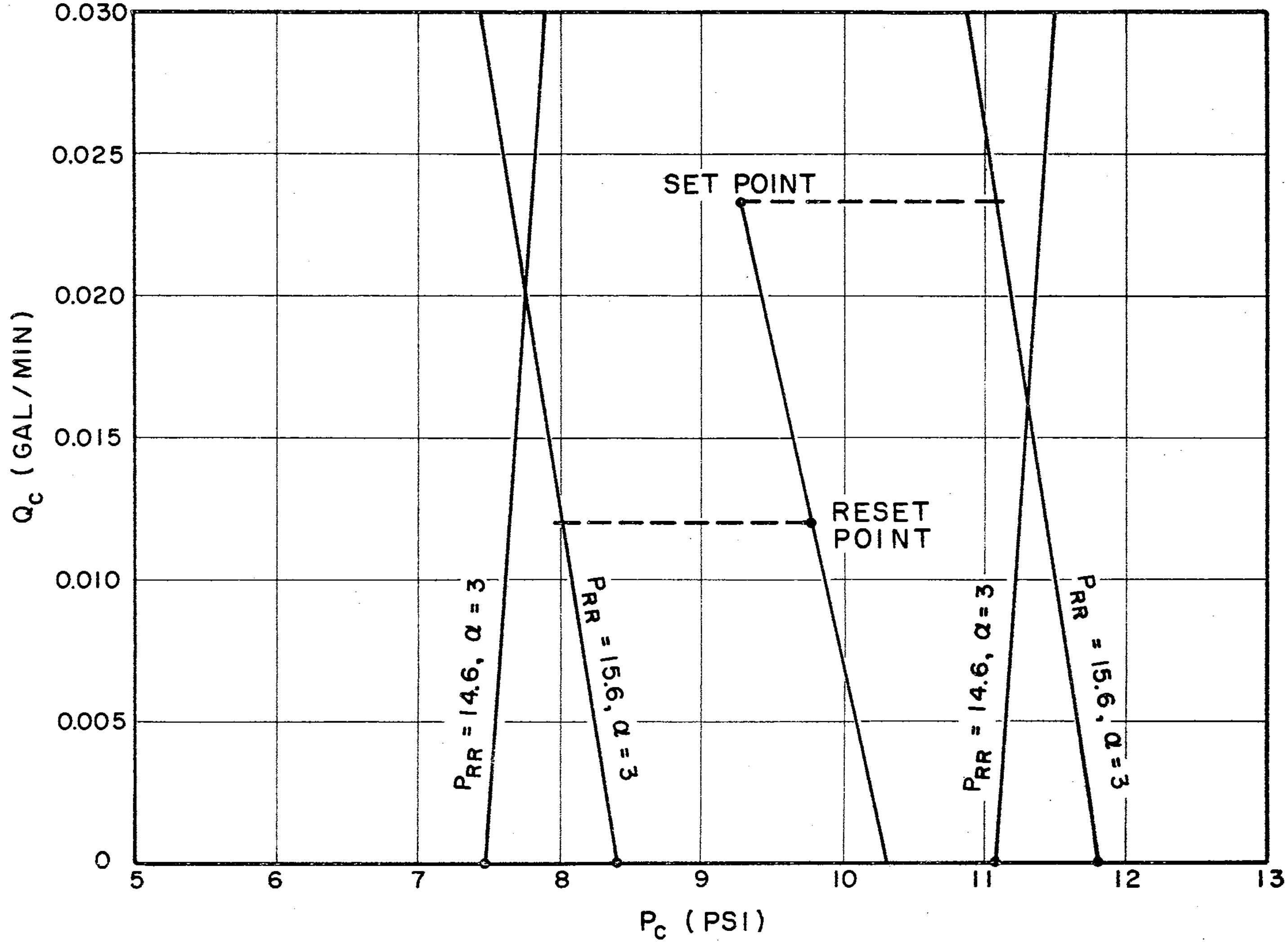

Fig. 37. Illustration of Decision Function for Amplifier A with α = 3.

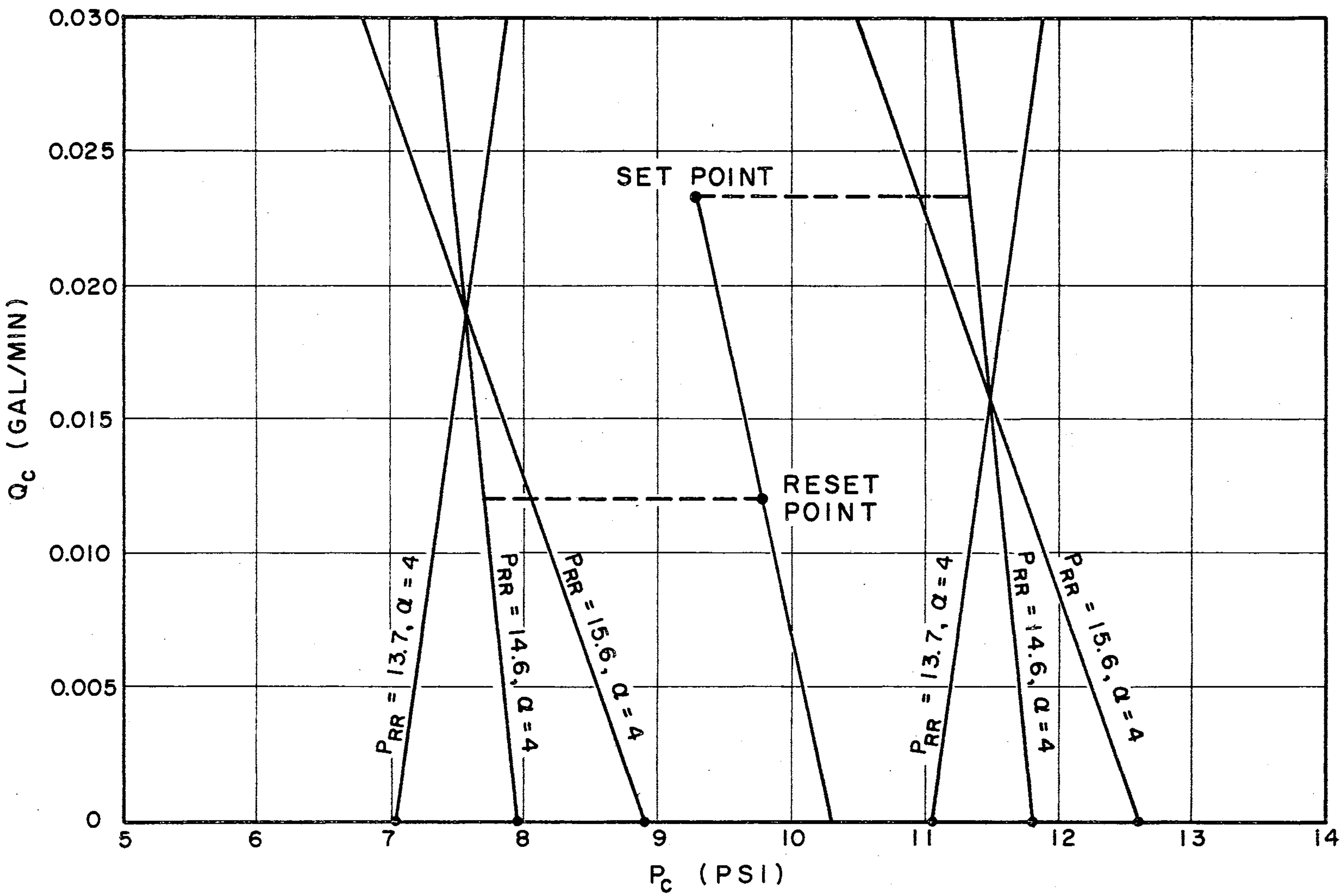

Fig. 38. Illustration of Decision Function for Amplifier A with $\alpha = 4$.

$$\alpha K'' = 176D^3 \tag{6-16}$$

From Equation 6-16, the diameter of resistor number 5 is found to be 0.0612 inches and its length 0.372 inches.

It remains to check the validity of the original assumption that $234\Delta PD^2$ is less than approximately 2.5. The ΔP for this parameter should be found at the set point. Solving Equation 6-12 for P_{RR} yields

$$P_{RR} = 1/\alpha[\frac{Q_c}{K''} - P_1 + P_c(1 + \alpha)] \tag{6-17}$$

If the values of control flow and pressure at the set point are substituted into Equation 6-17, the solution is $P_{RR} = 12.05$ psi. Thus, $234\Delta PD^2$ becomes $234(12.05-9.29)D^2 = 2.42$. Similarly, if Equation 6-13 is solved for P_2 at the set point, $234\Delta PD^2$ becomes 0.076. Thus, the original assumption was valid. Had it not been valid, it would have been necessary to derive a new equation similar to Equation 6-11 which would have been more nearly correct for the region of diameters and pressure drops under investigation. This could have been done by writing a different linear equation for some line segment of Fig. 33.

Essentially the same procedure was followed for the remaining amplifier. In the case of amplifier C, an infinite number of maximum pressures upstream of the resistors are obtainable, regardless of the supply pressure at the point of origin of the input signals, by using another fluid resistor in series with the input resistor. The upstream pressures were selected at the proper magnitude to give approximately the same set stability margin as amplifier A. The magnitude of the reset stability margin was neglected.

The fluid resistors 1, 2, and 6 were required to regulate the output pressures of the amplifiers to the values derived in the interconnection procedure just discussed. To design these resistors, it was necessary to find the relation between flow rate and maximum output pressure of the right leg with the amplifier in the reset position. This output impedance is shown in Fig. 39.

Fig. 39 was used by assuming that the total output flow Q_{RR} of an amplifier was the sum of the flow through the bleed-off resistor (e.g., resistor 1, 2, or 6) and the flow through the input resistor required to set the amplifier being driven. This assumption is not entirely accurate.

Since the true set operating point (i.e., the intersection point of the right hand resistor line and the set line on the control impedance curve) is not defined, the true control flow Q_c is not known when the driving amplifier is operating at maximum output pressure. However, it is known that the control flow will be less than that at the set point and greater than that at the reset point. Thus, the maximum range of possible true values of Q_c would only be about five per cent of Q_{RR} which in turn would cause an error of approximately three per cent in the assumed rate of flow through the bleed-off resistor. Such an error was considered acceptable, and it was not necessary to obtain the entire control impedance curves.

A photograph of the control system is shown in Fig. 40. A schematic diagram of the entire hydraulic system is shown in Fig. 41, and an actual photograph of the system appears in Fig. 42. The two reduced pressure manifolds with surge tanks were required to filter noise, caused by rapid opening and closing of the power valves, from the control system supply manifold.

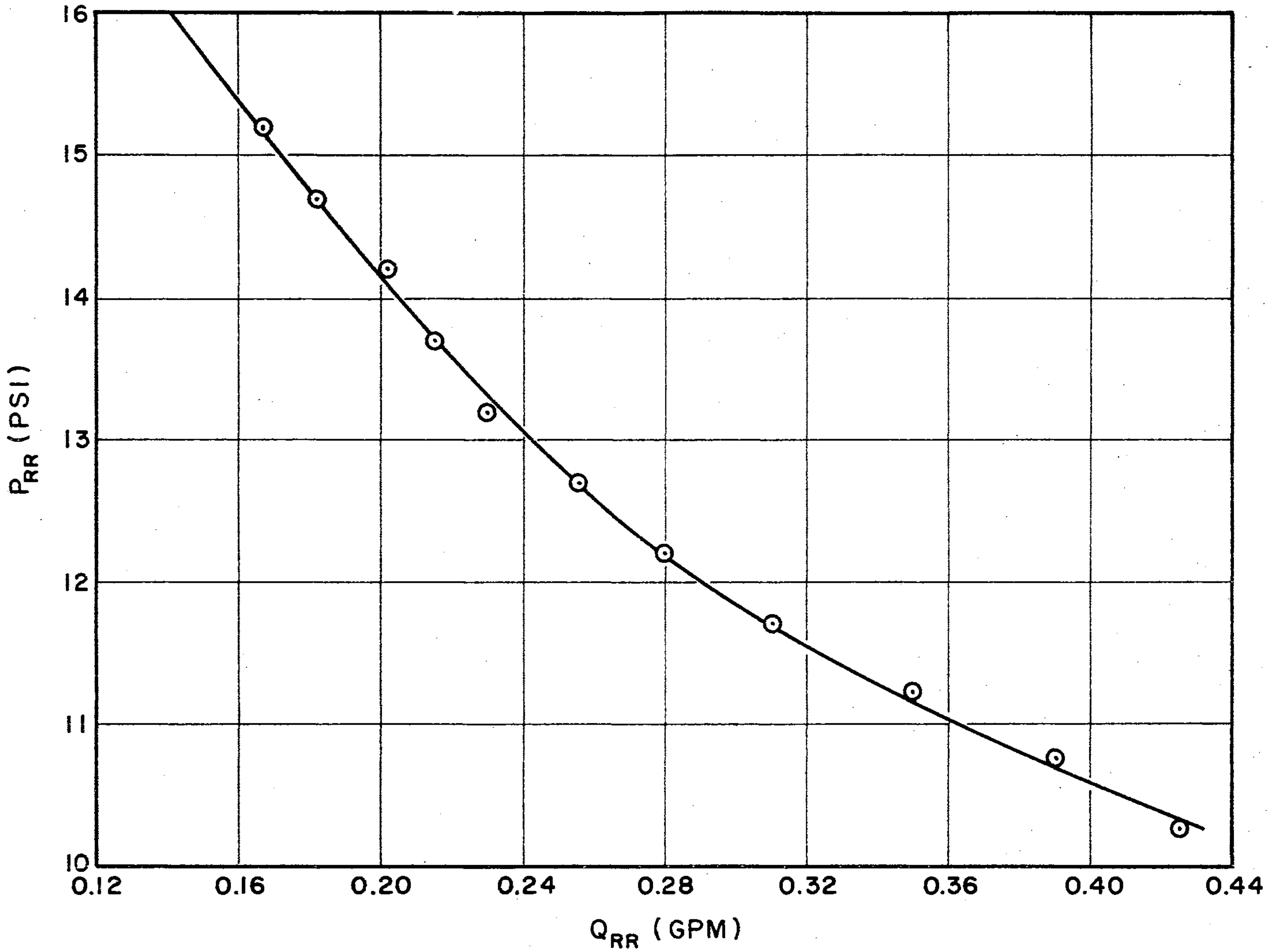

Fig. 39. Output Impedance of Right Leg -- Amplifier in Reset Position.

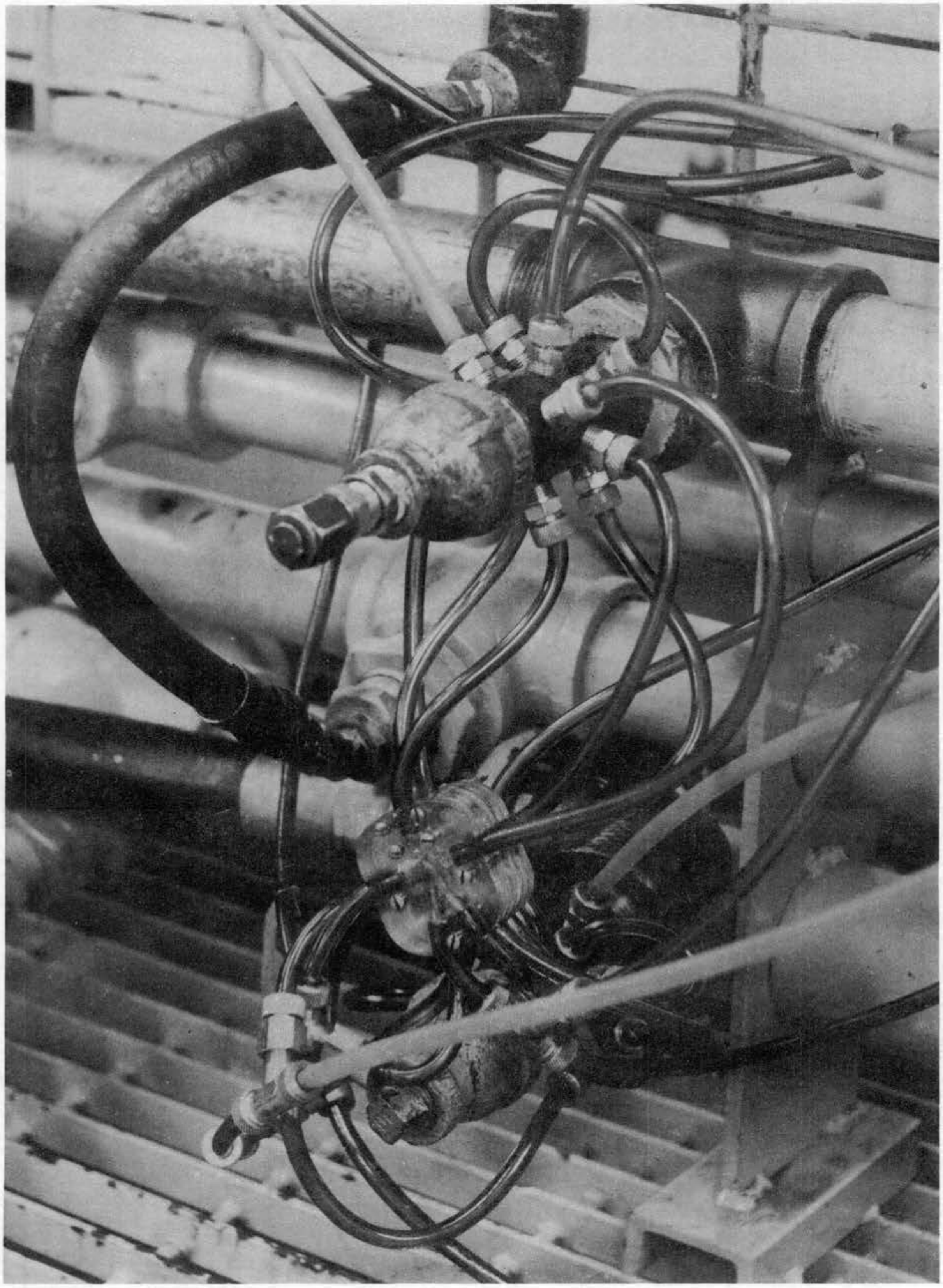

Fig. 40. Photograph of Control System.

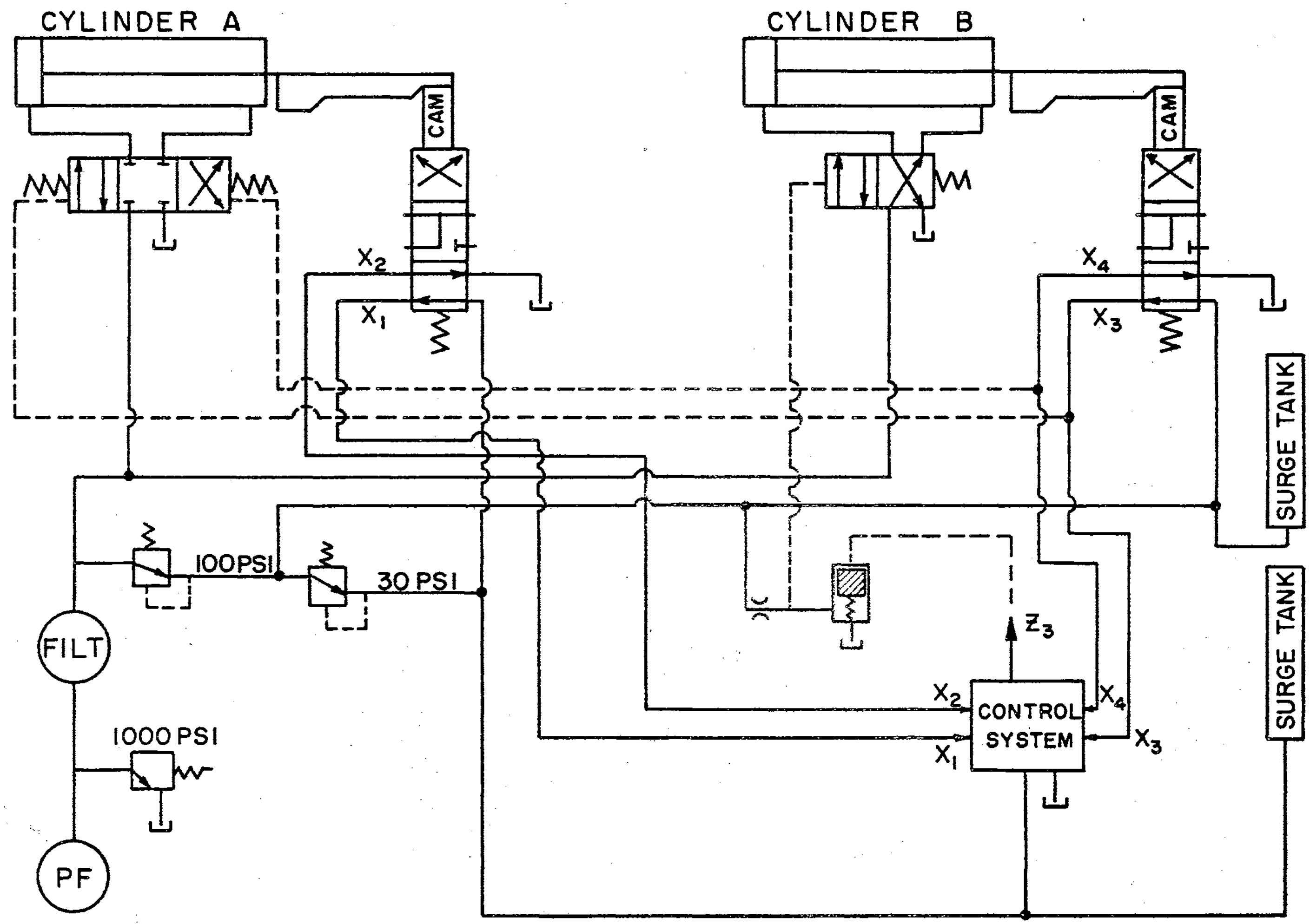

Fig. 41. Schematic Diagram of Hydraulic System.

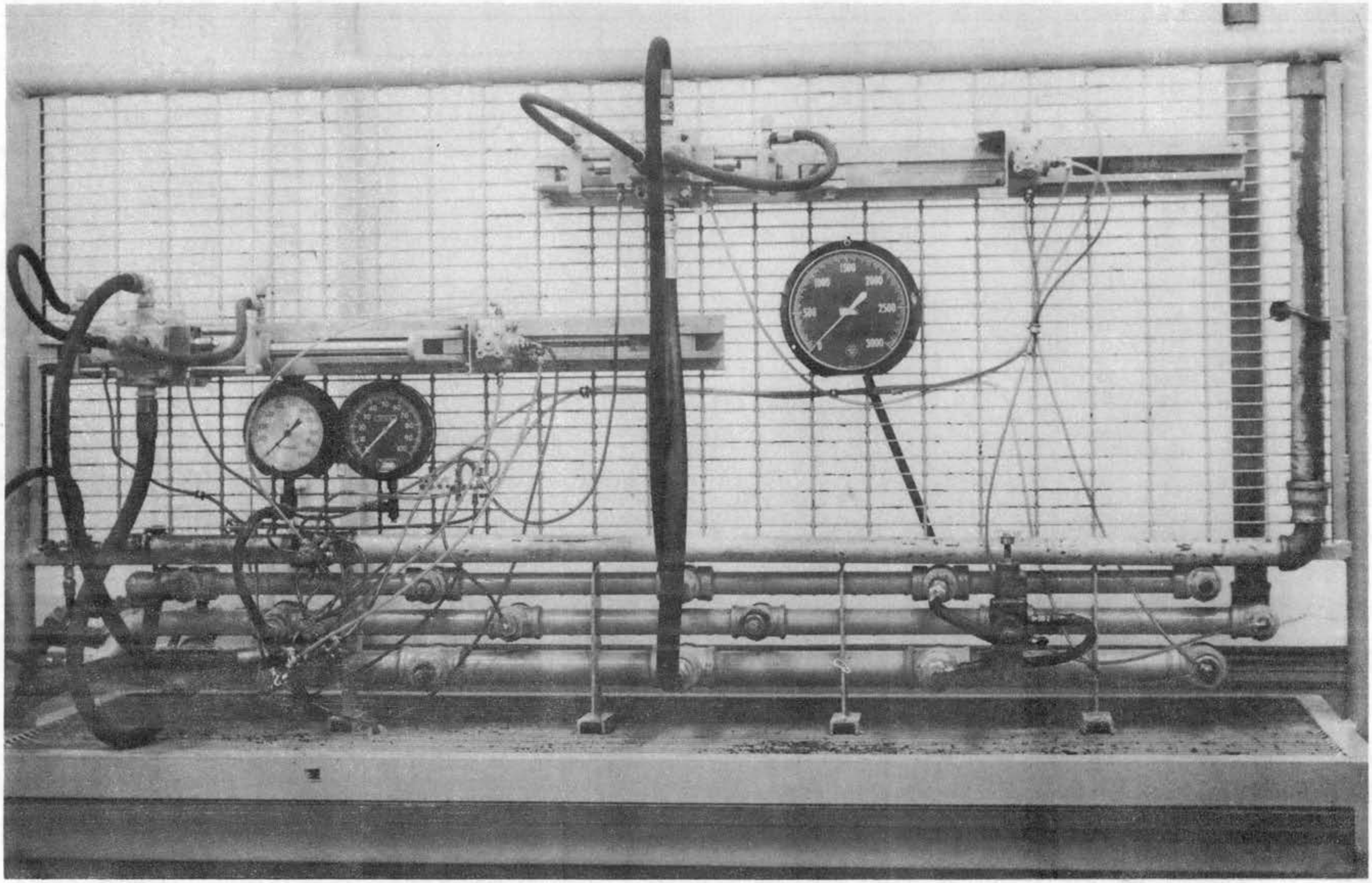

Fig. 42. Photograph of Hydraulic System.

CHAPTER VII

RESULTS AND CONCLUSIONS

The original objectives of the feasibility study were met. A scheme for interconnecting currently available fluid amplifiers into a control system requiring logic, using hydraulic fluid as the working medium, was devised. This control system was used to control a high-power hydraulic machine. Also, as a direct result of the feasibility study, recommendations for future work on basic amplifier design were made.

However, several deficiencies must be pointed out. Although the interconnection procedure was successful, the effects of load sensitivity of the fluid amplifiers used in this study made the interconnection procedure much more complicated than would be required for load insensitive units. Due to load sensitivity, it became necessary to match the output load of the driving amplifier to the control impedance of the driven amplifier successively backwards through the flow path.

The power loss through the control system was high. The flow rate through the three amplifiers was approximately 2.5 gpm. Since this volume was originally pumped at 1,000 psi, the power loss through the control system was about 1.5 hp. In addition, the high flow rate in itself could be inefficient or inconvenient.

Due to these deficiencies, it is the opinion of the author that presently available bistable fluid amplifiers are not readily nor economically adaptable for use in control systems on high-power hydraulic machinery using hydraulic fluid as the working medium. However, this study has shown that the basic idea is sound and should be further investigated. If new amplifiers can be designed with desirable characteristics, fluid power control systems can be devised that have all the advantages of "no moving parts" operation plus the advantages gained by the absence of energy conversion devices for transmission of signals between the power system and the control system.

Initially, the control system was synthesized using capillary tubes made exactly according to the dimensions calculated in the interconnection procedure. When the system failed to work, it became necessary to check the flow rates and pressure drops of the various resistors and adjust them to the proper specifications. The bias resistors were the most critical.

One other adjustment had to be made before the control system operated satisfactorily. It became necessary to use two stages of billet valve amplification to increase the output pressure of the switching circuit sufficiently to operate the cylinder B power valve. However, it was felt that the billet valve could have been modified to achieve the required gain with only one stage of amplification.

As anticipated, the control circuit did not switch very quickly. The interconnection procedure was biased toward maximum stability which adversely affected switching time. The switching time was estimated to be approximately 20 milliseconds by comparison with the known switching time of billet valves. This speed of operation is sufficient for most applications in hydraulic machinery.

CHAPTER VIII

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

One problem, only indriectly related to fluid amplifiers but still very important to their interconnection, is that of accurately predicting the flow rate and pressure drop through a small capillary tube. Before the interconnection procedure was undertaken, another experimental nondimensional plot of flow rate and pressure drop was obtained for a capillary tube with half the diameter but the same length-to-diameter ratio as that shown in Fig. 33. The two curves did not exactly coincide, but a few sample calculations showed them to be sufficiently close that either could be used for the purpose at hand. This must have been merely coincidental, for most of the resistors designed by use of Fig. 33 had to be adjusted to the correct flow rate in order to obtain the desired operating characteristics of the amplifiers. No pattern could be recognized -- for some resistors the flow rate was greater than predicted, and for others it was less. Basic research is needed to find an accurate analytical method of calculating diameters and lengths for desired flow rates and pressure drops, or to determine the cause of failure of the nondimensional plot method of calculating sizes so that affecting parameters can be controlled during construction of the resistors.

As discussed in Chapter IV, previous investigations into basic design of fluid amplifiers have been primarily concerned with optimizing the efficiency of pneumatic type amplifiers. For applications to control systems on high-power hydraulic machinery, some efficiency could be sacrificed in favor of other operating characteristics. Basic design research is needed to develop liquid type amplifiers with operating characteristics of load insensitivity, high pressure and flow gains, and a high ΔP_R.

If the amplifiers were load insensitive, it would not be necessary to match the control impedance of the driven amplifier by adjusting the load on the driving amplifier successively backwards through the flow path. When such successive load matching is required, the interconnection procedure becomes much more complicated and time consuming that would otherwise be required. If all component amplifiers were load insensitive, they could all be operated at the same output load and bias flow which would guarantee that the optimum decision function, or any desired deviation from the optimum decision function, could always be accomplished. The bias flow could be used to adjust the control band width and thereby give the designer easy control of the relation between stability and switching speed.

Further research is needed in the area of stability margin and switching time. It would be very desirable for control system designers to be able to predict the operating speed of a control system by the magnitude of the stability margin used in the decision function. Further study is also needed on different methods of achieving bias flow for the purpose of adjusting the slope of the line drawn through the two switching points, for the stability margins could also be adjusted in this manner.

If an amplifier does not have a high pressure difference between reset position output pressure and set position output pressure, i.e.,

ΔP_R, the difficulty of amplifying system output signals to levels sufficient to pilot power valves is increased. Also, little adjustment of the control band width is available if ΔP_R is initially narrow.

Two other characteristics which would be desirable in fluid amplifiers are high flow and pressure gains. A high flow gain would increase the fan-out of an amplifier. That is, one amplifier could be used to drive several others. A high-pressure gain would increase the fan-in of an amplifier. That is, the number of inputs to one amplifier could be increased.

All the aforementioned desirable characteristics should be accomplished at a low power jet flow rate (Q_S). At the 30 psi supply pressure, the supply flow of the Bowles amplifiers was approximately 0.8 gpm (the supply flow decreased as the output load was increased). This volume of flow causes inefficiencies of far greater concern than those caused by low flow and pressure recoveries. If the supply flow could be decreased to approximately 0.1 gpm, complex control systems requiring many amplifiers could be operated at an insignificant power level.

If further work is done in the area of designing fluid amplifiers specifically adapted for use in hydraulic digital control systems, the turbulence amplifier should not be overlooked. Raymond Auger (1) of Fluid Logic Control Systems has developed pneumatic turbulence amplifiers that require no interconnecting fluid resistors and, therefore, no interconnection procedure. In a turbulence amplifier, the fluid jet flowing from the supply tube to the output tube with no input signal is laminar, producing a high output pressure. A small input signal flow causes the air stream to become turbulent decreasing the output pressure. It might be feasible to adapte the same theory to hydraulic turbulence amplifiers.

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VITA

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Master of Science

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