FLUIDIC TECHNOLOGY AND SOME APPLICATIONS TO THE TRAINING SITUATION

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INTRODUCTION

This paper presents a comprehensive introduction to fluidic technology state-of-the-art including some advanced concepts being investigated for future applications. The technology is then related to training devices and industrial applications.

A cataloging and discussion of each basic type of flueric device, such as the digital and analog beam deflection element, vortex amplifier, turbulence switch, impact modulator, etc., is furnished for a thorough understanding of the available building blocks and the relative merits of each type. In several cases, the electronic analog is drawn for comparison. Considerable engineering information is given on each type of device for the purpose of providing potential users with a realistic idea of the design considerations. Characteristics of the various devices are given with a discussion of the methods used for constructing more complex systems. The objective is to present those component data which are required for system design and to create a familiarity with the manipulation of that information. A critique of present vendor practice in this area is given since necessary and sufficient design data are never furnished and quite often are not even available.

One section of the paper is devoted to the discussion of using fluidics for storing and/or displaying information, both in the active and passive mode. Examples are used to show how this technique in conjunction with supporting fluidic logic can be used to monitor or position simulator servo components, plus doing vision measurement and simulation. Some computation techniques using fluidics are presented to illustrate the degree of sophistication which is being achieved. Examples presented include integrators and the method of adjusting reset rates, differentiators, square root extractors, summing, subtraction, multiplication by constants, etc. After establishing the above capabilities of fludic components and systems, additional discussion is offered pertaining to mechanization of systems for testing human performances both with and without feedback. Examples using visual and audio stimulates are used to represent what can be achieved. Automatic checkout of performances and conditions mechanized with fluidic circuits including sequencing is furnished to show feasibility in this area.

DISCUSSION

Most fluidic devices today fall into three classes based upon their operating principles. These three phenomena that are most common are:

1. Wall Attachment (Coanda effect)
2. Momentum Interaction
3. Transition Between Laminar and Turbulent Flow

The wall attachment or Coanda effect is aphenomena in which an unbounded fluid jet shows a tendency to cling to a nearby surface. Figure 1(a) illustrates a two dimensional jet issuing from a nozzle; if the jet is turbulent, it will "entrain" or "carry along" surrounding fluid, primarily by a mixing action. When a wall is placed nearby, the jet begins to evacuate the space between the wall and itself forming a low pressure region as in Figure 1(b). The pressure differential which exists across the jet causes the jet to bend towards the wall. The process is self-reinforcing until, as in Figure 1(c), the equilibrium condition is established with as much fluid recirculating from the jet into the low pressure "bubble" as is being entrained. If fluid is injected into the bubble from outside the system, the pressure in the bubble can be raised causing the jet to become disattached from the wall. Typically, a flow rate of 1 to 10% of the main jet flow will cause disattachment.

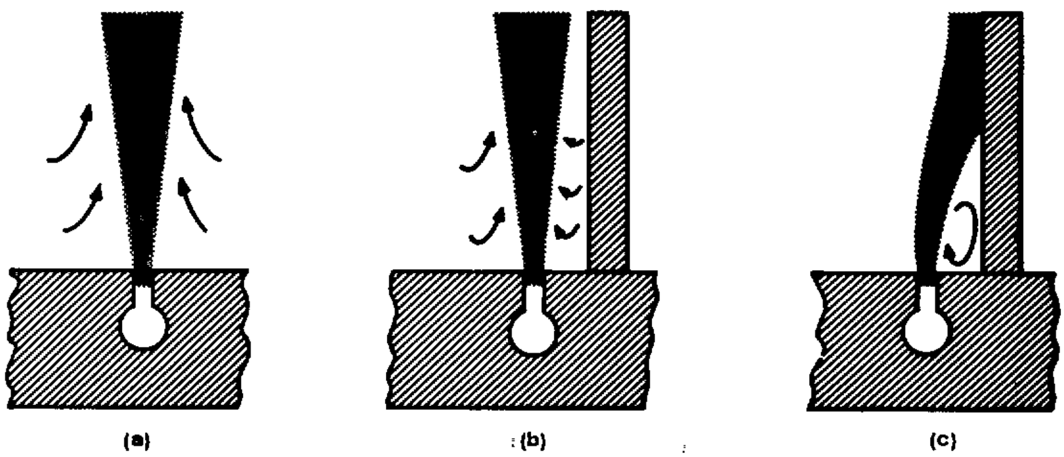


FIGURE 1

Momentum interaction devices are based on the fact that, if two moving fluids interact in such a way that they mix, the resultant motion is determined by the sum of the momentum of the components. Figure 2(a) shows a situation in which two nozzles are 90° apart. Figure 2(b) illustrates the momentum diagram; after mixing and the momentum interaction, the flow pattern appears as in Figure 2(c).

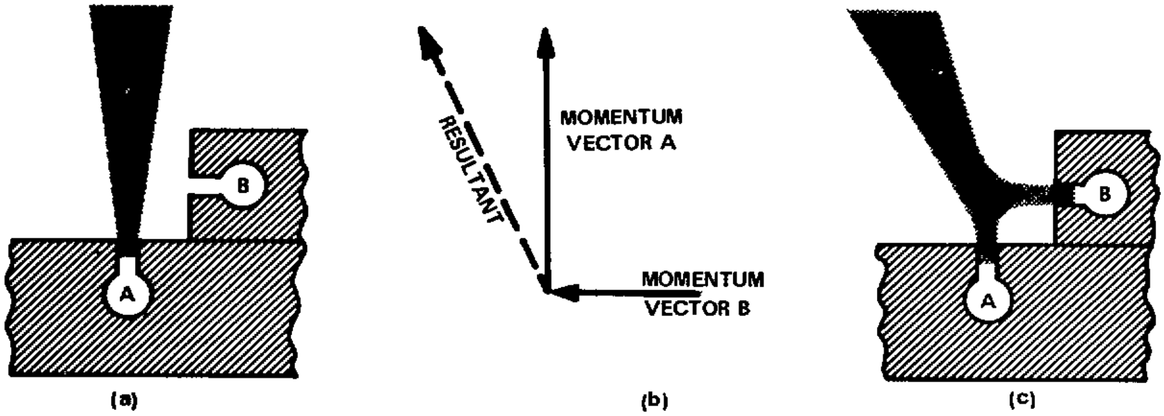


FIGURE 2

The transition of a laminar free jet to turbulent flow always takes place eventually. In Figure 3(a), a jet issues from a nozzle and, as it spreads and slows, eventually reaches a marginally stable condition and becomes turbulent. A disturbance in the surrounding media such as an acoustic wave or a transverse flow, such as shown in Figure 3(b), will cause the turbulence point to move upstream. This principle can be of use since the total pressure is much less in the turbulent region than in the laminar region.

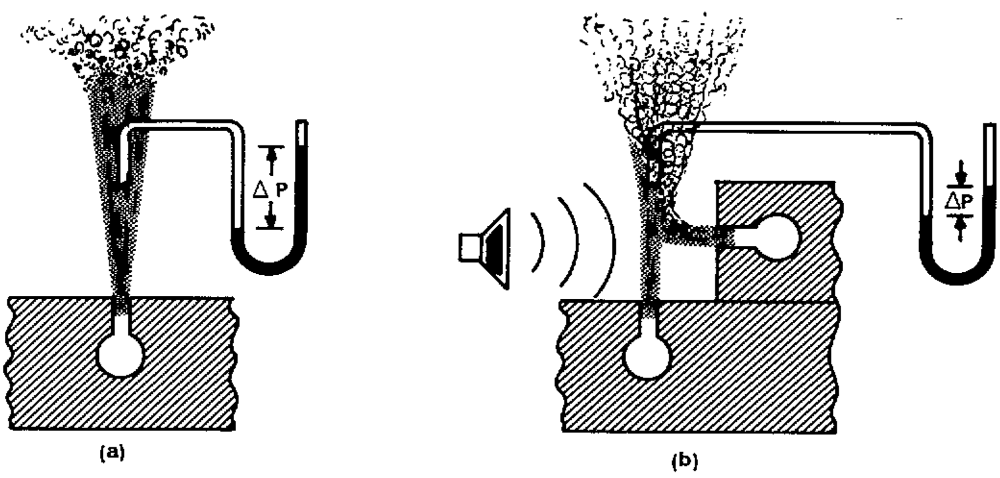


FIGURE 3

These three principles, along with slight variations, are put to work in some ingenious devices. Consider first a pure fluid, no moving part, flip-flop. Such a device is illustrated in Figure 4. A relatively high pressure supply (0.1 to 1000 psi) is provided as illustrated. The jet exits through the nozzle and attaches to one or the other of the side walls by formation of the low pressure "bubble". Assume that the power jet attaches to the right wall in Figure 4 and exists through the output leg arbitrarily assigned the value of "0" in a binary system. If a pulse of fluid is presented through the right control port, the power jet will be forced off of the right wall and will attach to the left wall. When the control pulse is removed, the jet will continue to flow through the left leg of the bistable device.

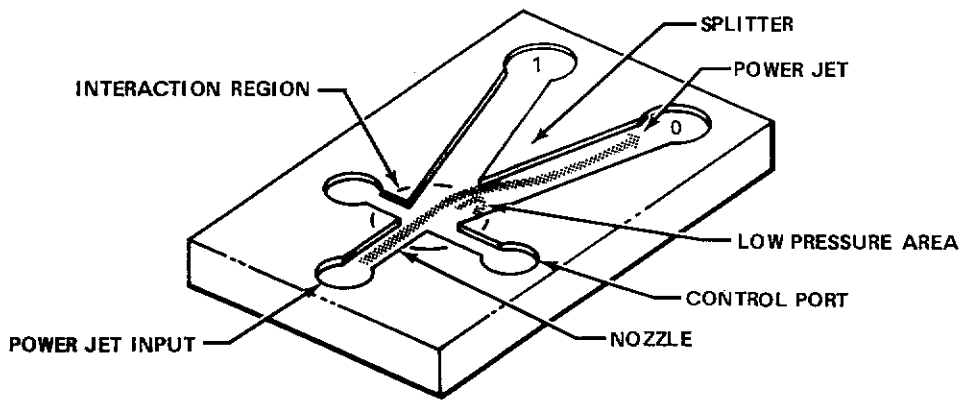


FIGURE 4

A monostable element can be built such as is illustrated in Figure 5. This is a NOR gate, and can be used to build all of the usual logic functions such as AND, OR, etc. The NOR gate is similar to the bistable element except that a portion of one of the walls has been cut away such that the low pressure bubble cannot form and the jet cannot attach to that wall. Therefore, in the device illustrated, the jet will attach to the right wall only but can be forced off the wall and down the left leg by a flow into the control port. In this case, the right leg of the device furnishes the NOR output, and the left output leg provides the OR output.

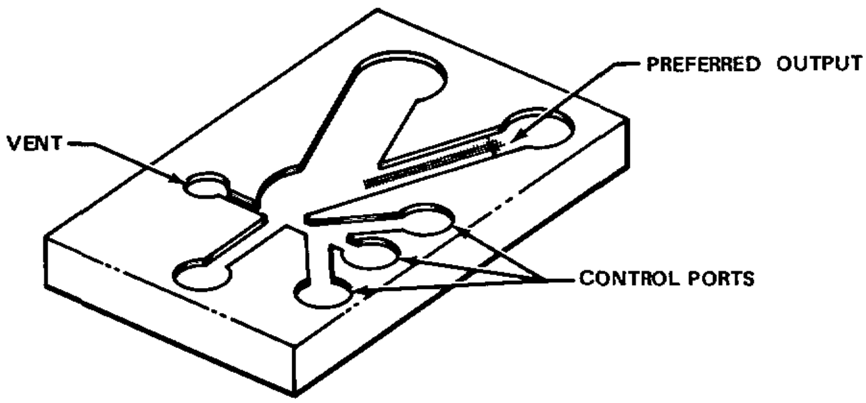


FIGURE 5

Several devices use the momentum interaction principle. Consider first of all the proportional pressure amplifier shown in Figure 6 without the top or cover plate. In practice, flow is provided in both the left and right control ports at all times. The supply jet is deflected by the difference in momentum between the right and left control ports. As the jet is deflected, more or less of the jet is "captured" by the individual output ports. The fact that the velocity profile of the jet is in the shape of the Gaussion "bell" curve introduces some non-linearities as do the effects of pressure gradients transverse to the jet axis. Nevertheless, the device can be made to perform quite accurately as a pressure amplifier with gains on the order of 5 to 10, where:

$$\text{Gain}/_{\text{pressure}} = \frac{P_{01}-P_{02}}{P_{c2}-P_{c1}} = \frac{\Delta P_{out}}{\Delta P_{in}} \qquad (1)$$

where P is pressure in pounds per square inch.

Another type of momentum device relies on angular momentum in a vortex flow field. This is called a Vortex Valve and is shown in Figure 7. In this example, the supply pressure, which can be fairly high, forms a jet which ordinarily would flow out the sink hole taking the most direct radial path through the circular cavity. When a control flow is present, the jets mix with a resultant velocity having a tangential component which causes a circulation. As the jet approaches the sink hole, its tangential velocity increases since angular momentum must be conserved. This sets up large shear forces in the fluid and a corresponding energy loss. Thus, the device effectively acts as a throttle between the supply and the output.

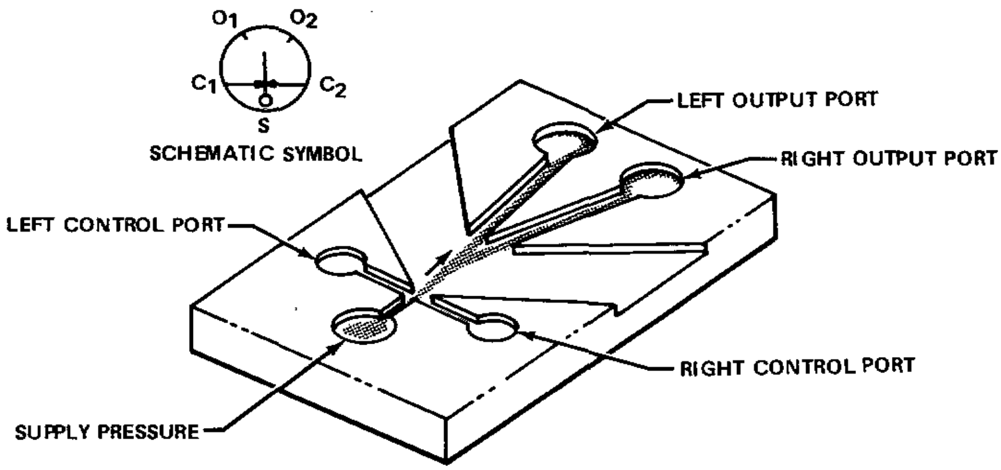


Figure 6. Jet Interaction Amplifier

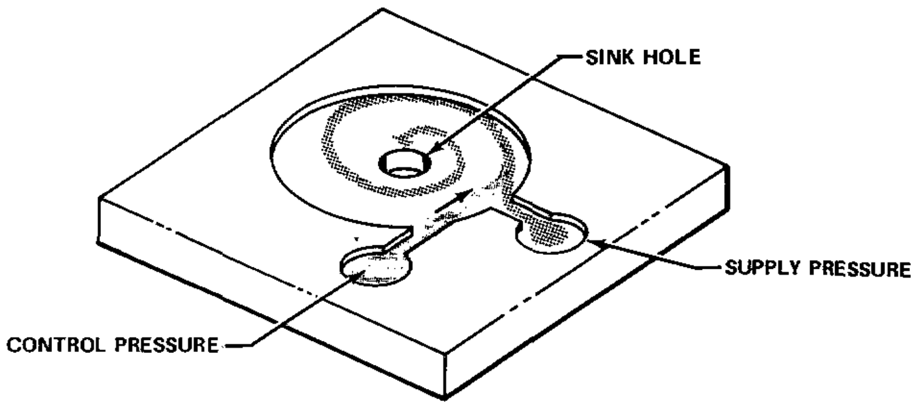


Figure 7. Vortex Valve

Still a third momentum exchange device is the impact modulator shown in Figure 8 in cross section. In operation, fluid is supplied to the ports marked Supply #1 and #2. The jets exit their nozzles and impact to a radial flow cone at some equilibrium point which is a function of the ratio of supply pressure #1 to #2. When a control flow is impressed on the device, the supply flow from Channel #1 is "pinched" down increasing the momentum flux of the left jet. This causes the point of impact to move to Supply #2. The movement of the impact point results in a change in the flow seen by the output port. It is interesting to note that this device, in contrast with the others discussed, has a positive amplification factor; that is, the output pressure, flow, and power increase with an increase in the pressure, flow, or power of the control. In practice, the difference is only important when the device is single ended as with the impact modulator or the vortex valve.

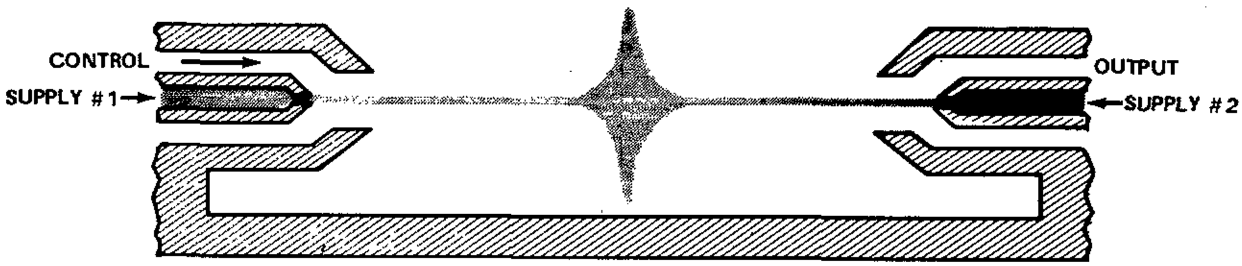


Figure 8. Impact Modulator

The last principle, of the three mentioned earlier, is utilized in the "turbulence amplifier" shown in Figure 9. In practice, the supply pressure is adjusted to provide a laminar jet which becomes turbulent downstream of the receiver entrance. When a disturbance is allowed to disrupt the calm air in which the laminar stream is submerged, the point of turbulence moves upstream in front of the receiver. When the receiver "sees" a laminar stream, the recovered pressure and/or flow is high; when the turbulence point moves in front of the receiver, the recovered pressure/flow drops. Therefore, the device acts as a sensitive switch. The disturbance of the ambient fluid can be accomplished by a low velocity transverse jet, an acoustic input, or a solid member touching the jet.

Claims of superior performance are made for each type of device. In the last analyses, the relative merits are strictly a function of the application. The wall attachment devices are reasonably easy to use. One must not exceed the fan-out capabilities. Problems sometimes result from simultaneous fan-out and fan-in situations which overtax the power capabilities of the driving amplifier. This is primarily a result of the fact that the inputs to a wall attachment device are not isolated from each other. This occasionally gives rise to circuit instabilities since waves can be reflected throughout a circuit. The turbulence amplifier has an extremely high fan-out capability and all inputs are essentially isolated. The devices are very easy to interconnect. They operate typically on very low supply pressures, less than 1 psi, as compared to the wall attachment devices which operate typically around 10 psi but anywhere between 0.2 and 2000 psi. Thus, the turbulence amplifier is a low power consumption device; it is also a lower power output device as well which can be a disadvantage. Turbulence amplifiers are also very slow in comparison to the wall attachment elements; turbulence element switch times are in the order of 5 to 10 milliseconds or 10 to 100 times slower than wall attachment amplifiers. The turbulence amplifiers are sensitive to noise but have been effectively shielded and used on locomotives and in factories.

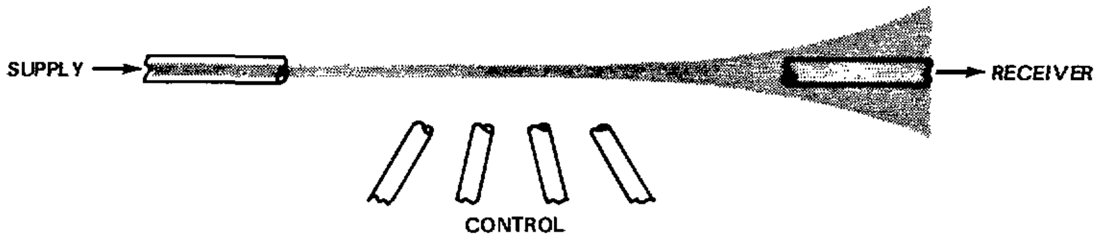


Figure 9. Turbulence Amplifier

Progress has been made in analog circuits at a rapid rate. The linearity of the devices is generally better than ±1% with techniques available to reduce that figure by more than an order of magnitude. Frequency response is as high as 1000 cps, but 300 cps is more typical for a device in a circuit. Time delays are negligible for most control systems. The vortex valve is generally slower but its speed is highly dependent on its size and therefore its power handling capability; in any case, even these devices are much faster than other power handling equipment such as servo valves, servo motors, and the like. In general, the input impedance and output impedance are about equal on all the devices except the impact modulator. This causes difficulties in staging. In addition, the quiescent pressure on the controls, as a function of supply pressure, is quite critical.

From a dynamic standpoint, the fluidic devices are actually combinations of every conceivable circuit element and, in a circuit, must be examined on a lumped parameter basis. Consider the simple circuit of Figure 10. Assuming the input signal generator has zero output impedance, we can trace through the schematic listing the elements to be considered.

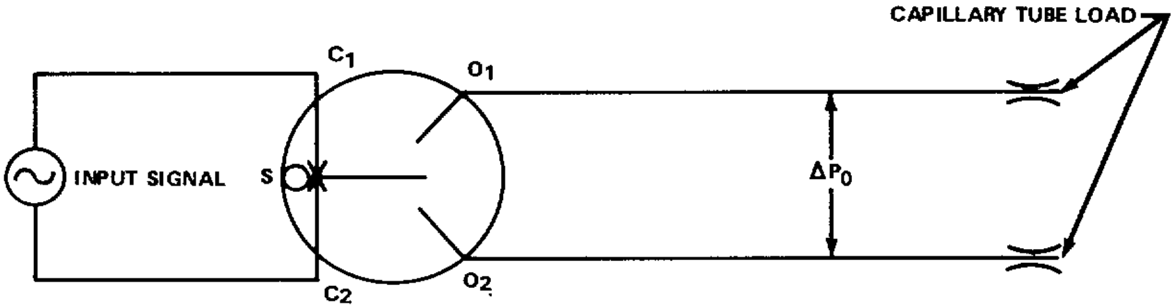


Figure 10. Amplifier Circuit

First of all the signal is fed to the amplifier through tubes that have inductance and capacitance. The control ports of the amplifier have some capacitance, a significant resistance, and some inductance. Next, there is a "gain" involved in deflecting the jet which would have the unit radians/psid. Incidently, psid is used to mean pounds per square inch differential. The signal is now confronted with a delay time dependent upon the amplifier size and jet velocity - but then time delays have been associated with other items also and have been tactfully ignored. When the deflected jet reaches the output receivers there is another "gain" associated with the slope of the jet velocity profile and the receiver width; however, the two gains and time delay can be lumped into one statement of:

$$Ke^{-st}$$

The receivers have a resistance, a capacitance and an inductance as do the tubes connecting the amplifier to the capillary load.

Let us now examine these circuit "components" in our fluidic-electronic analogy.

CAPACITANCE

A fluidic capacitor is simply a tank, but unlike the electrical capacitor, the fluid capacitor is a low pass device thus acting more like an electrical capacitor between the signal and ground. Fluid capacitance of a volume is defined as the change in the weight of fluid contained within a volume divided by the associated pressure change, or:

$$C_{fluid} = \frac{\int Q_f(t)\,dt}{\Delta P_f(t)} \qquad (2)$$

The electrical equivalent is:

$$C_{elect.} = \frac{\int I_e(t)dt}{\Delta E(t)} \tag{3}$$

For air at room temperature, the isothermal and adiabatic capacitances can be shown to be respectively:

$$C_f = 2.95x10^{-6} x \text{ volume} \quad \text{(square inches)}$$

$$C_f = 2.107x10^{-6} x \text{ volume} \quad \text{(square inches)}$$

The actual capacitance is ordinarily somewhere between these figures depending upon how much heat transfer is allowed.

INDUCTANCE

Fluid inductance in a tube is defined as the pressure change divided by the rate of change of flow or:

$$L_f = \frac{\Delta P_f(t)}{dQ_f(t)/dt} \tag{4}$$

which is analogous to the electrical relationship:

$$L_e = \frac{\Delta E(t)}{dI_e(t)/dt} \tag{5}$$

By making a few assumptions, including that the acoustic wave length is long compared to the tube length, it can be shown that the inductance of a tube is:

$$L_f = 0.002589 \frac{\text{length}}{\text{area}} \quad (sec^2/in^2) \tag{6}$$

RESISTANCE

Fluid resistance of a long narrow tube is defined as the pressure drop across the tube divided by the weight flow through it.

$$R_f = \frac{\Delta P(t)}{Q_{f(t)}} \tag{7}$$

The electrical analogy is, of course:

$$R_e = \frac{\Delta E(t)}{I_e(t)} \tag{8}$$

For the fluidic resistance of a tube to be constant, there must be no loss of energy due to turbulence. Long narrow capillary tubing will satisfy the condition necessary for laminar flow. If the flow is laminar, the resistance for air at room temperature is:

$$R_f = 2.44 \times 10^{-3} \frac{\text{length}}{(\text{diameter})^4} \quad (\text{sec/in}^2) \qquad (9)$$

If we do not have laminar flow or if the resistance element is an orifice, we have a much more complex situation and probably should drop the subject in this discussion.

Using the definitions and analogies just presented, Figure 11 shows the electrical equivalent of the amplifier circuit in Figure 10. The circuit, however, can be simplified as in Figure 12, without introducing much error. Such a circuit would typically exhibit a bandwidth of 50 to 100 Hz, using commercially available amplifiers and tube lengths of about 2 to 5 inches. Static pressure gains of up to 6.0 per amplifier are reasonable. If the amplifiers are staged in series, gains of 4.0 to 5.5 per stage are obtained with the commercial devices. When staging the amplifiers, the quiescent pressure $\left[\frac{(P_{c1}+P_{c2})}{2}\right]$ on the control ports must be adjusted properly (typically 10% of supply pressure). The pressure gain of these devices, which is low, will drop from 6.0 to 1.0 or less if the control quiescent pressure is 40% instead of the optimum 10% of supply pressure.

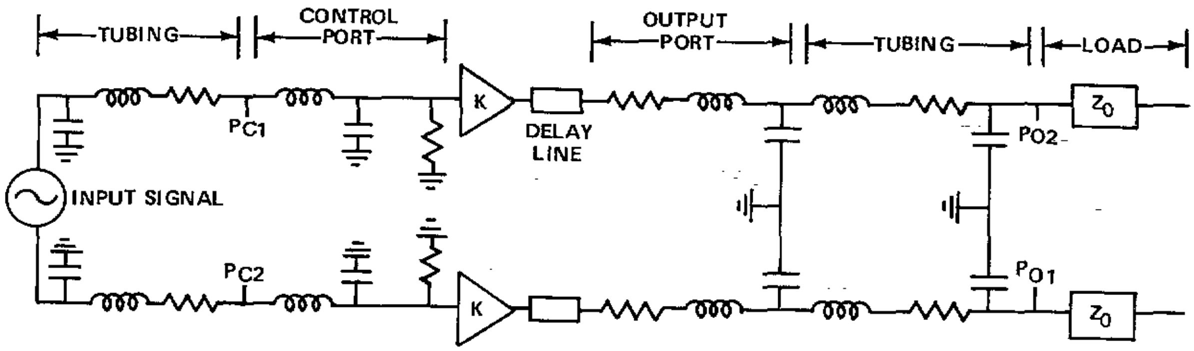


Figure 11. Equivalent Circuit

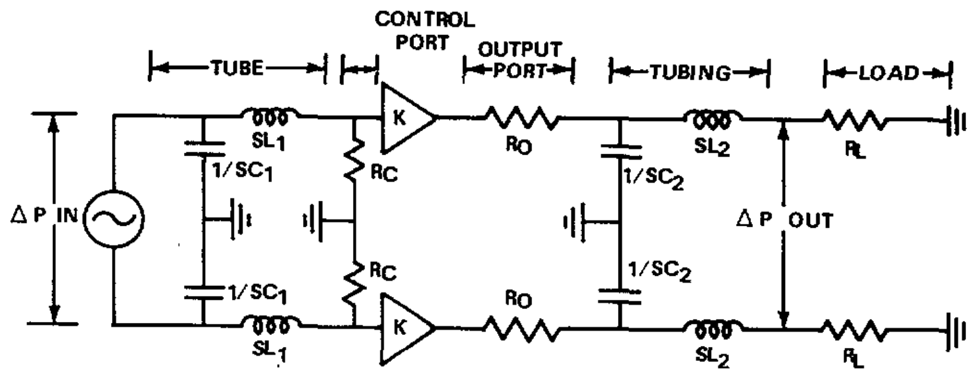


Figure 12. "Simplified" Equivalent Circuit

Unfortunately, the effect of changing circuit parameters is seldom known, in a quantitative sense, if one is relying on vendor published data. In general, the data that are published to describe commercial amplifiers and devices are sketchy or only describe the device when it is functioning under a specific, well constrained set of conditions.

Figure 13 presents a set of five curves that are necessary to describe a bistable device in a manner sufficient for subsequent circuit design. Of course, conditions could be postulated where the data in Figure 13 would not be sufficient; however, it is felt that these circumstances are rare enough to be treated as special cases. Curve Number 1 is a graphical representation of the output impedance, Curve 2 is the input impedance; it is interesting to note that the device exhibits a significant change in admittance before and after the switch. Curve 3 is a plot of the cross coupling between output load and switch point. This information is rarely given but often has a significant effect on circuit operation. Curve 4 gives the amount of "spillover" from one output leg to the other which will result from loading; this is generally small and could probably be expressed as being less than some number. The plot of Curve 5 is the power consumption curve.

Figure 14 presents similar charts for a typical beam deflection pressure amplifier operating on the momentum exchange principle such as has been discussed. Curve 1 is unique so far in this discussion and presents the effect on pressure gain, which is the usual figure of merit, of various input quiescent pressures which is analogous to grid bias on an electron tube. Generally, manufacturer's instructions simply give a desired quiescent as a percent of supply pressure (indicated by the dotted line). *More often than not, it is not convenient to operate precisely* at this point; however, the effect of off optimum conditions is not specified. Likewise, output quiescent is a function of load on the output due to the relatively high output impedance of the fluidic devices. The

BISTABLE ELEMENT CHARACTERISTICS

1. OUTPUT FLOW VS OUTPUT PRESSURE (FOR VARIOUS SUPPLY PRESSURES)
2. CONTROL FLOW VS CONTROL PRESSURE (BEFORE AND AFTER SWITCHING, FOR VARIOUS SUPPLY PRESSURES)
3. CONTROL PRESSURE AT SWITCHING VS OUTPUT LOAD (AT VARIOUS SUPPLY PRESSURES)
4. "OFF" LEG FLOW VS "ON" LEG LOAD (AT VARIOUS SUPPLY PRESSURES)
5. SUPPLY FLOW VS SUPPLY PRESSURES

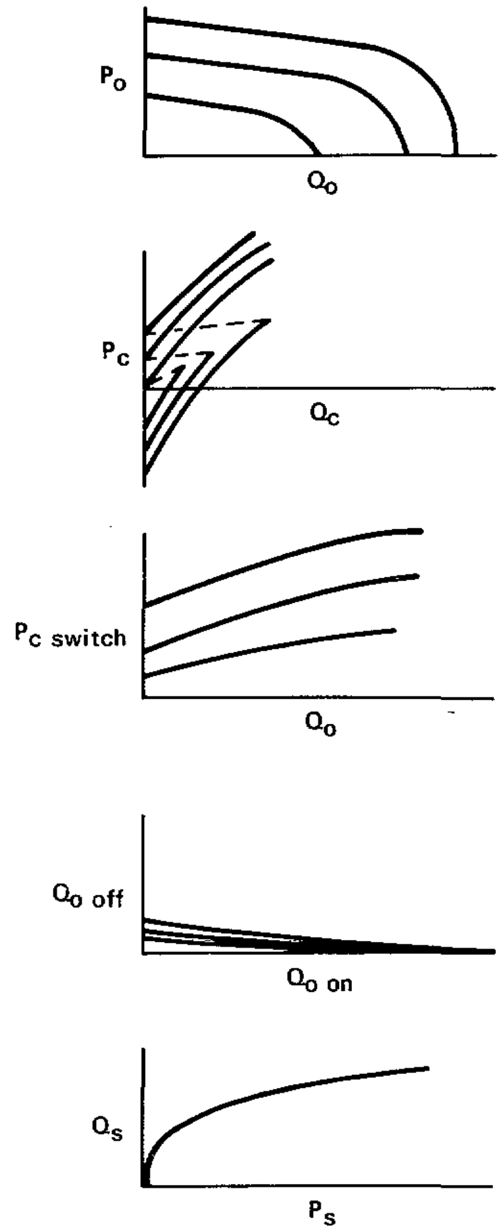
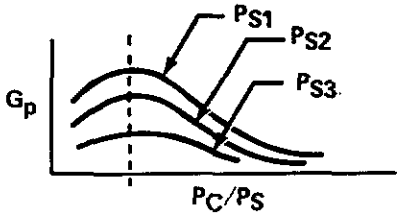


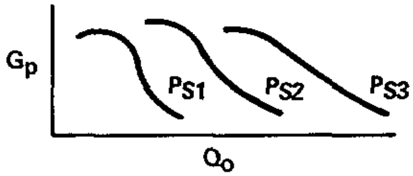
Figure 13.

PROPORTIONAL ELEMENT TESTS CHARACTERISTICS

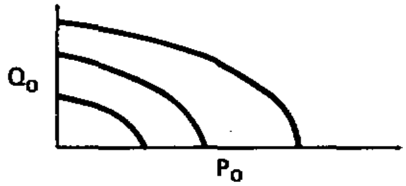
1. PRESSURE GAIN VS CONTROL QUIESCENT PRESSURE (AT FIXED LOAD OF ONE SIMILAR ELEMENT AT VARIOUS SUPPLY PRESSURES)



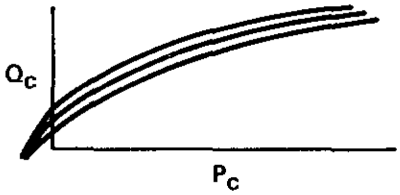
2. PRESSURE GAIN VS OUTPUT FLOW (AT OPTIMUM CONTROL QUIESCENT FOR VARIOUS SUPPLY PRESSURES).



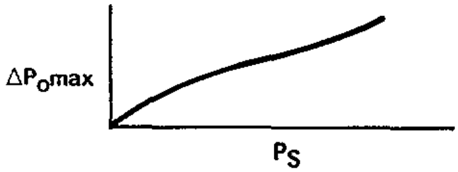
3. OUTPUT FLOW VS OUTPUT PRESSURE (FOR VARIOUS SUPPLY PRESSURES).



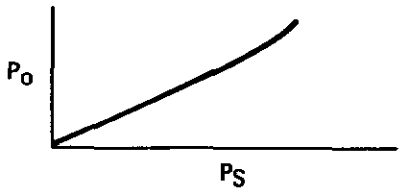
4. CONTROL FLOW VS CONTROL PRESSURE (FOR VARIOUS SUPPLY PRESSURES)



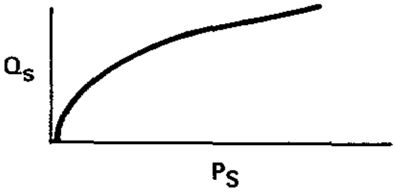
5. OUTPUT RANGE VS SUPPLY PRESSURE (OUTPUT DIFFERENTIAL PRESSURE AT SATURATION)

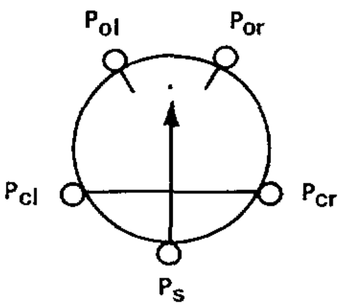


6. OUTPUT QUIESCENT VS SUPPLY PRESSURE (AT LOAD OF 1 SIMILAR ELEMENT)



7. SUPPLY FLOW VS SUPPLY PRESSURE.





$$\overline{P}_o = \frac{P_{ol} + P_{or}}{2}$$

$$\Delta P_o = P_{ol} - P_{or}$$

$$\overline{P}_c = \frac{P_{cl} + P_{cr}}{2}$$

$$\Delta P_c = P_{cl} - P_{cr}$$

$$G_p = \Delta P_o / \Delta P_c$$

P_o = OUTPUT PRESSURE
P_s = SUPPLY PRESSURE
P_c = CONTROL PRESSURE
$\overline{P}$ = QUIESCENT PRESSURE
ΔP = PRESSURE DIFFERENCE
G_p = PRESSURE GAIN

total range to saturation is also affected. Curves 2, 5, and 6 quantitatively describe these effects.

The use of these curves in circuit design is described in Figure 15 for the example of staging amplifiers for maximum pressure gain. At McDonnell Douglas, this precedure is used to stage five active amplifiers into one package with a resultant gain of approximately 15,000 to one. This package of five amplifiers is used as an operational amplifier and can be programmed in the same manner as an electronic analog computer. Some additional benefits accrue in fluidics from the operational amplifier approach since linearity is improved by reducing it to a function of the "tracking" of input and feedback resistors. This also improves the temperature insensitivity since the operation is dependent on a ratio of two values rather than their absolute value.

Figure 16 illustrates the characteristics of the vortex amplifier. Note that for control pressures less than the supply pressure, the output pressure is equal to the supply pressure indicating very little loss through the device. When the control pressure rises above the supply pressure, control flow begins to enter the vortex chamber (which was essentially at supply pressure). At this point, the throttling action of the device begins and the output flow is "turned down" while the output pressure is likewise reduced. At saturation or maximum throttling, the output flow consists almost entirely of control flow. Notice also that the gain of these devices is high, typically 100 or more. One of the difficulties is that the control pressure level must be above the level of the controlled pressure. The throttling action has caused the vortex amplifier to be termed a "vortex valve".

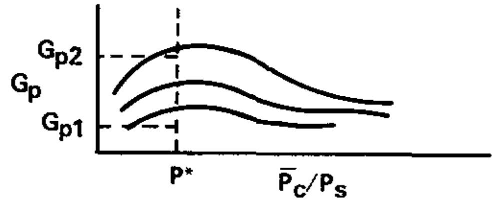
The impact modulator performs in a manner very similar to the beam deflection amplifiers; however, the input impedance is typically much higher making the device a much easier one to use in a circuit. Conversely, the elements are much more difficult to fabricate and are very sensitive to geometric imperfections and pressure variations. Furthermore, they do not lend themselves to integrated circuits, wherein the capacitances and time delays of interconnecting tubing can be minimized.

In instances where the output of a fluidic system is going to be put into a display it is desirable to use a fluidic display, that is, a display which minimizes the use of mechanical moving parts. In addition, it is very desirable that this display work directly from the fluidic logic eliminating additional power sources or interface devices.

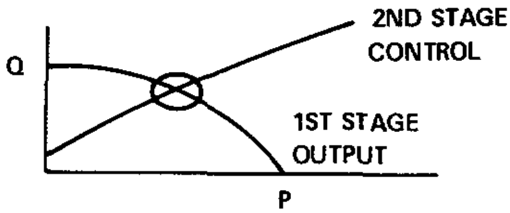
As the output of a fluidic is a flow and a pressure, conventional flow and pressure measuring devices such as the rotameter, liquid manometer, and bourdon tube may be used as fluidic displays. Of these, the liquid manometer is the most versatile as it can be used as either a digital or an analog display, and is thus the most desirable. When used as an analog display, a calibrated scale is placed beside or behind the manometer tube. The height of the liquid in the tube then gives the desired readout.

GIVEN $\bar{P}_{c1}$

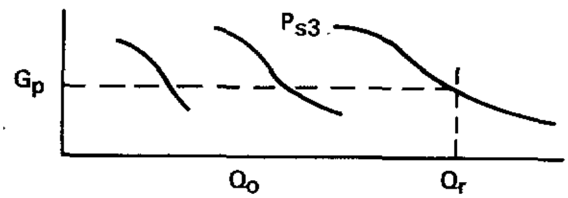
1. SET 1ST STAGE P_{s1} TO SATISFY:
   $\bar{P}_c/P_{s1} = P^*$



2. SUPERIMPOSE CURVES 3 AND 4 (FIGURE 4) TO DEFINE OPERATING POINT OF 1ST AND 2ND STAGE INTERFACE THUS DEFINING:
   $\bar{P}_{o1} = \bar{P}_{c2}$



3. SET P_{s2} TO SATISFY:
   $\bar{P}_{c2}/P_{s2} = P^*$
4. REPEAT PROCEDURE FOR 3RD STAGE
5. GAIN OF 1ST AND 2ND STAGE ARE DETERMINED FROM CURVE #1 TO BE G_{p1} AND G_{p2}.
6. GAIN OF 3RD STAGE IS DETERMINED FROM G_p VS OUTPUT FLOW, GIVEN CHARACTERISTICS OF LOAD, R_o.



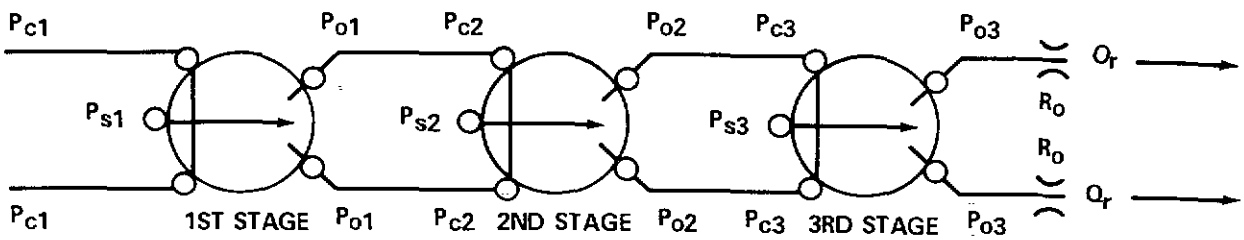


Figure 15. Staging of Proportional Amplifiers

1. OUTPUT FLOW VS. CONTROL PRESSURE FOR VARIOUS SUPPLY PRESSURES.

2. OUTPUT PRESSURE VS. CONTROL PRESSURE FOR VARIOUS SUPPLY PRESSURES.

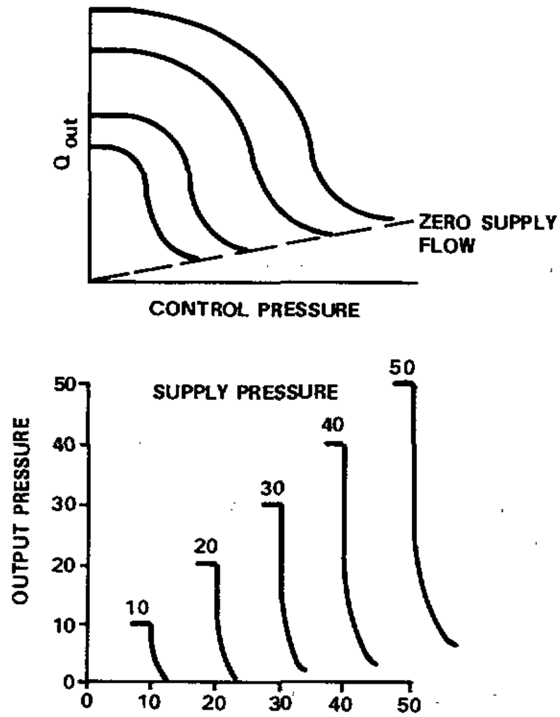


Figure 16. Vortex Amplifier Characteristics

See Figure 17. When used in the digital mode, one or a series of viewing windows are placed in front of the tube. In this condition, the operator either sees or does not see the liquid.

An interesting extension of the manometer display uses the manometer tube filled with immiscrible fluids of different colors and specific gravities. Once again a viewing window is supplied through which the operator will see one or more colors. In the example shown in Figure 17 (d) three colors; red, amber, and green, have been chosen. If the pressure exceeds a certain level, the operator will see a red indication after an amber warning.

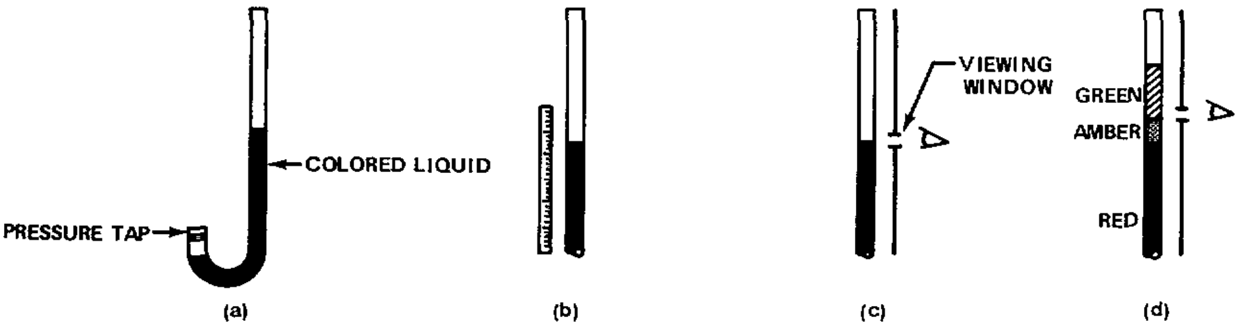


Figure 17.

A fluidic device which is extremely versatile is the passive - liquid bead - bistable element. The advantages inherent in this device, shown in Figure 18, are that it can not only double as a fluidic logic device and a display at the same time, but also that its memory is non-destructable, that is, it will retain its last position even when the power is turned off.

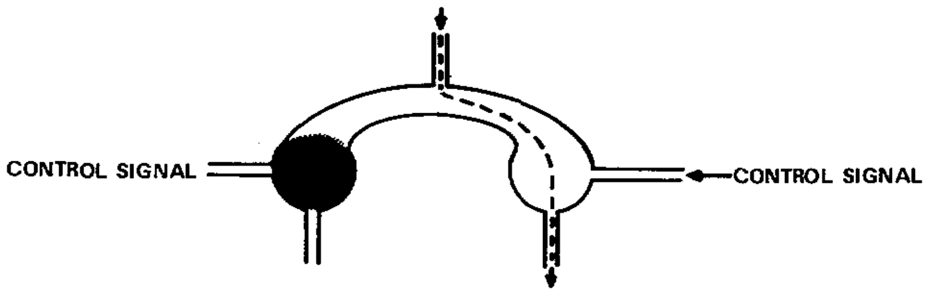


Figure 18

In operation, a drop of fluid in the system will tend towards a spherical shape due to surface tension forces. When a pneumatic signal is applied, the drop of fluid will be forced into the other cavity where it again assumes its spherical shape. The location of the sphere of fluid represents the visual display.

A fluidic display presently under development makes use of the property of certain chemicals called thermochromics to change color with changes in temperature. In general, these chemicals change from one color to another with a temperature change as small as one degree centigrade. In practice, the chemical is usually coated on a glass screen and kept in its warm state. When cool air passing through a fluidic element impinges on the display surface an area is cooled yielding a color change. The warmed and cooled air necessary to operate this device could be obtained through a Hilsch tube eliminating the need for warming and/or cooling devices external to the fluidic system.

Some display devices which are presently on the market contain moving mechanical parts. Typical of all of these is the brightly colored piston in a long tube. See Figure 19. When pressure is applied to the base of the piston, it pushes the piston forward indicating an "on" signal, a small spring provides the return to "off" position when the fluidic signal is removed.

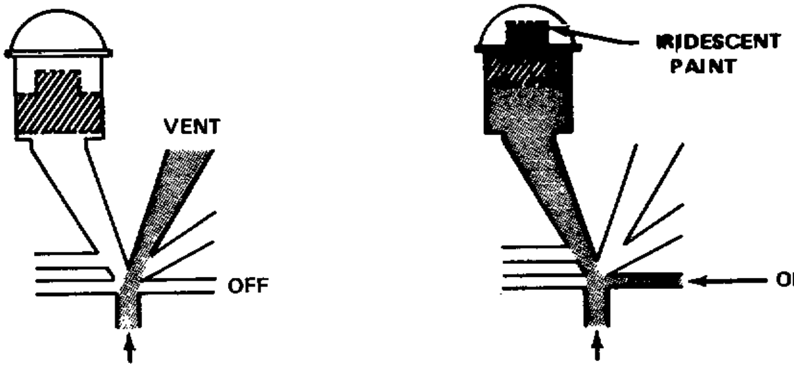


Figure 19.

Indicating devices which make use of some of the other senses are also being developed. A turbulent jet stream flowing past the input port of a proportional high gain fluidic amplifier whose output port is attached to a megaphone gives a loud audible sound capable of being used as a warning signal.

Some examples of the circuits that can be implemented using fluidic techniques can be discussed with the background now established. It should be emphasized, nevertheless, that there are many devices having unique and rather specialized characteristics that have not been discussed. Often these components can be utilized to accomplish the interfaces that are necessary.

Computation and analysis of fluidic circuits is performed using the classical system analysis methods established by the electrical/electronic technologies. To use this technique, a series of analogies have been defined so that an equivalent linear circuit can be drawn which represents the fluidic circuit to be studied. The three circuit elements; capacitance, inductance, and resistance were discussed earlier including the simplified design parameters with the associated coefficients.

In actual practice several conditions arise which require special consideration. The only way to hold the capacitance relatively constant is to take all precautions to assure small tank pressure variations and that the tank has rigid walls. Under these conditions capacitance can be calcualted for a given tank size and operating pressure or a tank can be sized to provide a specific capacitance using the following relationship which assumes negligible thermal transfers:

$$C_f = \frac{V}{nP_t} \left(\frac{in^5}{lb} \right) \qquad (10)$$

where P_t = Absolute tank pressure (lb/in^2)

V = Volume of tank (in^3)

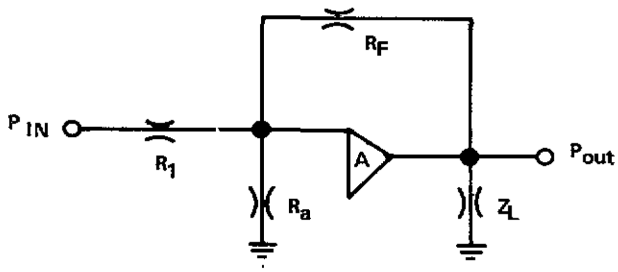
n = Polytropic exponent (dimensionless)

Calculating values for resistance (capulary tube) is at best a close approximation and the most accurate is:

$$R_f = \frac{8\mu_v 1}{\pi\gamma r_o^4} \qquad (11)$$

One important condition which has not been taken into consideration in equation 11, and it is impractical to do so, is the effect the down stream pressure has on resistance values. Since there is a change in density which adds 1-2% variations in resistance, it is mandatory to empirically size resistors for each application.

Several examples of computation will be presented based on the use of a fluidic operational amplifier. The operational amplifier is normally made up by staging several proportional amplifiers for very high open loop gain and then add input and feedback resistors. Ideally the operational amplifier satisfies the following conditions:



$$\text{GAIN} = \frac{P_{out}}{P_{in}} \simeq \frac{R_F}{R_1}$$

IF, $A = \infty$ AND $Z_L = \infty$

WHERE R_a = OPEN LOOP INPUT IMPEDANCE

Figure 20. Operational Amplifier

Since the gain and load are never infinite the relationship

$$\text{Gain} = \frac{R_F}{R_1}, \text{ where } R_1 = \frac{\text{Max } \Delta P_{in}}{\text{Quiescent}} \times R_a \qquad (12)$$

is an approximation which can be used to analytically size resistors for a given gain. To achieve a specific gain the resistors are sized empirically using data from the approximation.

To demonstrate the methods used to design a particular function generator, let us consider a fluidic integrator. Integration over a specific band can be performed by a passive lag circuit on the output of an amplifier but has many limitations, and cannot be used for this function. The true integrator in electronics replaces the feedback resistor of an amplifier with a capacitance which produces a transfer function:

$$\frac{E_o}{E_{in}} = \frac{1}{\tau s} \qquad (13)$$

The flueric capacitor has one terminal grounded internally and cannot be used in point-to-point networks. An electronic integrator which uses no point-to-point capacitor is the bootstrap integrator. The figure below is a schematic of a flueric bootstrap integrator.

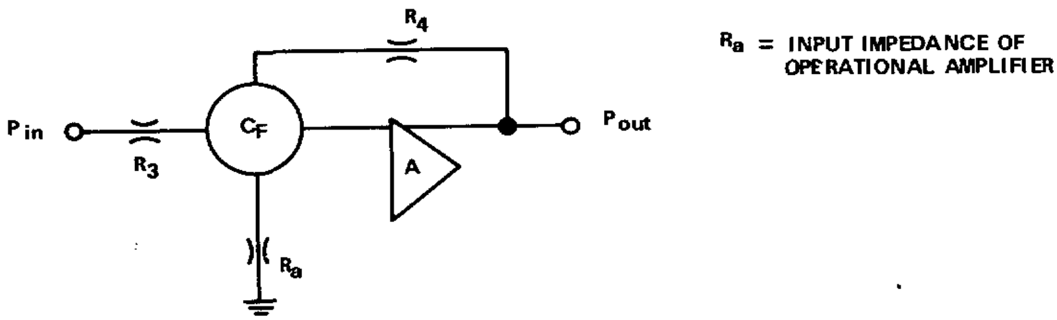


Figure 21. Fluidic Integrator

Summing flows into and out of the tank volume produces the following pressure relation:

$$\frac{P_{out}}{P_{in}} = \frac{1}{\dfrac{R_3 C_F(s)}{A} + \dfrac{1}{A}\left[1 + \dfrac{R_3}{R_4} + \dfrac{R_3}{R_a}\right] - \dfrac{R_3}{R_4}} \qquad (14)$$

which says this circuit will be a true integrator if the second and third terms of the right hand denominator are equal which would produce:

$$\frac{P_{out}}{P_{in}} = \frac{A}{R_3 C_F (s)} \tag{15}$$

At this point it is convenient to select a value for A which will simplify the solution of:

$$\frac{1}{A}\left[1 + \frac{R_3}{R_4} + \frac{R_3}{R_a}\right] = \frac{R_3}{R_4} \tag{16}$$

Let us assume A = 4 since we can make an operational amplifier with any gain as discussed earlier. When this value for A is substituted into the above equation,

$$\frac{1}{4}\left[1 + \frac{R_3}{R_4} + \frac{R_3}{R_a}\right] = \frac{R_3}{R_4} \tag{17}$$

it is found that it can be satisfied by,

$$R_3 = R_4 = 2R_a \tag{18}$$

At this point it is necessary to size the volume for a value of C_F which will produce the desired reset rate (break frequency).

$$\frac{1}{\tau} = I = \text{reset rate} \tag{19}$$

From

$$\frac{P_{out}}{P_{in}} = \frac{1}{\frac{R_3 C_F (s)}{A}} = \frac{1}{\tau (s)}, \quad I = \frac{A}{R_3 C_F} \quad (20) \tag{20}$$

therefore

$$C_F = \frac{A}{R_3 I} \quad \text{but} \quad C_F = \frac{\text{Volume}}{\text{Absolute Signal Level}} \tag{21}$$

or

$$\text{Volume} = \frac{A \text{ xAbsolute Signal Level}}{R_3 \text{ x } I} \tag{22}$$

In summarizing the integrator design technique, the design outline discussed here produces a very good approximation, but some empirical adjustments will certainly be necessary. The figures below show some typical examples of the trends when the components are not exactly as predicted.

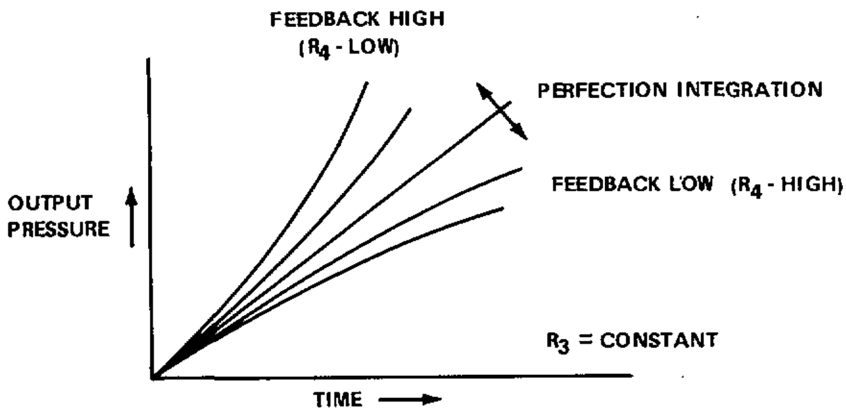


Figure 22. Effect of Feedback Resistor on Response to Step Input

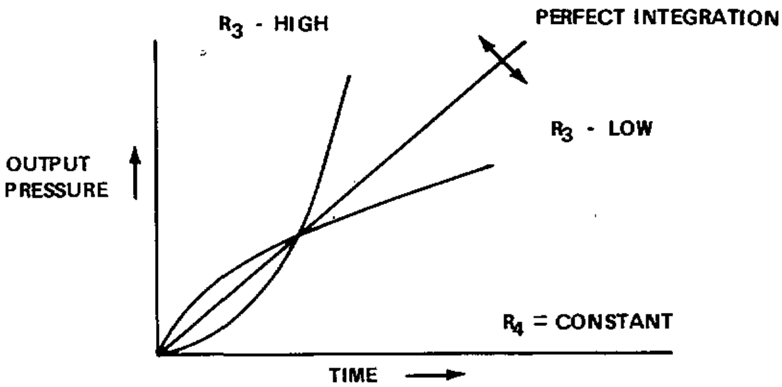


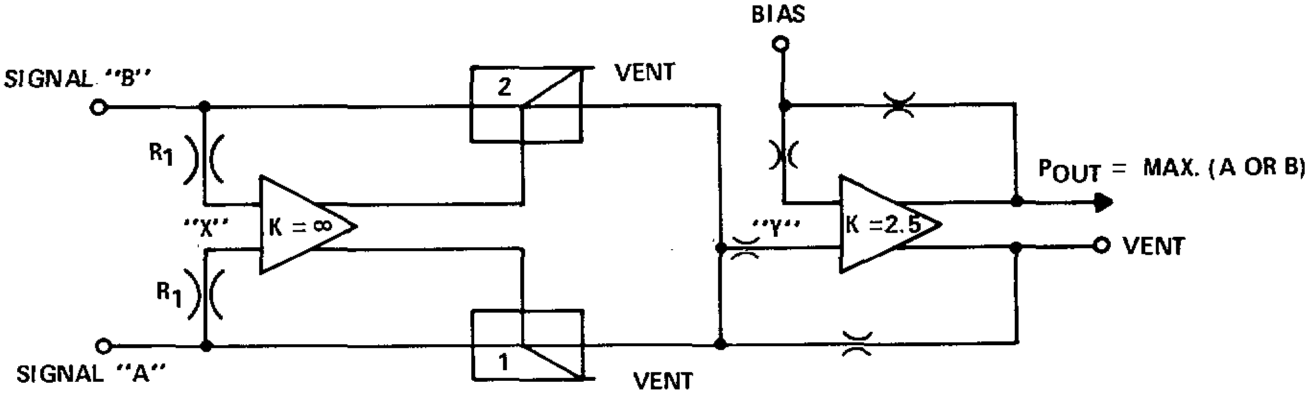
Figure 23. Effect of Input Resistor on Response to Step Input

Other factors enter into the performance of an integrator in addition to the two shown by curves and include shifts in gain etc. It is possible though, to produce flueric integrators with good characteristics such as hold capability, stability, and linearity.

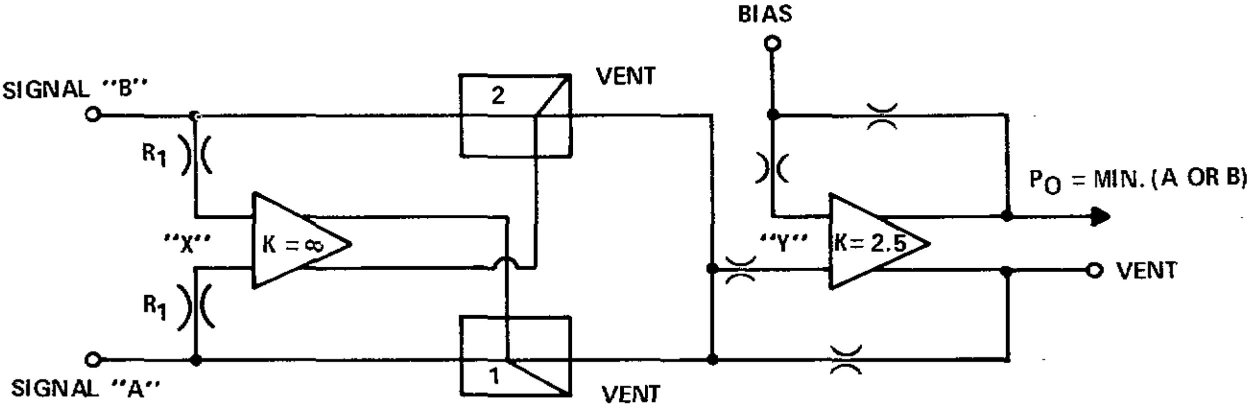
Some additional function generators which have been mechanized using the fluidic technology are; differentiator, square root extractor, proportional plus integral controller, minimum/maximum signal detectors, etc. A brief discussion of these devices is presented to demonstrate the methodology.

MINIMUM/MAXIMUM SIGNAL DETECTOR

Figure 24 is a schematic of the circuitry required to mechanize a minimum or maximum signal detector.



A. MAXIMUM SIGNAL DETECTOR



B. MINIMUM SIGNAL DETECTOR

Figure 24. Minimum/Maximum Signal Detector Circuitry

The inputs to these devices are designated signals "A" and "B"; the object is to differentiate between the two and in one case reproduce the maximum signal and in the other reproduce the minimum signal. All of the circuitry is accomplished in passive network modules and couples two computing components to achieve the desired function. The first component "x" in both circuits is a high open loop gain amplifier which operates as a Schmitt trigger. Resistor R is sized using equation (12) and turns out to be approximately ten times greater than the supply nozzle of the passive NOR. Computing component "Y" is an operational amplifier with feedback whose gain is set as a function of the recovery of the passive NOR's.

Both components operate as follows:

A = B; P_o (quiescent) of "x" 9 psig, the passive NOR is switched from its preferred leg with $P_c < 10\% P_s$, no signals at the left side of "y", therefore bias drives output to vent. so that P_o of "y" = 0.

A > B; Element "x" is saturated to the right permitting element #1 on the max. detector and #2 on the min. detector to switch back to the preferred leg, thereby allowing approximately 40% of A to appear at the "y" component of the max. detector or 40% of B to appear at component "Y" of the min. detector where these signals are amplified 2.5 times to reproduce the desired signals.

B > A; Same as A > B except the signals are reversed.

The gain of 2.5 for the computing components "y" is the first approximation and should be sized using the technique discussed in operational amplifier deisgn once the magnitudes of the NOR outputs are established.

The outstanding feature of this particular circuit is the fact that no overshoot can occur yet very small differences can be detected. Total response of this component is the combined switching time of three elements plus transport lag or approximately one millisecond maximum.

SQUARE ROOT EXTRACTOR

An extractor has been produced which provides $P_o = k\sqrt{P_{in}}$ which sums a linear function with a nonlinear function. For this discussion, Figure 25 is a schematic of the circuit to be used to produce this function.

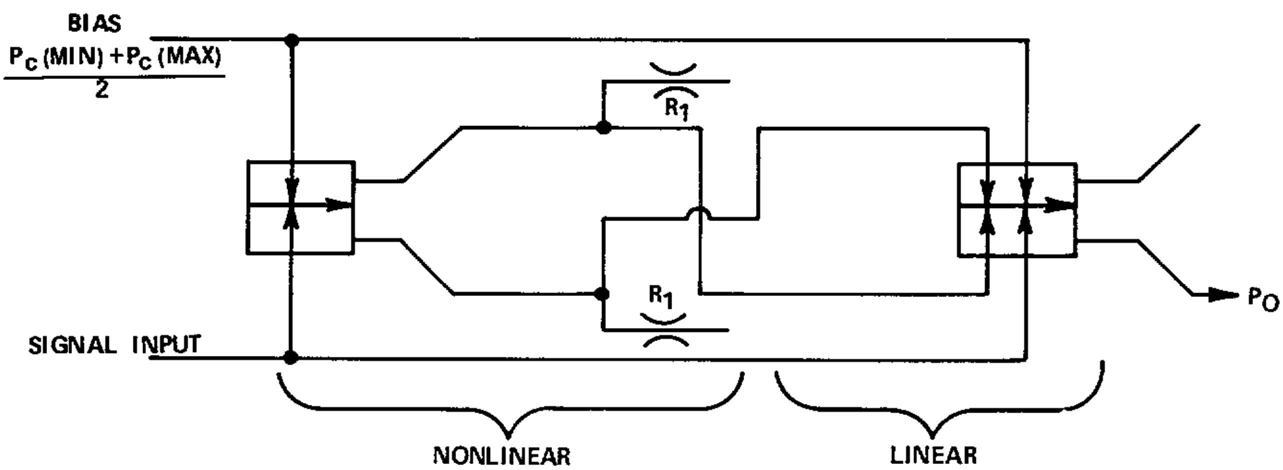


Figure 25. Square Root Extractor

Utilizing the proper biasing, it is assumed this circuit can be made to operate single-sided to produce $P_o = k\sqrt{P_{in}}$ where k can be eliminated with an operational amplifier. The components utilized are two computing components, the first loaded excessively by R_1 so that it operates in its *nonlinear range, and the second component operating in its linear range.* Figure 26 is an example of the function produced by this function generator.

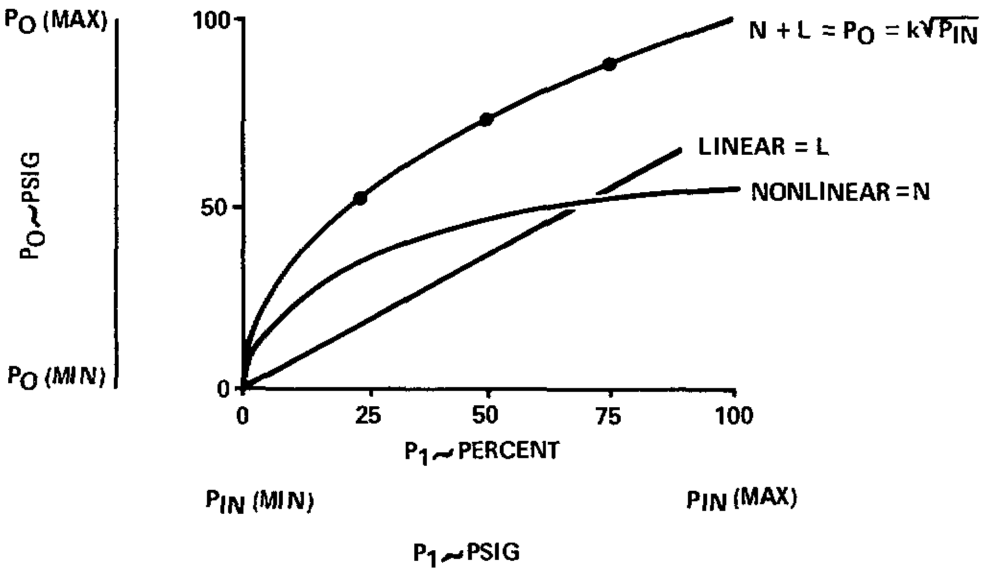


Figure 26. Output vs. Input for Square Root Extractor

PROPORTIONAL-PLUS-INTEGRAL

This function can be achieved by combining the output of a nominal gain computing component with the output of an integrating computing component in a summing component. Both computing components receive identical input signals and perform the computation as shown in Figure 27.

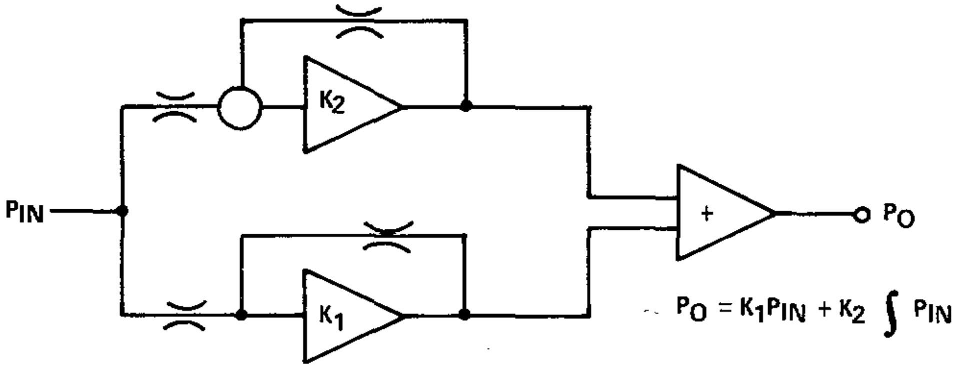


Figure 27.

Combining these functions into one computing component furnishes a linear computation with the capability of having high proportional gain while maintaining stability. This combination also features no steady state error and increasing control with continuous error at the input. In addition, the response of the combined unit is considerably better than pure proportional with all of its advantages. Equation (26) represents the operation of the system shown in the block diagram (Figure 27).

$$P_{out} = K_1 P_{in} + K_2 \int P_{in} \qquad (23)$$

where K_2 should be adjusted for the following:

$$K_2 = \frac{K_1}{\tau_1} = \frac{\text{Controller Sensitivity}}{\text{Integral Time}} \qquad (24)$$

thus producing the relationship

$$P_{out} = K_1 \left[1 + \frac{1}{\tau_1 (s)} \right] P_{in} \qquad (25)$$

The character of the response depends upon the ratio of controller sensitivity and integral time and is increasingly improved if large controller sensitivity and large integral time are used.

SERVO-MECHANISM

The function of a control system is to maintain a desired value of a quantity or condition by measuring the existing value, comparing it to the desired value, and employing the difference to initiate action for reducing this difference. A simple control system consists of three parts: (a) the quantity being controlled, (b) the controller, and (c) the feedback sensor. Figure 28 shows a simple fluidic servo control system for maintaining the position of an arm. In this system, the quantity being controlled is the position of the arm, the control actuator is the air cylinder, and the sensor is the fluidic back pressure sensor. The operation of this system is as follows. The servo system is initially set up such that with the arm in its desired position, the pressure in the fluidic back-pressure sensor maintains the cylinder at its proper extension. If the arm should move upward, the pressure in the sensor would decrease causing the cylinder to retract thus bringing the arm back to its desired position; similarly, if the arm moves downward, the pressure in the sensor increases, causing the cylinder to raise the arm.

In many applications, it is necessary for human beings to monitor a control system or even be a part of that control system. For instance, if the arm shown in Figure 28 were part of a pilot trainer simulator, the reference pressure could be replaced by a command input pressure. This command input pressure could be an operational signal which comes about through movement of the stick. The pilot trainee then becomes part of the system, receiving feedback signals visually through the position monitor and adjusting the stick position to gain a desired reading.

The fluidic proportional amplifier shown in Figure 28 represents the *simplest type of analog control possible and is shown mainly for reference* purposes. The fluidic controller would in most real applications contain a more sophisticated circuit to produce a function such as a differential, proportional plus integral, minimum-maximum, or any other control mode required to obtain the desired output.

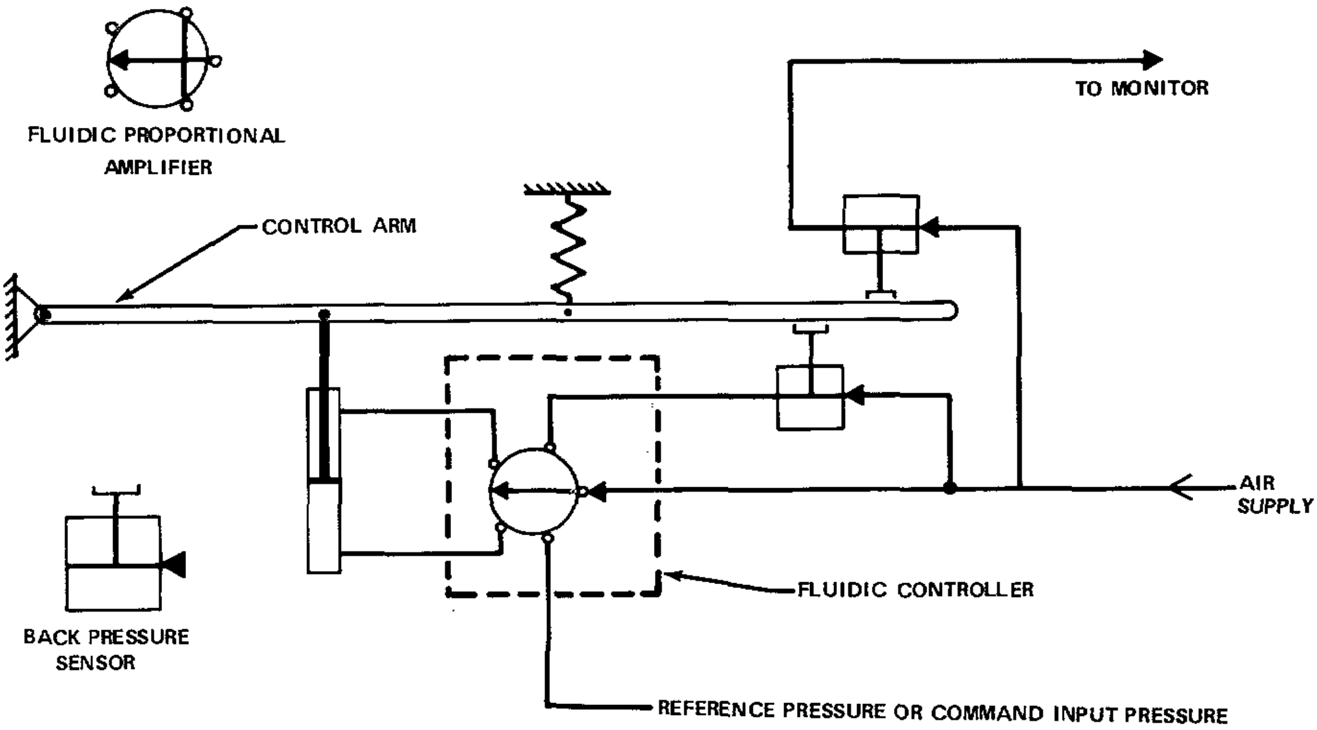


Figure 28. Proportional Controller

To consider any system for testing human performances, it is necessary that the system be as fast or faster than the person to be evaluated. Singular fluidic elements can be made to perform in 50 microseconds with negligible transport delays. The time and delay are direct functions of the size and geometry of the design. In 1957, McRuer and Krendel[1] provided a very general and useful form of the human transfer function. It is given as

$$G_h(s) = K \frac{(1 + T_a s)e^{-d\,s}}{(1 + T_L s)\,(1 + T_n s)} \qquad (26)$$

where d represents the operator's transportation lag, T_a represents the operator's anticipation time constant, T_L represents the operator's error-smoothing lag time constant, and T_n represents the operator's short neuromuscular delay. The gain K, and the time constants T_a and T_L are usually considered to be variable according to the control task being performed. The transportation lag d and the time constant T_n are generally assumed to be fixed per operator, but they are variable among operators within certain bounds. This transfer function has met with reasonable success in closed-loop tracking tasks utilizing compensatory displays. Representative values for the elements in the above equation are as follows:[2]

d = 0.2 sec ±20%
T_a = 0 to 2.5 sec (variable)
T_L = 0 to 20 sec (variable)
T_n = 0.1 sec ±20%
K = 1 to 100 (variable)

Analysis of these values indicates that the human transfer function is variable over a wide range and exhibits the characteristics of adaptivity.

From the above, it is obvious that fluidic controls and circuitry are capable, that is, fast enough to perform tests on the human machine. Any simulator or testing device which requires a response on the part of the individual, must consider the human controller functions. A block diagram including the human element is shown in Figure 29.

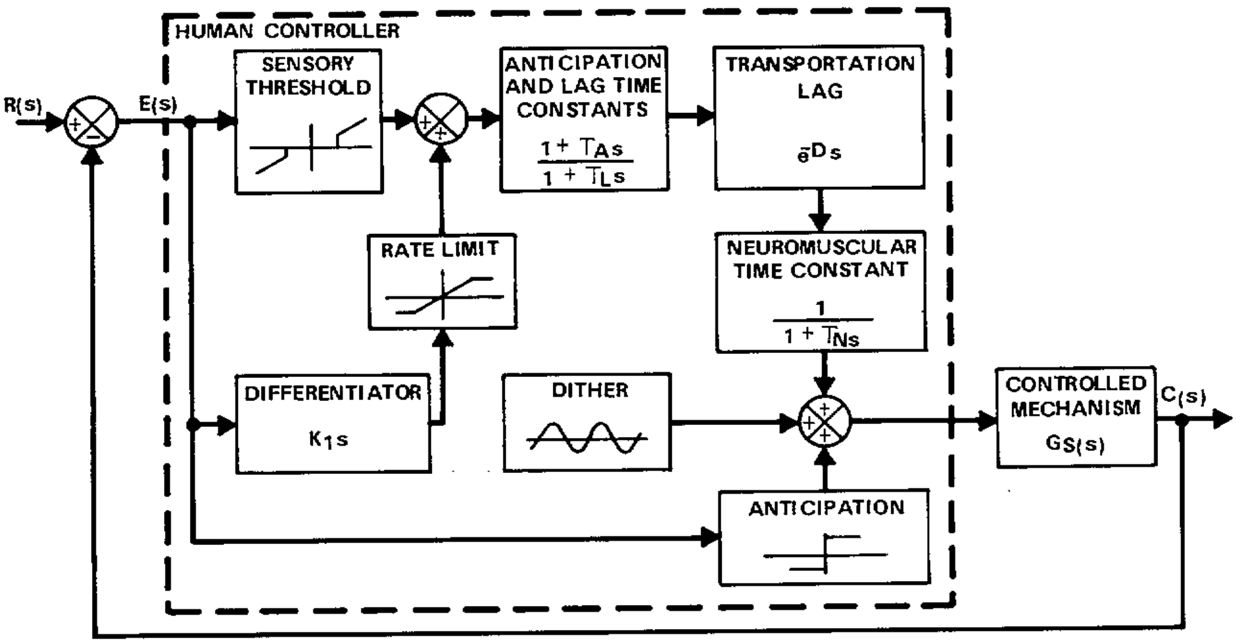


Figure 29. A Manual Control System Utilizing a Nonlinear Model of the Human Controller as Proposed by Diamantides[3-4]

An example of a feedback or response system would be one in which the controller would be required to perform specific correct actions to satisfy a continuous run fluidic sequence. Both visual and audio signals can be generated as the key for particular response which, if performed properly and in time, will advance the program in sequence; if improper or not in time, the sequence can be caused to stop, generate an alarm or increase the degree of difficulty for the next response.

A system requiring no feedback and consequently one which does not require the human transfer function considerations could be a memory testing device. In this case, a continuous run fluidic sequence of visual and audio stimulants could be generated with code symbols. After the run, the operator would insert the code symbols in the order he remembered them and receive a display which scores him on his performance.

Additional concepts for training purposes, which are feasible and could be mechanized with fluidic sensing and logic for scoring and control are Closing Rate Calculator, Target Tracking Coordinator, Ship Station Simulators, etc. The closing rate calculator could double as a range estimator trainer if operated in the static mode. The theory being that a simulated target could be advanced per fluidic programming and scored by comparing location sensors with the controller's calculation which he would introduce into the system. A target tracking coordinator would consist of a fluidic controlled target display and a companion firing station whose position is monitored with fluidic sensors for comparison with input information for scoring. In the case of the ship station simulators, many ratings could be instructed and trained using devices mechanized with fluidic sensors and controls. For example, it would be possible to simulate any of the engine room stations and program them for malfunctions requiring remedial actions, sequencing and synchornizing problems which would have to be solved, etc.

Figure 30 is a representative block diagram of the systems discussed above.

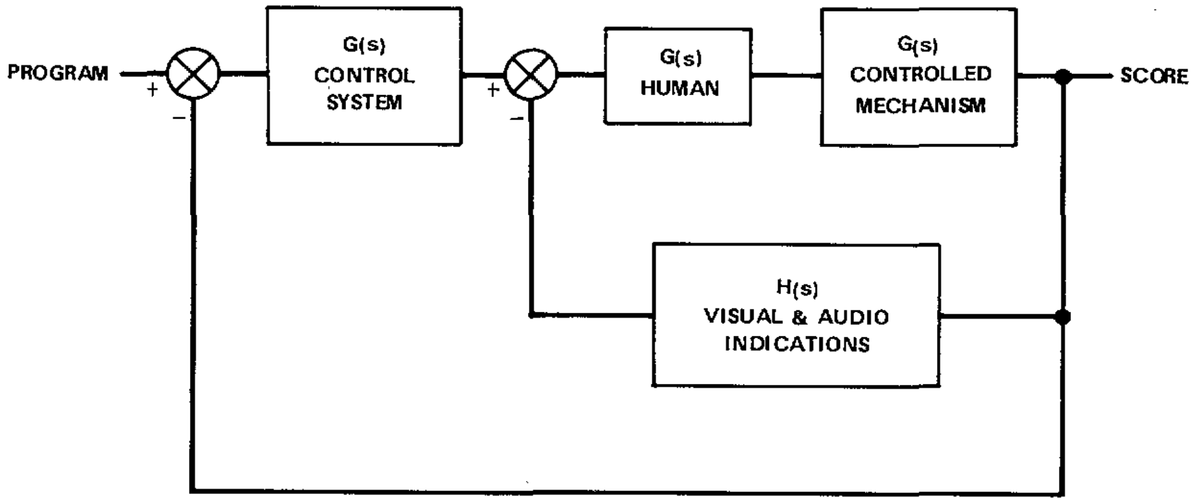


Figure 30. Representative Block Diagram Including the Human Controller

The input is a predetermined fluidic program which can be generated from tape, cards or initial condition setups. This program is introduced to the fluidic control system through a summing junction where the low level fluidic signals can be processed for activating any type of transfer or working media. Output from the system is fed to the human controller via a junction so that he can respond and apply the necessary input to the controlled mechanism which will produce the desired results. The output is fed back directly to the human controller via visual or audio indications and closes his response loop. This furnishes him with his environment, attitude orientation and contact link for continued participation. In addition, the output is fed back and summed with the input to modify the program as a function of the controller's performance.

The present state-of-the-art in fluidic technology is capable of producing any functions required in the system loop to make it compatible with the human controller and furnish a realistic training or testing device.

CONCLUSION

As of this time last year, the combined DOD and NASA R&D expenditures on fluidics were approximately 20 million dollars. It is estimated that industry funded R&D was approximately 80 million dollars over the same time period, i.e., 1959-1968. Much of the research was entirely analytical; a considerable amount was devoted to the study of geometric design for optimum characteristics. These development monies produced fluidic components and systems which continuously advanced the state-of-the-art. All of the government funded programs were thoroughly documented and these reports are available for general use.

Fluidics as a monitor and control media has been accpeted by the production, manufacturing and process industries on a limited scale for special applications. The advantages of fluidics over conventional means of control are considerable but not advanced to the point where total retrofit would be practical. Most of the machine tool manufacturers offer the prospective customer a choice between conventional or fluidic control systems on their line of equipment. For some special applications, operaing in a hazardous area for example, fluidics has completely replaced the conventional control system in very complex and critical production processes.

Attention is directed to the fact that fluidics is technically well founded and is becoming generally accpeted. All of the knowledge and experience discussed above is directly applicable to the training and simulation field because the requirements for monitoring, controlling and displaying are analogous. The one disadvantage fluidics has, when compared with conventional control, is speed of operation but is generally adequate when the human is in the loop.

REFERENCES

1. D. T. McRuer and E. S. Krendel, Dynamic Response of Human Operators, USAF, WADC TR 56-524, 1957.

2. Meredith B. Mitchell, System Analysis - The Human Element, Electro-Technology, April 1966.

3. N. D. Diamantides, Information Feedback in Jet-Pilot Control Stick Motion, AIEE Applications and Industry, November 1957.

4. N. D. Diamantides, A Pilot Analog for Airplane Pitch Control, Journal of Aeronautical Sciences, Vol. 25, pp. 361-371, June 1958.