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FLUERICS

1. Basic Principles

by

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ABSTRACT

After a brief historical introduction, the physical phenomena underlying most flueric devices are discussed. Brief descriptions of the operation of proportional and binary devices of various kinds are given including wall attachment, momentum interaction, vortex, and turbulence devices

FOREWORD

This report is one of a series on fluerics (fluid amplification) being issued by the Harry Diamond Laboratories. The present document is the second edition of TR-1039 (Aug 1962) written by S. J. Peperone and R. W. Warren.

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ILLUSTRATIONS

1. INTRODUCTION

Fluerics as a technology dates from 1959 when intensive efforts on no-moving-part fluid devices began at the Harry Diamond Laboratories (then the Diamond Ordnance Fuze Laboratories) as a result of a search for methods and devices for increasing the reliability of systems.

Looking back into the past, however, we find that many no-moving-part fluid devices were already in existence at that time oftentimes as a part of some other device and sometimes coupled with a moving part. As is true, in general, the devices to be included in a historical survey depend on where the line is drawn. In the following I have selected only (1) those items which seemed to me to be most closely related to the devices invented since 1959 and (2) those items which are now in use or are objects of research which actually were invented in essentially their present form prior to 1959. Where an inventor has several closely related patents, I have selected only one, and I have omitted jet pipes and boundary layer control methods as well as ball and diaphragm devices.

Since apparently the first consciously invented no-moving-parts fluid device was the diode, we begin our history with that subject.

1.1 Fluid Diodes

In 1920[1] Nicola Tesla obtained a patent on a device he called a "Valvular Conduit." In the text of the patent, Tesla states, "Mechanical devices exist which allow fluid impulses to pass more or less freely through suitable channels or conduits in one direction while the return is checked or entirely prevented in the other direction. As a rule the valve is a delicate contrivance very liable to wear and get out of order and thereby imperil ponderous, complex, and costly mechanisms and moreover it fails to meet the requirements when the impulses are extremely sudden or rapid in succession and the fluid is highly heated or corrosive;" and he continues "though these and other correlated facts were known to the very earliest pioneers in the science and art of mechanics no remedy has as yet been found or proposed to date so far as I am aware and I believe that I am the first to discover or invent any means which permit the performance of the above function without the use of moving parts and which it is the object of this application to describe." Tesla states that theoretically a very great difference in the flow in the two directions is obtainable. His discussion relates primarily to rapid oscillation and he claims that "in my construction as above indicated the resistance in the reverse may be 200 times that in the normal direction."

Although no one has reported recent tests on a Tesla diode operating at high frequencies, preliminary reports using d-c flow give values considerably less than 200.

A patent on a vortex diode[2] was issued to Jean Bertin and Raymond Marchal in 1951, and in 1955 a patent entitled "Aerodynamic Check Valve"[3] was issued to Erik T. Linderoth.

Recently the latter two types of diodes (together with a third type) were compared by P. J. Baker.[4] For the particular designs tested, the vortex diode was considerably better than the scroll diode (aerodynamic check valve).

P. J. Baker[4] refers to investigations by R. Heim[5] and by R. Zobel[6] on vortex diodes. This 1929 paper by Heim refers in the title to the "Thoma Counterflow Brake" and is based on a device patented June 4, 1928 by D. Thoma in U. S. Patent 1,839,616 entitled "Fluid Lines." Unfortunately copies of neither the paper by Heim nor by Zobel could be obtained before this paper was published; however, the references given by Baker are included as given by him.

1.2 Laminar to Turbulent Transition Devices

In 1886 Chicester Bell[7] described a series of experiments with gas and liquid sensitive jets. His paper discusses such things as amplification of sound by jets and the transduction of electrical signals into sound by use of jets.

In one experiment, he used a circular piece of paper with a hole in its center arranged so that the jet normally (i.e., in the absence of sound) passed through the hole in the center of the paper. In the presence of sound, however, the jet spread and the paper was pushed away from the nozzle.

In 1916 a patent was issued to Ray E. Hall[8] in which the description is given of a method of actuating a relay by means of an input sound which is very similar to Bell's experiment described above. The device uses a sensitive jet which is ordinarily in the laminar state. When laminar it passes through a hole in a plate perpendicular to the stream. A control nozzle very close to the nozzle of the sensitive jet is used to apply a sound signal to this jet. Upon the application of the signal the jet becomes turbulent and spreads so that most of the momentum flux associated with the jet hits against the plate instead of passing through the hole. As a result the plate is deflected thereby closing a relay.

1.3 Throttling Mechanisms

Christopher Davy[9] obtained a patent in 1940 on a conduit through which the flow was controlled "by projecting one or more secondary streams of fluid at higher pressure across the flow in the conduit thereby reducing the effective area of the passage to the flow of the fluid to be controlled."

In a "Fluid Control Apparatus" patented in 1941 by K. McMahon[10] flow through a venturi-type nozzle is controlled by varying the pressure at its throat. The pressure variation is accomplished by surrounding the venturi opening by a housing that completely incloses it and from which a duct leads to a variable pressure source.

John B. Nichols and William E. Wayman[11] in a patent issued in 1954 control the flow through a cylindrical duct by placing a second duct around and concentric with the main duct at its output end. The outer duct has a lip at the end so that fluid flowing between the two cylindrical ducts comes out directed toward their common axis. This fluid impinges on the flow from the inner duct tending to decrease the duct's effective area and thus restricting the flow.

1.4 Jet Deflection Devices

R. Braithwaite and K. Wilcox[10] in a 1946 patent and T. Harris[13] in a 1955 patent both describe methods of deflecting a jet from alignment with a receiving orifice. M. Kadosch[14] obtained a U. S. patent in 1958 on "Jet Propulsion Units" in which the main jet is deflected into either one of two outlets by means of two control jets, one on each side. M. Kadosch and J. LeFoll also obtained a patent[15] on a type of jet-controlled vortex diode and a jet-controlled three-state vortex device capable of providing any one of three pressure levels. In the diode a control jet is used to attach a jet to a curved wall after which it flows tangentially around a circular housing and spirals in toward the drain to obtain the high resistance. In the three-state device a set of jets within a circular housing can be turned off or used to add either clockwise or counterclockwise angular momentum to the already rotating flow.

Except for the diodes all of the devices previously mentioned are actually amplifiers; however, only Hall, the inventor of the sensitive-jet relay actuating apparatus, thought in terms of amplification (of a binary signal), the others thought essentially in terms of controlling mass flow rather than information; however, a German patent issued in 1953 to V. Ferner[16] refers specifically to the amplification of small (analog) signals by use of jet deflection.

1.5 Birth of a New Technology

Although the above items existed prior to 1959, they existed as separate entities and except for the last mentioned item were each conceived of for particular rather than general purposes. Recognition that these fitted into a new technology only came about after the concept of this technology and the invention of a family of devices had occurred at the Harry Diamond Laboratories.

Romald Bowles and Raymond W. Warren had been investigating the problem of fluid controls having no moving parts other than fluids but had not developed a no-moving-part power modulation device to take the place of spool valves. When the problem of no-moving-part control was presented to Billy M. Horton he almost immediately sensed the need for and arrived at the concept of a fluid amplifier using the deflection of one stream by another. Warren and Bowles very shortly thereafter came up with the wall-attachment device. Within a year these three individuals and their co-workers had formulated a great number of concepts and had built many types of devices. Then on 2 March 1960 the announcement of the invention of this family of components was made to an invited press audience.

Initially the technology was called either "fluid amplification" or the field of "pure fluid devices." The first name is inadequate since more than amplification is involved but, on the other hand, the second name is misleading.

As a result, two new names now exist -- "fluerics," which is restricted solely to no-moving-part devices, and "fluidics," which is a somewhat broader definition. In the United States the term "fluidics" is defined so as to include peripheral equipment such as transducers and certain hybrid devices such as accelerometers containing a moving mass. The European definition of fluidics is even broader and includes diaphragm, ball, and foil devices.

Common usage in the United States, however, often disregards the accepted U. S. definition of fluidics and also includes the diaphragm, ball, and foil devices.

2. AREAS OF RESEARCH

The various areas of research and development in this field can be divided in several ways; for the present purposes, it is convenient to divide them as follows:

(a) component invention and improvement,

(b) the development of simplified techniques for incorporating the devices into systems, and

(c) building systems using flueric components

The distinction between the last two is made because although most of those interested in this field are concerned with the devices in systems; they do not want to be concerned with fluid dynamic considerations or the internal workings of the various devices. That is, they would like to have black box descriptions, together with procedures for assembling these black boxes. For this reason, a great deal of research today is concerned with the development of systems techniques such as circuit theory, transfer function descriptions, and characteristic curves.

3. COMPONENTS

An important part of component invention and improvement, is understanding the phenomena involved well enough to design the devices from a mathematical basis.

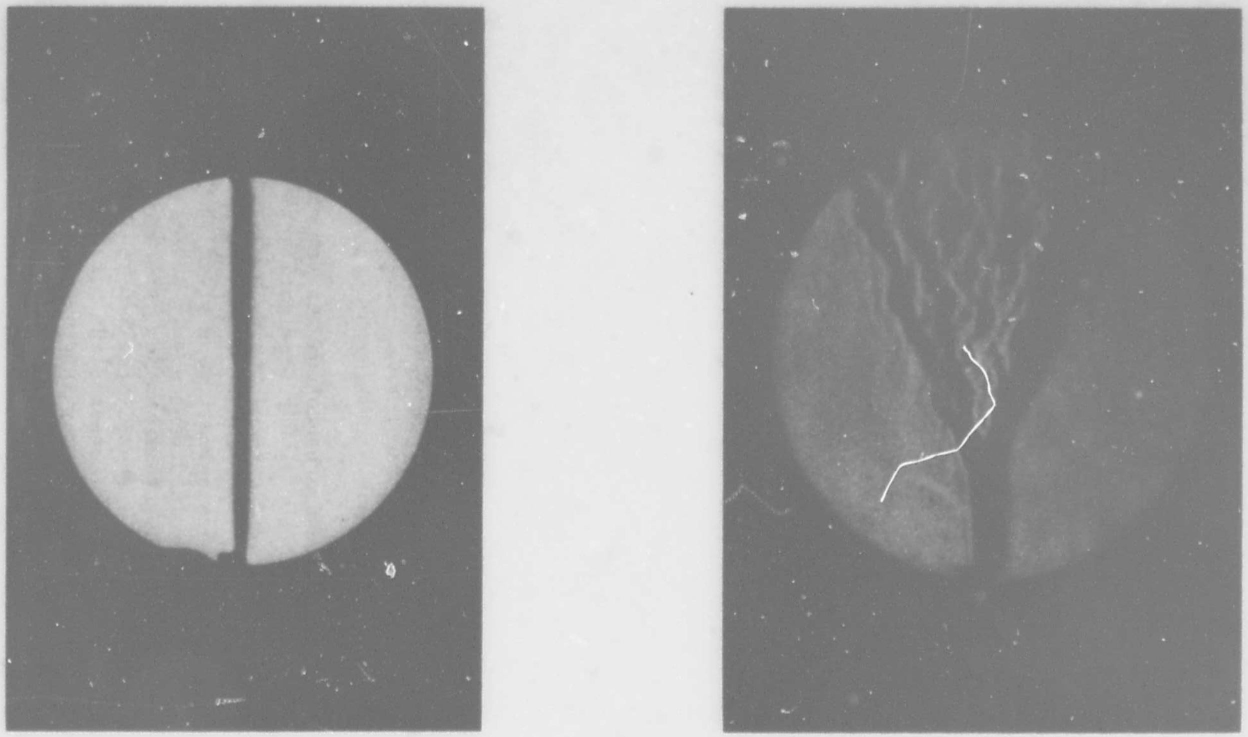
Although we have separated component design from system techniques, the design of components should include considerations of what can be done to them to simplify their use in systems.

3.1 Jets

In most components, jets and the interaction of jets with each other and with their environments are of primary importance. Some of the devices use axisymmetric jets and others use more or less planar jets. In either case the jet profile is described relatively well by a bell-shaped velocity distribution. Another important characterization of the jet is whether it is laminar or turbulent and the degree of turbulence. The Reynolds number is usually used for this purpose.

In general the effect of disturbances on the velocity distribution depend on the Reynolds number; low number (laminar) jets change more in profile for a given small disturbance than do high number jets.

Jets of low Reynolds numbers entrain less fluid than do high Reynolds number jets; however, disturbances will increase the turbulence and thereby the entrainment of the jet, the percentage increase of the entrainment being inversely related to the Reynolds number so that a disturbance that increases the entrainment of a laminar jet by more than 100 percent may increase the entrainment of a sufficiently turbulent jet by less than 1 percent. Figure 1 shows a schlieren photograph of the effect of a disturbance on a jet.



(a) No sound

(b) f = 1,000 cycles/second

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Figure 1. Effect of injecting sound into the power nozzle of a jet of helium exhausting into air.

Figure 2 shows Albertson's model of a turbulent jet issuing from a slit. Except that it is axisymmetric, a jet issuing from a circular orifice has a similar cross section.

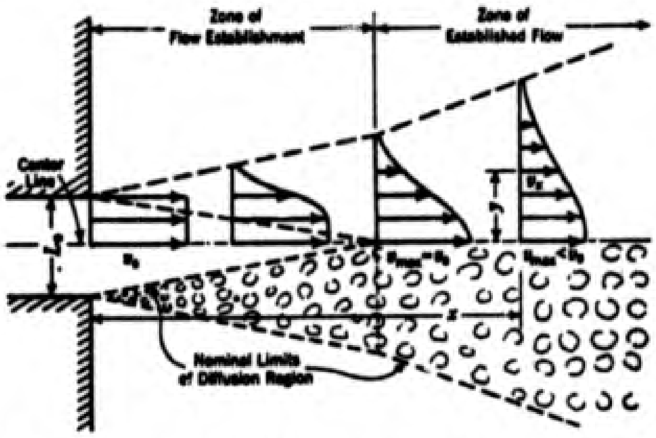


Figure 2. Schematic representation of jet diffusion

Albertson divides the jet into two main regions: a zone of flow establishment and a zone of established flow.

Within the zone of flow establishment lies the core, which is a region of the jet not yet appreciably affected by interaction with the surrounding fluid and where the velocity is therefore appreciably the same as the nozzle velocity. For the two-dimensional jet, the core is wedge shaped. For the round jet, it is conical.

Downstream of the core the profile takes on a bell shape and becomes self-preserving. This region is the zone of established flow.

3.2 Wall Attachment

Because many of the important devices are based on the phenomenon of wall attachment, it is fitting to give a little of the history of that effect; since M. Kadosch has already done this, we shall essentially repeat his references as given in two of his papers on flow along convex walls.[17,18]

In 1800 Thomas Young reported on some experiments he had carried out:[18] "The lateral pressure which urges the flame of a candle towards the stream of air from a blow pipe is probably exactly similar to that pressure which eases the inflexion of a current of air near an obstacle. Mark the dimple which a slender stream of air makes on the surface of water. Bring a convex body into contact with the side of the stream and the place of the dimple will immediately show the current is deflected toward the body; and if the body be at liberty to move in every direction it will be urged towards the current."

The phenomenon was rediscovered by Chilowski in connection with experiments on projectiles, and was applied by Lefay[20] and by Ravelli[21] in 1929.

Henri Bouasse and Abbott Carriere repeated Young's experiments and Bouasse described them in 1931.

In 1910 Henri Coanda built a twin engine jet type engine. As a result of the jet flames attaching to the celluloid fuselage, it went up in smoke. Coanda forgot about this phenomenon until 1933 at which time he began to study the effect and look for applications, and in 1935 he obtained a U. S. patent on a "Device for Deflecting a Stream of Elastic Fluid Projected into an Elastic Fluid".[23]

Subsequently, Professor A. Metral[24] named the phenomenon L'effet Coanda; although this is the name by which the phenomenon is usually called, a name more equitably dividing the honor is Young-Coanda effect.

The Young-Coanda effect is often confused with or lumped together with the teapot effect, but as defined in this paper, the Young-Coanda effect is the attachment of a stream to a surface due to entrainment. In general this occurs in the case of a stream of liquid submerged in a similar liquid or gas stream in a gas atmosphere; however, there are exceptions, as in the case of a spray of liquid that may entrain large quantities of air. In the Young-Coanda effect a low pressure region is formed near a wall by molecules from the jet sweeping molecules out of the region between the wall and the jet. The teapot effect on the other hand is the attachment of a liquid to a wall in a much less dense fluid such as air and is primarily due to molecular attraction, i.e., adhesion rather than to the transverse pressure gradient which results from entrainment.

3.3 Wall Entrainment Devices

To see how entrainment can be used to produce a switching device, consider a two-dimensional turbulent jet leaving a slit-like nozzle, as in figure 3, shortly after it has been turned on. The jet entrains fluid on both sides. Because of the presence of the walls, some of the molecules are evacuated between the jet and each wall, causing a low pressure region into which there is a counterflow down the wall. Because of turbulent fluctuations of the jet, the jet may momentarily bend toward one wall, thus tending to cut down the counterflow, and thereby lowering the pressure between the jet and that wall

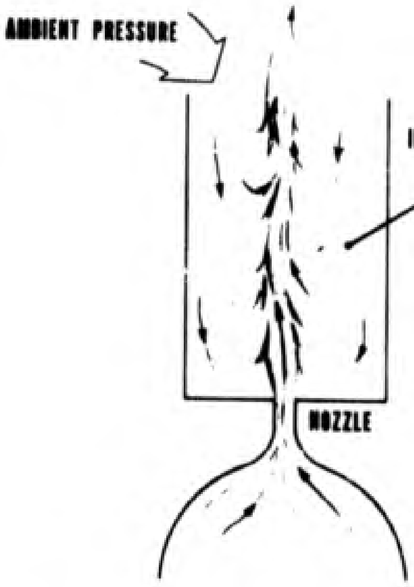


Figure 3. Initial fluid flow between parallel walls.

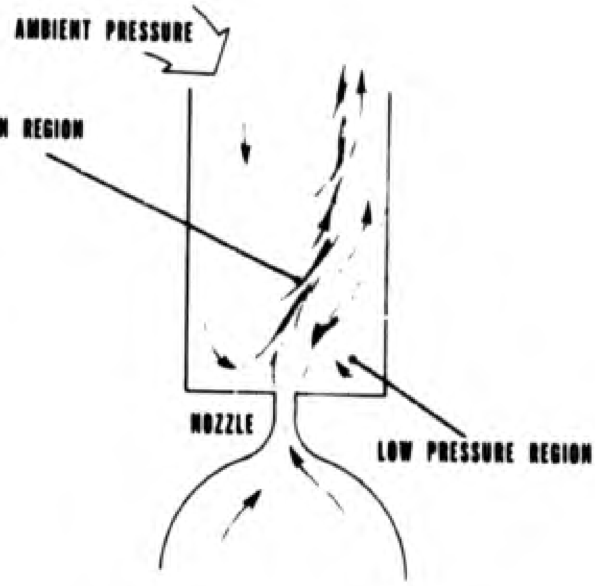


Figure 4. Final fluid flow between parallel walls.

more than that along the other wall. This mechanism therefore quickly causes the jet to attach to the wall as shown in figure 4. The wall attachment effect enables us to make a bistable device (fig. 5). The jet will at random attach to either wall A or wall B. In either case we can shift it to the opposite wall by use of the controls.

If the jet is attached to wall A as in figure 5 and both controls are open, the pressure in the bubble is lower than that on the opposite side of the jet. Fluid is being entrained through both controls. Now if we temporarily close off the flow through control b, the pressure on that side will become lower than that in the bubble and the jet will flip to wall B. We can also cause the jet to flip from A to B by temporarily increasing the pressure at control A with a pulse of pressure.

If the controls are made sufficiently wide and the offset is not too small, the entrainment through the controls will allow the jet to be tristable as shown in figure 6, where if both controls are open, the jet proceeds down the center, but if one control is closed, the jet will attach to that side.

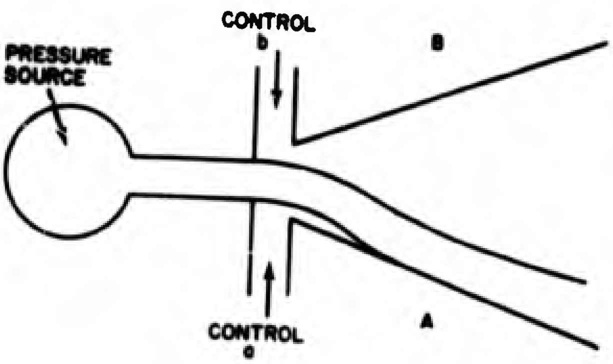


Figure 5. Bistable jet.

Returning to the bistable device, it is relatively simple to make the step of having two outlets by adding a splitter as shown in figure 7. The method of switching is as before, but the jet is switched from one outlet to the other. Devices of this kind have been used but are difficult to work with because loading of the outlets affects the switching characteristics.

3.3.1 Effect of Loading

Figure 8 shows the effect of complete blockage on a flip-flop having memory. This means that the distance from the nozzle to the splitter is long enough so that the forces holding the jet to the wall are sufficient to keep it attached to the blocked side even though the fluid itself is leaving from the opposite receiver. An appreciable static pressure will exist in the blocked receiver and the jet will again flow out of that side once the blockage is removed.

3.3.2 Effect of Splitter Distance

If the splitter distance (from the nozzle) is small, the device will not have memory; that is, blocking the outlet will cause the jet to detach and the static pressure in the blocked receiver will be low.

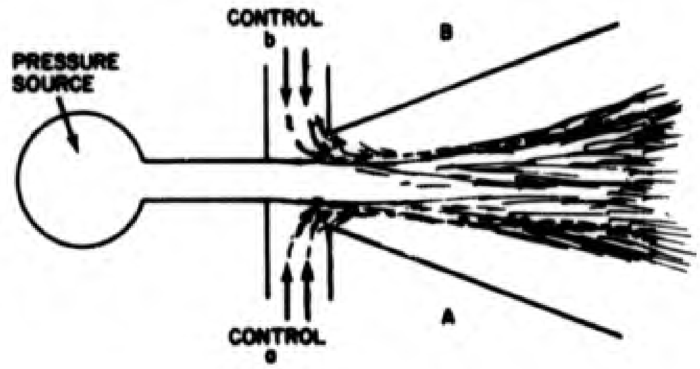


Figure 6. Tristable jet.

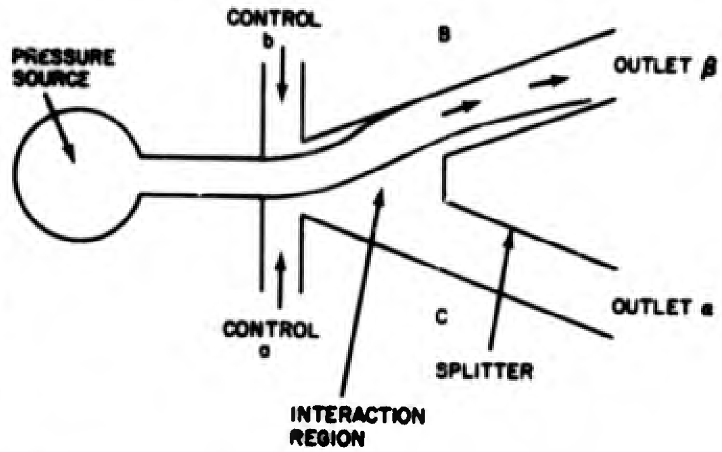


Figure 7. Closed binary amplifier.

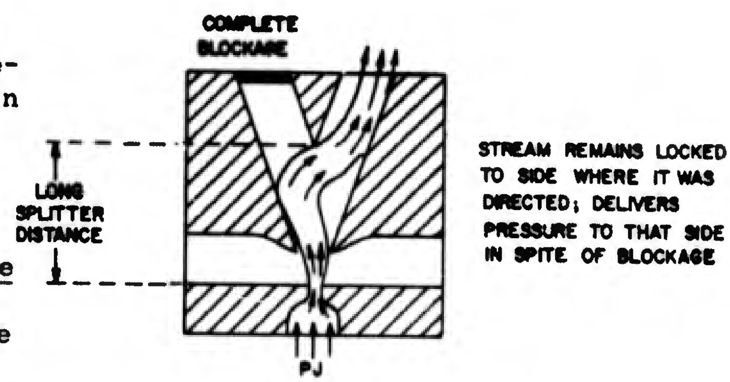


Figure 8. Memory flip-flop.

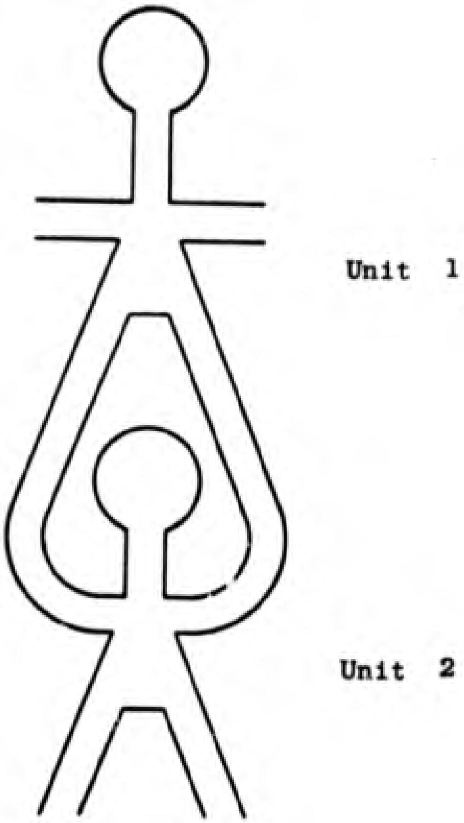


Figure 9. Staged digital units.

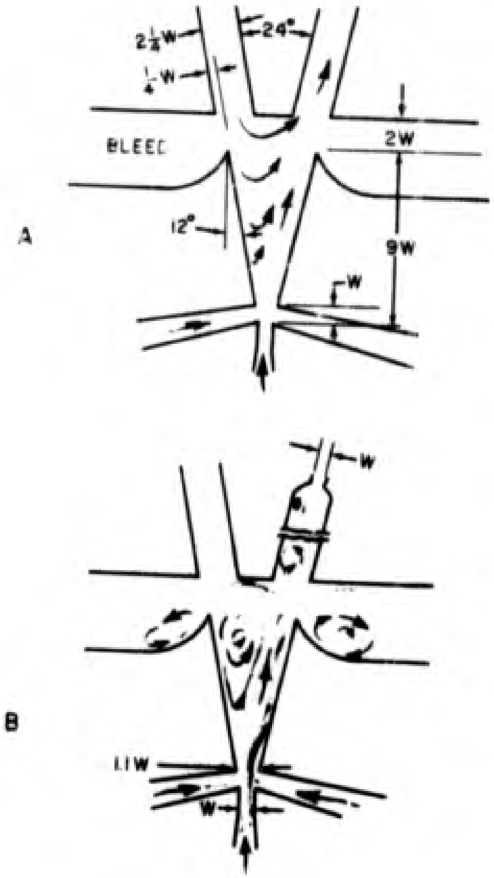


Figure 10. Wall interaction fluid amplifier.

3.3.3 <u>Staging and Bleeds</u>

Although loading may increase the pressure at the outlets as in the case of complete or partial blockage, it may also be of a type that lowers the pressure at the outlets as occurs in driving another unit as shown in figure 9. If unit 2 is sufficiently large with respect to unit 1, then since unit 2 normally entrains flow through its controls, the pressure in the outlets of unit 1 will be lowered. A little consideration of these two units as shown, that is, of the same size will force us to conclude that these units will not actually operate. This is obvious from the fact that the flow through unit 2 includes the flow from its own power jet plus all the flow from unit 1. If we are concerned with power devices, this may be what is desired (staged power units are each larger than the preceding unit). If, however, we are concerned with computation devices, we would like to use units all approximately the same size. To accomplish this as well as to minimize the effects of loading in general, bleeds that vent the excess flow (or supply additional flow if needed) are used as shown in figure 10.

Figure 10. gives the dimensions of a device having good pressure recovery and high fan-out ratio. Fan out is defined as the number of similar units that can be switched by the output of a single unit. The dimensions are given in terms of the power jet nozzle width to which all lengths are usually normalized. An aspect ratio (ratio of channel height to nozzle width) of 2 is common in molded devices, but the aspect ratio is often about unity in etched devices.

In a device with bleeds the pressure in the interaction region tends to be approximately ambient regardless of the load on the outlets. If the units are operated with air as the medium in an air environment and if there is no reason to seal the units off from the environment, the bleeds are left open to atmospheric pressure. In other cases, the bleeds are connected to a reservoir.

3.4 Logic Devices

Various logic devices[25] can be built using the Young-Coanda effect. We mention only two of the many in existence. Figure 11 shows an induction AND unit.[26] If only one signal is present, the flow will attach to the wall and exit from the outlet on that side. However, if both signals are present, the two streams will mutually entrain and exit from the center outlet. Bleeds (as shown in the figure) aid in obtaining proper operation.

Figure 12 shows a NOR element.[25] If no signal is present, flow from the power supply will proceed out of the NOR outlet. If a signal is present at either of the controls, the power jet will be pushed into the bleed or dump and there will be no output. There is, therefore, an output only if neither one control input nor the other is present.

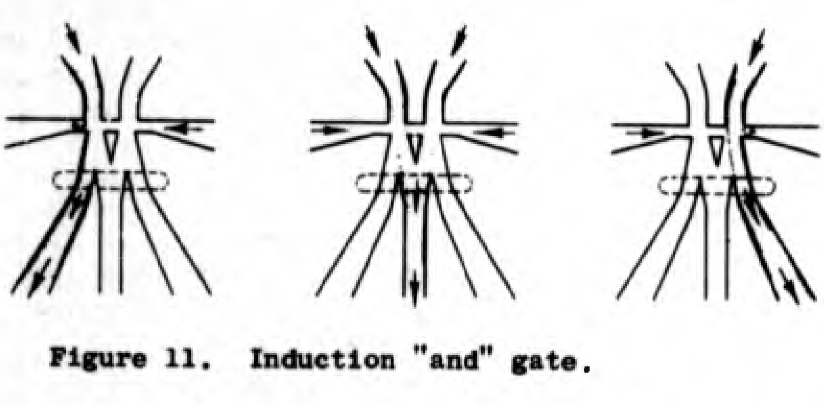


Figure 11. Induction "and" gate.

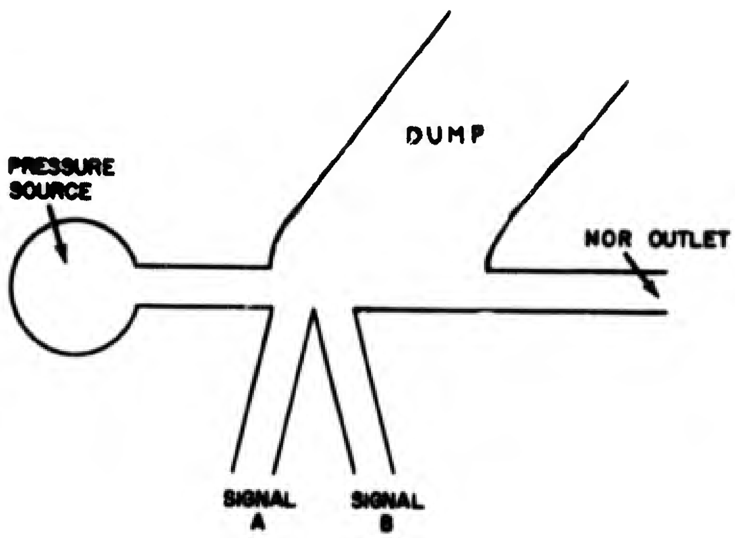


Figure 12. NOR element.

3.5 Proportional Devices

We can get proportional control by minimizing the effect of the walls (fig. 13). To do this, the walls are set back and the interaction region is opened to the atmosphere or a reservoir through bleeds, which may be perpendicular to the paper as in the view shown. In this case, the power jet is deflected by the momentum of the control jets so that a pressure difference appears across the outlets which (over some pressure region) is proportional to the pressure difference across the controls.

Bleeds may also be incorporated as shown in figure 14. If stacked units are to be used, the configuration of figure 14 is easier to work with; on the other hand the configuration of figure 13 has advantages for integrated circuits etched on a single plate. It is, however, possible to use either configuration both for stacking and single-plate circuits.

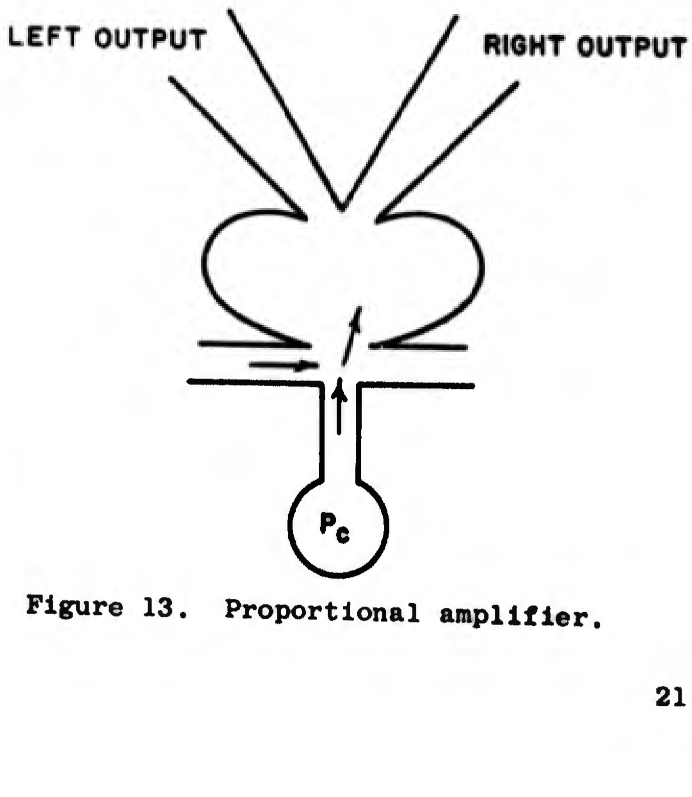
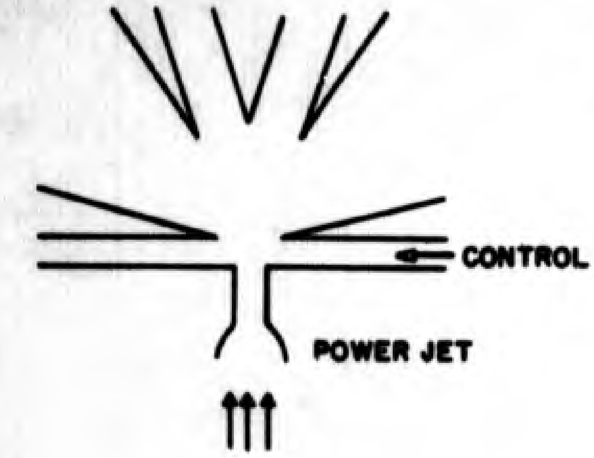


Figure 13. Proportional amplifier.



$$\text{FLOWGAIN } G_Q \equiv \frac{\Delta(Q_L - Q_R)}{\Delta(Q_2 - Q_3)}$$

$$\text{PRESSURE GAIN } G_P \equiv \frac{\Delta(P_L - P_R)}{\Delta(P_2 - P_3)}$$

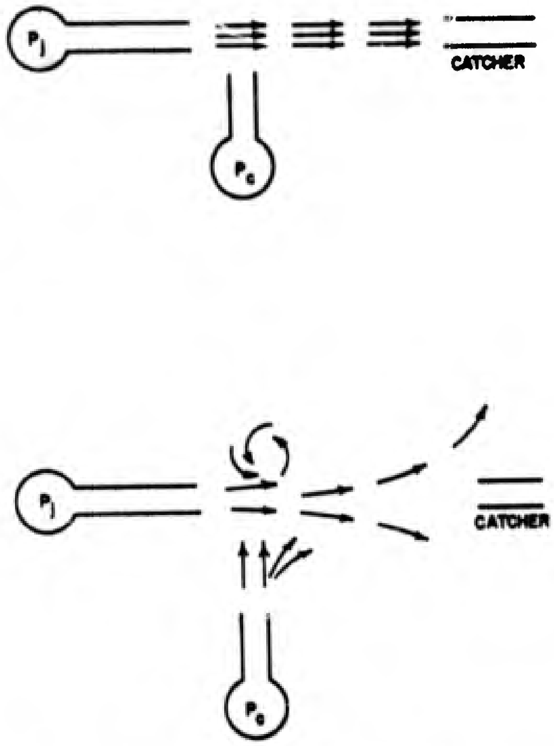


Figure 14. Proportional amplifier. Figure 15. Turbulence amplifier.

The signal-to-noise ratio is an important consideration in proportional devices. Since the boundary layer tends to damp out the noise, low aspect devices have less noise than those of higher aspect ratios. Unfortunately they also have less gain. Aspect ratios of unity or less are common in proportional amplifiers.

3.6 Transition[27] and the Turbulence Amplifier[28,29,30]

Low velocity jets may remain laminar for an appreciable distance after leaving a nozzle, whereas higher velocity jets (actually high Reynolds number jets) become turbulent shortly after leaving the nozzle. As previously discussed, there is a Reynolds number region where the jet, although normally laminar, is very sensitive to disturbances and easily becomes turbulent. In particular, it can become turbulent by disturbing it with a second jet of much lower flow.

This property may be used to produce a NOR unit. A laminar jet issuing from a small pipe is allowed to enter another small pipe in line with the first one but an appreciable distance downstream. If the jet is disturbed by another jet (fig. 15), it will become turbulent and very little of the flow will reach the downstream (receiver) pipe.

If there are two (or more) control jets, this device is a NOR unit. Because there is almost no effect on the controls when the outputs are loaded, this device is very easy to stage.

Turbulence amplifiers cannot furnish much power and after performing computations it may be necessary to amplify their output using some other type of device. One of the disadvantages of the axisymmetric turbulence amplifier is that it does not lend itself easily to modular construction; however, efforts have been made to remove this disadvantage by a two-dimensional type construction.[30]

3.7 Impact Devices[31,32]

If two round jets of the same diameter are directed head on at each other and both lie on the same axis, the following phenomena are observed:

(1) If the jets have the same amount of momentum, the fluid will fan out in all directions in the plane perpendicular to the axis from the region of collision of the two jets.

(2) If the momentum of one jet is changed, the impact region will move toward the lower momentum jet nozzle.

(3) If the impacting jets are caused to misalign by a third (control) jet applied at right angles to one of the impacting jets, the fluid will no longer fan out perpendicularly from the point of impact but will be tilted away from the perpendicular. The control jet will also cause the jet with which it impacts to increase its turbulence and consequently it will spread more than previously. In the devices the power jet from the receiver side impacts with the other power jet within a small chamber to which the outlet of the device is coupled (fig. 16, top). A control jet perpendicular to the impacting jets causes misalignment and spreading of one of the jets thus allowing less of its momentum to

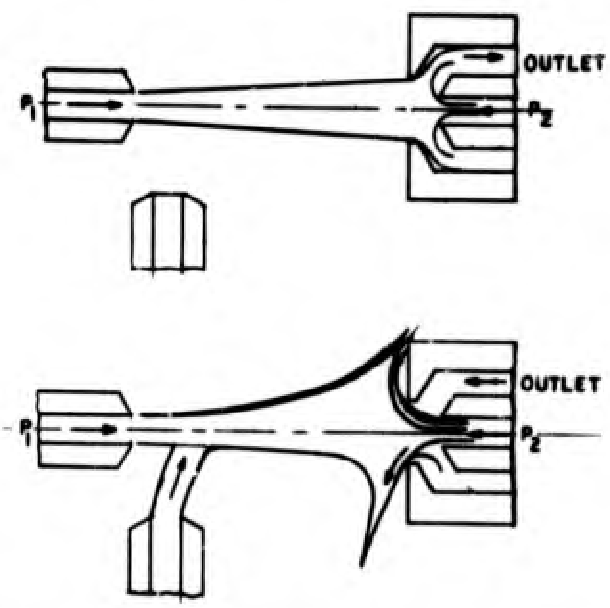


Figure 16. Transverse impact modulator and NOR element.

enter the chamber. As a result the impact point moves out of the chamber and the flow pattern radiating from the impact point tilts (fig. 16, bottom). This lowers the pressure in the chamber and decreases the flow into the outlet. The change in outlet pressure is thus of the opposite sense to the change in control pressure. The effect is used to produce both proportional and digital elements.

3.8 The Edgetone Effect[33,34]

When a two-dimensional jet strikes an edge or the vertex of a wedge, an oscillation is induced. The phenomenon is due to the alternate shedding of vortices off the vertex causing it to seem like a dipole source of pressure fluctuation. These pressure fluctuations cause the jet to oscillate, which in turn leads to the alternate shedding of the vortices. Thus, we have a closed loop with positive feedback. There is sufficient gain in the jet so that the loop gain can be unity and the oscillations will continue once they are started. Fluctuations that are always present in the jet are sufficient to start the process. The frequency of oscillation depends upon the distance from nozzle to edge and the fluid velocity.

By placing resonant cavities adjacent to the jet, large amplitude oscillations can be obtained if the cavity and jet frequencies are approximately equal.

Since edges and/or wedges together with cavities often appear in fluid devices where oscillations are unwanted, it is necessary to minimize the effect or to design the device so that any oscillations present are outside the band of frequencies of interest.

3.9 Vortex Devices

Consider fluid entering a cylinder tangentially and leaving through an axial drain as in figure 17. For simplicity, we consider

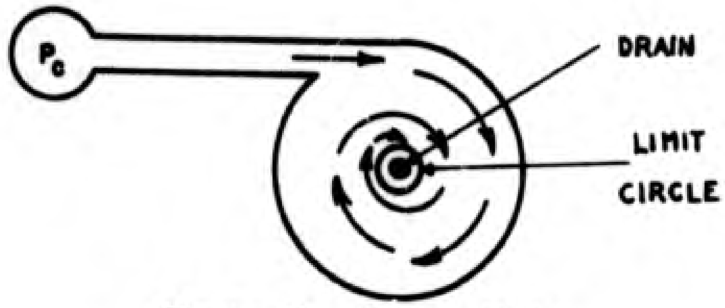


Figure 17. Vortex diode.

an incompressible fluid. Because of the conservation of angular momentum, the tangential velocity of the fluid will increase as it spirals in toward the drain. For an inviscid fluid it is easy to show that the tangential velocity v_t, is given by

$$v_t = \frac{k}{r}$$

where k is a constant and r is the radial distance from the center.

If the total pressure is p_c, then for an incompressible, inviscid fluid, we have

$$p_c = p_s + \frac{1}{2} \rho v^2$$

where p_s is the static pressure and v is the fluid velocity. Now since $v_t = \frac{k}{r}$ and $v_t \leq v$, it follows that for a small enough value of r, the term $\frac{1}{2} \rho v^2$ can, at most, become equal to p_c, at which point $p_s = 0$, where

$$p_c = \frac{1}{2} \rho v^2_{max}$$

Because it is physically impossible for p_s to become negative, v cannot take on values greater than v_{max}. There exists, therefore, a minimum value of r that defines a limit circle within which the fluid cannot penetrate (fig. 7).

Another way of thinking about this phenomenon is to consider the fact that the centrifugal force increases as the fluid spirals inward until eventually the centrifugal force of the inner layers of rotating fluid is sufficient to balance the total pressure forces.

3.9.1 Vortex Diode

It follows that if the radius of the drain is less than that of the limit circle, an inviscid fluid would be trapped and merely continue whirling around without ever leaving the train. Flow in the other direction (from the drain toward the tangential arm), however, would not "see" such a phenomenon, so that the geometry of figure 17 results in a fluid diode. Unfortunately, viscosity effects in any real fluid are quite important so that actual vortex diodes cannot really completely cut off the flow.[38] If we define diodicity as the ratio between the flows in the easy and hard directions, under the same pressure drop, a diodicity of the order of 6 has been obtained. Diodicity is also defined as the ratio of pressure drops in the two directions for the same flow or at the same Reynolds number, in which case, the diodicity is approximately the square of that which one gets by the first definition.

3.9.2 Vortex Triode

If we add another source of flow as in figure 18, a basic vortex triode is obtained.[37,38,39] Fluid from the power source p_j, ordinarily proceeds straight in toward the drain. The addition of flow from the control p_c causes the resultant flow to spiral in toward the center, resulting in a decreased output because of the centrifugal force effect. Since the change in net flow is greater than the control flow causing it, the device has gain.

3.9.3 Vortex Rate Sensor[40,41]

In the vortex rate sensor (fig. 19), fluid is introduced from all around the circumference of the cylinder through a porous ring or something similar. This fluid moves radially toward the drain and then out of it. However, if the cylinder is rotated about its axis, giving a tangential velocity to the entering flow, the tangential velocity will increase as the inverse of the radius (fig. 20) and will therefore be more easily measurable in or near the drain than on the rim. Furthermore, the measurement can be made by an element which is itself moving with the cylinder. This is easily seen in the following description: Let the velocity at the rim be V and the radius to the rim be R. If the velocity detector is at a point on the solid structure which is at a radius of 1/10 R, its tangential velocity will be 1/10 V. On the other hand, the fluid that spirals inward will at the same point have a tangential velocity of (approximately) 10 V. There is therefore an appreciable relative velocity between the fluid and the measuring element.

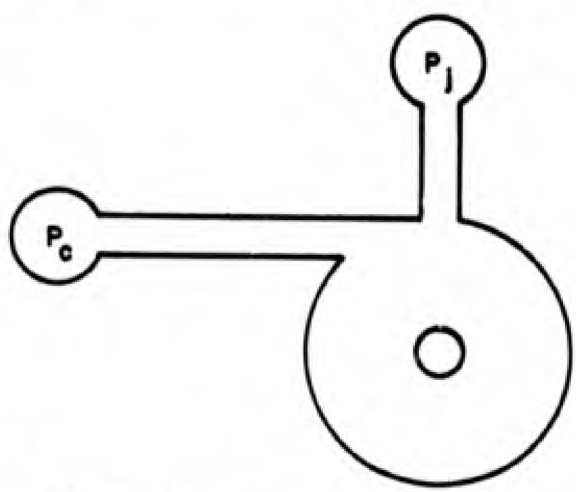


Figure 18. Vortex triode

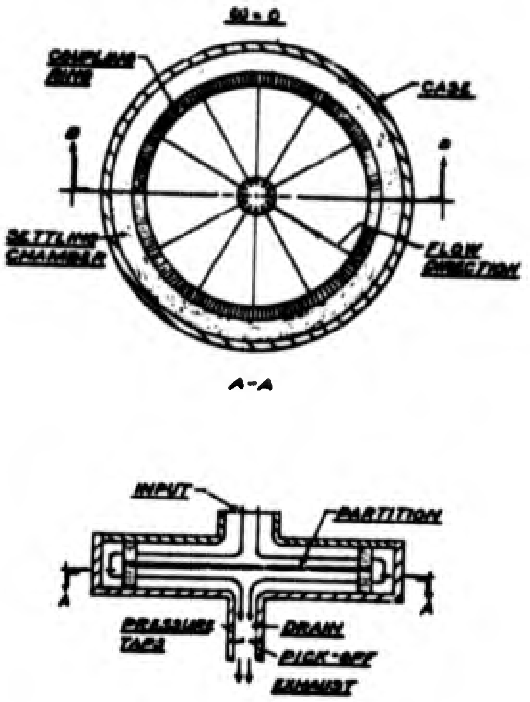


Figure 19. Illustration of vortex rate sensor flow with angular rate ($\omega = 0$)

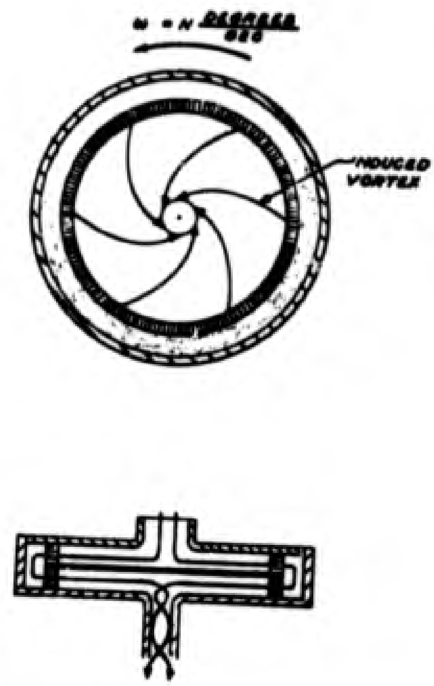


Figure 20. Vortex rate sensor flow with angular rate $\omega = n \frac{degrees}{sec}$

3.10 Secondary Mechanisms

Besides the basic phenomena underlying these devices, there are many other phenomena (possibly not all known) that affect their operation. These include interaction with sound[35] and thermal effects[42].

4. CIRCUIT AND SYSTEMS CONSIDERATIONS

Let us now discuss problems of putting the components together.

We have already briefly mentioned the staging of two binary amplifiers and the difficulties one may encounter unless bleeds are used. Without bleeds, all fluid from one stage must flow into the next stage. This is, of course, a result of the conservation of mass, which is stated as the continuity equation.

Fluid devices are not unique in obeying a continuity equation. We also have to take continuity into consideration in electronic circuits, where in staging amplifiers we bypass the power supply to ground through coupling circuits and send on the signal. The bleeds in a fluid amplifier are also coupling circuits, which bypass most of the flow to ground.

4.1 Characteristic Curves

Because of continuity considerations, characteristic curves[43,44] for the outputs and inputs of the various devices are very useful. When two units are connected together, the inputs of the second units must be connected to the outputs of the first unit. If we know what we can expect from the first unit for any loading condition and know what we can expect from the second unit for any input, we can predict the conditions that will occur when the units are hooked together. This is a technique borrowed from electronics.

For example, figure 21 shows the output characteristic of a proportional amplifier, which is going to be used to drive a second amplifier. The characteristic is obtained by gradually changing the valve position from fully open to closed and measuring the flow and pressure for the various conditions.

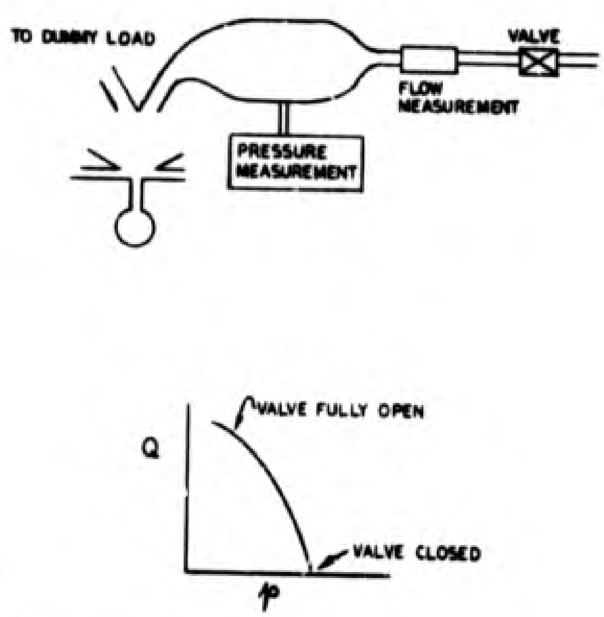


Figure 21. Output characteristics.

Since the output characteristics of one output leg depend on the loading of the other leg, and since the outputs usually feed into similar devices, the standard procedure is to place a similar orifice or valve opening on both legs and close them down simultaneously. However, the most meaningful procedure depends on the intended use.

The input characteristics are found as in figure 22. The input characteristics of one side are not very greatly affected by the input from the other side so that the problem of the other connection is not so severe as in the determination of output characteristics; but here again the determination of what is best as the opposing control depends on the intended connections of the device.

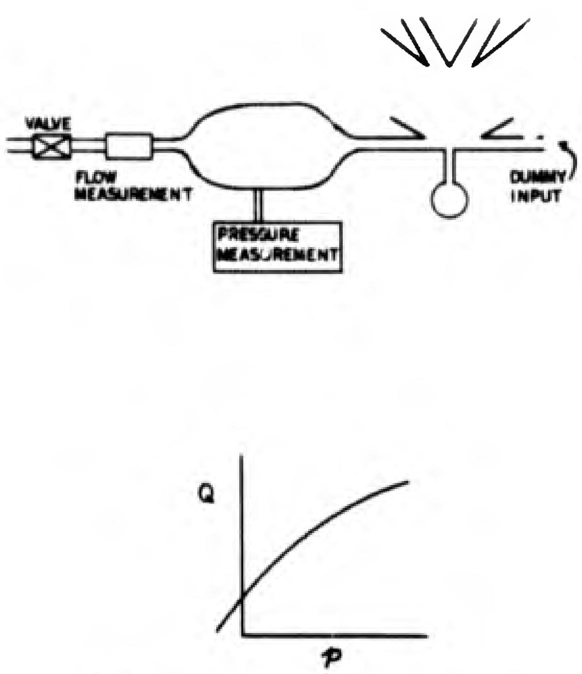


Figure 22. Input characteristics.

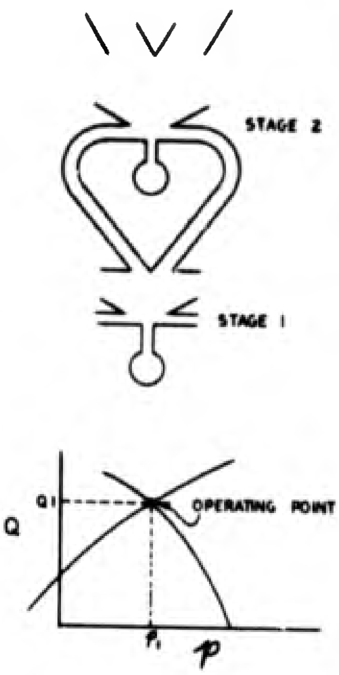


Figure 23. Output characteristics of stage 1 superimposed on input characteristics of stage 2.

The flow and pressure at the connection between the two stages can be found by superimposing the curves for output of stage 1 on that for input of stage 2, as shown in figure 23.

4.2 Analogs of Kirchhoff Laws

Relations analogous to Kirchhoff laws would be useful in designing fluid circuits. However, the counterparts of current and voltage are not clearcut. Mass flow has been chosen for current since this should obey continuity.

From the energy equation it can be shown[44] that the proper form for the analog of the voltage drop for a duct is

$$de = d\left\{ \overline{\int \frac{dp}{\rho} + \frac{v^2}{2}} \right\}$$

where de is the differential change of energy per unit mass flow in the direction of flow, p is pressure, ρ is density, v is the fluid velocity, and the average is taken over the cross-sectional area of the duct. Since de is not a perfect differential, the functional form of e is not fixed but depends on the thermodynamic path. This fact complicates considerably the problem of fluid circuit analysis.

Unfortunately the continuity and energy equations are not sufficient in general to specify fluid motion; the momentum equations are also necessary.

Since along with the above-mentioned problems, the fluid equations are nonlinear and fluid characteristics change with turbulence, it is easy to see why there is as yet no general fluid circuit theory. However, if only small fluctuations in pressure are assumed, most of the problems disappear.

In the expression for de, for example, $\int \frac{dp}{\rho}$ is of the order of a^2 where a is the speed of sound. Thus if $v^2 \ll a^2$, v^2 can be neglected, and if in addition the change in ρ is small we can write de as

$$de = \frac{1}{\tilde{\rho}} \, dp$$

where $\tilde{\rho}$ is the density averaged over the circuit. It is seen that de in this case does not depend on the thermodynamic path. For these same conditions, the fluid equations become linear, and if there is no d-c flow, the acoustic equations are obtained, which for a duct result in transmission line equations very similar to those of the electrical transmission line. There still are differences, however, because the particular form of the various impedances is dependent on the thermal boundary conditions.

4.3 Transmission Line Equations

While in electrical circuits of not too high frequency the impedance of connecting wires can be neglected, in fluid circuits impedance between ducts cannot in general be neglected. Thus transmission line equations are important. In addition they may be used to define resistance, inertance, and capacitance for lumped circuits and to show the conditions under which it is permissible to consider circuits as lumped.

The forms of the series impedance and shunt admittance obtained depend on the thermodynamic assumptions. The assumption leading to the simplest expressions is that of adiabatic flow, but this assumption is not a good one. The one usually conforming closest to actual conditions is that of isothermal walls. Solutions have been obtained for this case.[45,46]

If we assume that the form of the mechanical potential (the analog of the voltage) is given by $e = \frac{p}{\rho}$ and that the mass flow $\dot{m}$ is the analog of current, then since impedance has the dimensions of the ratio of e to $\dot{m}$, the adiabatic capacitance and inertance per unit length of duct are given by[47]

$$C_\ell = \frac{\rho A}{a^2} = -\frac{\rho A}{\gamma RT}$$

$$L_\ell = \frac{1}{\rho A}$$

where

ρ is the density averaged over the circuit

A is the cross-sectional area

a is the speed of sound and

$a^2 = \gamma RT$

where

γ is the ratio of specific heats

R is the gas constant for the particular gas used

T is the absolute temperature

The linear resistance per unit length as obtained for fully developed (Hagen-Poiseuille) flow is

$$R_\ell = \frac{8\pi\mu}{\rho^2 A^2}$$

where μ is the visosity.

For small fluctuations where ρ is essentially constant, the volume flow Q may be used as the analog of current in which case the pressure p is the analog of voltage. Since pressure is easier to measure than $\frac{p}{\rho}$, impedances are nearly always defined in terms of pressure divided by volume flow, and consequently differ by a factor ρ^2 from the above. Thus

$$C_{\ell Q} = \frac{A}{\gamma RT} = \frac{A}{\gamma p}$$

$$L_{\ell Q} = \frac{\rho}{A}$$

$$R_{\ell Q} = \frac{8\pi\mu}{A^2}$$

where the subscript Q is used to indicate that volume flow is being used for the current analog; the lumped circuit impedance parameters then become

$$C_Q = \frac{A\ell}{\gamma p} = \frac{V}{\gamma p}$$

$$L_Q = \frac{\rho\ell}{A}$$

$$R_Q = \frac{8\pi\mu\ell}{A^2}$$

where ℓ is length and V is volume.

For these equations to hold, it is necessary that ℓ be small compared with the shortest wavelength corresponding to frequency f, where the relation between the frequency, f, the wavelength λ, and, a, the speed of sound is

$$f\lambda = a$$

Linear resistances are capillary tubes with lengths much larger than their diameters. Hypodermic needles, etched channels, and ceramic tubes have been used.

Linear resistances of particular values have also been obtained by slowly squeezing small-diameter copper tubing in a vise while the pressure across it and the flow through it are measured. The tube is compressed until slightly less than the desired resistance is obtained. A crimping tool is then used to obtain a fine adjustment.

Variable linear resistances can be made by inscribing a helical groove on a circular cylindrical plug that can be moved within a sleeve (fig. 24). Similar devices can be made using screws and plastic tubing.

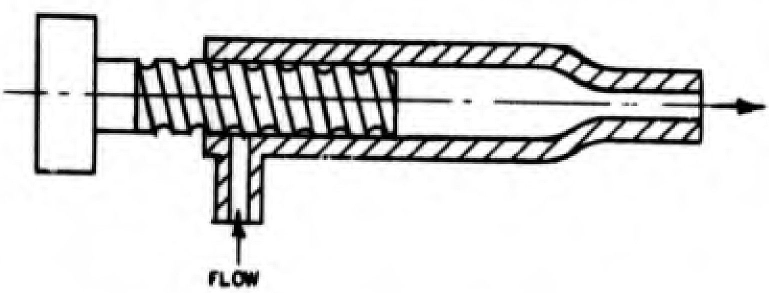


Figure 24. Variable linear resistor.

4.4 Finite Amplitude Waves

Small-signal theory is valid for much of the analog work of current interest in fluerics; however, there is also appreciable interest in large-amplitude signals. Although a number of papers relating to the propagation of finite amplitude waves have appeared in the literature, a practical way to apply the theory has not yet been found.

Waves of significant amplitude distort as they move down the duct, higher harmonics being generated at the expense of the fundamental. Since the velocity of propagation increases with amplitude, the maxima of the waves gradually overtake the rest of the wave so that high-amplitude sine waves eventually become saw-tooth waves.

A finite amplitude problem of particular interest is that of matching lines into the outputs of a binary switch so as to minimize reflections. If one is willing to neglect visosity, solutions of this problem have been available for some time.[48] If a propagating shock of some amplitude hits the open end of a pipe, an expansion wave will be reflected as shown at the top of figure 25. If a shock strikes a closed-end pipe, a shock (compression wave) will be reflected as in the center diagram. It follows that there exists some size opening which for a shock of given strength will result in no reflection, as shown on the bottom diagram.

Very little has been done toward treating finite amplitude waves in a pipe with some kind of transmission line theory. Perhaps this is not possible. Certainly we have to generalize our concepts of the passive components, since they will in general affect the momentum (a vector) as well as the energy (a scalar), and will have to probably invent some new ones in addition. So far this task has proved formidable.

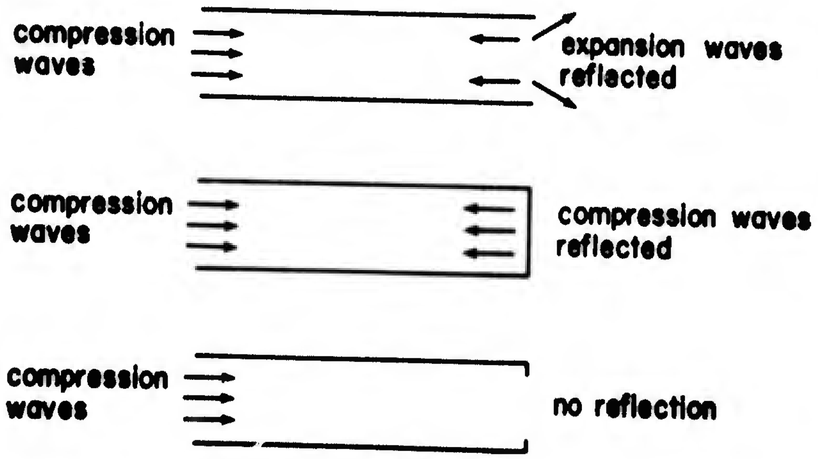
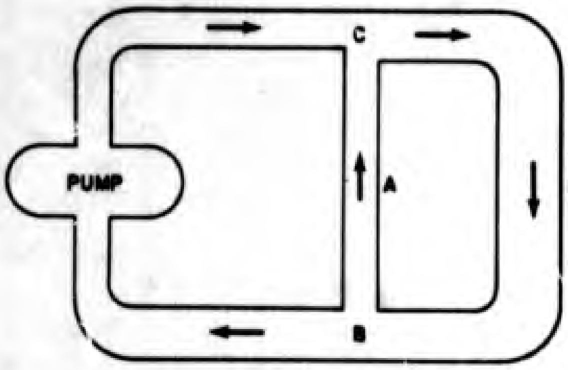


Figure 25. Terminating line with proper match.



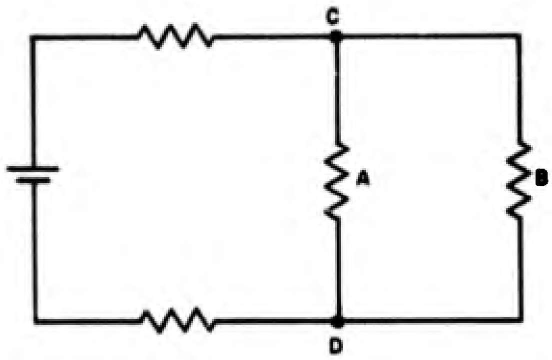


Figure 26a. A fluid d-c circuit.

Figure 26b. A topologically similar electric circuit.

When the d-c flow is not negligible or for finite amplitude waves, the effects of momentum must be considered.

Consider for example figures 26a and 26b. In the fluid system of 26a, we have a pump causing a d-c flow. Although on hasty consideration we might attempt to draw an electrical analog such as in figure 26b, a little thought shows that the two branches of the fluid circuit are not in parallel in the sense of the branches of electric circuit. In particular, we cannot think only in terms of an energy drop that is the same across both branches. Specifically, although the current in both branches of figure 26b must of necessity be in the same direction, this is by no means true for figure 26a where the flow in the central branch can be up while the flow in the end branch is down. The comparison above indicates the importance that momentum may play even in a rather simple fluid circuit.

5. SUMMARY

Through flueric devices have not as yet reached their optimum configuration, present designs permit systems to be constructed to do almost any desired operation.

The use of bleeds in components and the application of circuit theory concepts have very much simplified the construction of systems today compared with the difficulties encountered when the technology was new, but a great deal of work is still necessary in this area.

6. STANDARDS

The first published beginnings of standardization appeared at the October 1962 HDL Fluid Amplification Symposium in a paper by W. A. Boothe and J. N. Shinn entitled "A Suggested System of Schematic Symbols for Fluid Amplifier Circuitry."

The material in this paper was later revised and expanded by the authors under a contract sponsored by NASA.

In 1965 groups to develop standards were set up by three different organizations: The Naval Ordance Test Station to initiate the specifications for what would ultimately become a Mil Standard, the National Fluid Power Association, and the Society of Automotive Engineers.

The three groups began with the NASA document as a point of departure and, after the existence of a plurality of committees was recognized, coordinated with each other. As a result of this coordination, the documents arising from the work of these committees are in essentially complete agreement in those areas where items overlap.

Four individuals in particular were instrumental in working out the compromises necessary for this coordination: Rolf O. Gilbertson, James I. Morgan, Hans Stern, and Kenneth R. Scudder.

The standards documents are

1. Mil Standard 1306 - Fluerics Terminology and Symbols FSC-1650 17 July 1968 (available from the Clearinghouse for Federal Scientific and Technical Information).
2. NFPA Recommended Standard T3.7.68.1 Glossary of Terms for Fluidic Devices and Circuits.
3. NFPA Recommended Standard T3.7.68.2 Graphic Symbols for Fluidic Devices and Circuits.

Copies of the two NFPA Fluidic Standards can be obtained from the National Fluid Power Association, Box 49, Thiensville, Wisconsin, 53092.

4. Aerospace Recommended Practice ARP 993 Fluidic Technology. Available from the Society of Automotive Engineers, Inc., Two Pennsylvania Plaza, New York, New York 10017.

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There now exists an appreciable amount of literature on fluidics, most of which has been published as symposium proceedings. Because of space limitations we shall list here only the various symposium proceedings and two relatively comprehensive bibliographies.

Three books have been published on this subject:

"FLUIDICS" published by Fluid Amplifier Associates gives an overall view of the subject from a relatively nontechnical viewpoint.

"Fluidic Systems Design Guide" published by the Fluidonics Division of the Imperial-Eastman Corporation is a description of devices, systems, and applications contraining much information useful in working with fluerics.

"Fluid Amplifiers" published by McGraw-Hill discusses and develops much of the basic theory necessary for understanding fluerics.

A Fluidics Bibliography appears in Hydraulics and Pneumatics, Feb 1967 and June 1967.

One of the HDL series on fluerics is entitled Fluerics - 23. A Bibliography Jan 1967 AD 649269. It is available at $3.00 from the Clearinghouse for Federal Scientific and Technical Information, Sills Building, 5285 Port Royal Road, Springfield, Virginia 22151. (A revised edition should appear early in 1969).

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(The first issuance of the bibliography was as number 16 of the series. Unfortunately, the revision was inadvertently numbered 23 instead of 16, hence there is presently no report numbered 16)

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FLUERICS

1. Basic Principles

Errata:

The following list of symposia proceedings has inadvertently been omitted from the Bibliography (Section 8):

1. Fluid Jet Control Devices

A collection of ten papers resulting from the Symposium on Fluid Jet Control Devices, New York, N.Y. Nov 28, 1962 American Society of Mechanical Engineers.

2. 1st Fluid Logic and Amplification Conference Proceedings (Also known as the First Cranfield Conference) 24 papers September 1965.

3. 2nd Cranfield Fluidics Conference 50 papers January 1967.

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After a brief historical introduction, the physical phenomena underlying most fluerie devices are discussed. Brief descriptions of the operation of proportional and binary devices of various kinds are given including wall attachment, momentum interaction, vortex, and turbulence devices.

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