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FLUERICs

28: State-of-the-Art 1969

by

Joseph M. Kirshner

Richard Goitron

December 1969

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## ABSTRACT

This report consists of two parts. The first is a history of work on fluidics carried on at the Harry Diamond Laboratories set in a context of some of the other efforts in the field. The second discusses the state of the art.

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## 1. HISTORICAL BACKGROUND

As a result of the interest of Romald E. Bowles and Raymond W. Warren in improving the reliability of control systems by eliminating moving parts and of discussion that followed, Billy M. Horton early in 1959 saw the need for and conceived of a no-moving-parts fluid amplifier based on the momentum interaction of fluid streams. Bowles and Warren very shortly thereafter found ways to accomplish stream deflection using wall effects. Once the concept of no-moving-parts devices, including a no-moving-parts fluid amplifier, had been arrived at, various types of fluid phenomena and mechanisms were looked into to determine the possibility of using these phenomena in devices. The year 1959 was mainly one of invention, most of the time being spent in thinking up ways in which flow phenomena could be used to obtain no-moving-parts devices; some attention was also given to the fundamental problems. Instrumentation of various types was bought or constructed, including a water table, schlieren optics, and numerous pressure and flow gages.

Horton's original concept was of a proportional amplifier using round jets, but it was quickly realized that improved jet geometry was needed. Deflection of one round jet by another is inefficient since part of the flow and momentum of the control jet passes around the primary jet without appreciably affecting it. As a result, research was started on inclosed devices using rectangular nozzles and top and bottom plates. The initial design resulted in wall attachment devices rather than proportional ones and emphasis was applied to wall attachment concepts and components.

Simultaneously, efforts were continued on proportional amplifiers and on the use of flow phenomena to obtain other types of elements. Within a year, Horton, Bowles, Warren, and their coworkers had conceived and built many types of devices.

On 2 March 1960, the announcement of the invention of this family of components was made to an invited press audience and the publicity received resulted in the initiation of a number of small programs in industry. The original components were very difficult to stage, had low gains, and were quite noisy. In addition, very little was known as to the physical mechanisms involved and particularly as to their dynamic characteristics. In the face of these difficulties, many of the organizations that tried working with the devices soon (at least temporarily) abandoned the field.

However, the concepts had captured the imagination of a few professors and their students and research was in progress on a number of theses. Moreover, there were still a few companies attempting to perfect the devices and to build new types.

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In 1960, Horton initiated a course in fluidics (then called fluid amplification) at HDL. In this course, he discussed and provided notes on such topics as jet profiles, jet interaction, and other elements of fluid dynamics necessary to understanding the basic concept of the amplifiers. Possibly of more importance, he pointed out that concepts such as characteristic curves and impedance were very valuable in staging the devices. Lectures were given by J. Kirshner on flow-through lines and on temperature effects and by S. Peperone, who discussed the proportional amplifier as a two-terminal pair.

Although the notes for this course were never published, many copies were distributed outside HDL and helped in launching the technology. From 1959 until about the middle of 1961, emphasis at HDL was almost entirely on invention. Feasibility was shown for a number of devices, including the proportional amplifier and the bistable amplifier or bistable switch. The T-converter using the Warren loop was invented, as were also the rate sensor and various types of logic devices. Nearly all measurements that had been made, however, had been merely to determine whether or not a device operated, with possibly the single exception of Frank Manion's studies of the velocity profiles for the two-dimensional jet.

Toward the end of 1961, the fluids work at HDL was reorganized and the emphasis began to change. Efforts were made to apply impedance concepts to the devices and to determine characteristic curves so that devices could be staged with minimum difficulty. Work was begun on the development of an elementary theory of the proportional amplifier. Effort was put into the fabrication of devices by photoetching, a contract being initiated with Corning Glass for this purpose. Work was started on staging a proportional amplifier to be used with a vehicle for demonstrating that fluidics could indeed control large amounts of power. Consideration was undertaken of the use of a fluid amplifier to drive a heart pump.

A much needed impulse was given to the field in late 1961 when, as a result of conversations with Horton and Kirshner, Lt. Charles Bentz of the Air Force became interested. Bentz had become concerned by the trend to larger and larger control systems as aircraft turbine engines became more sophisticated. Fluid amplifiers offered the possibility of smaller engine controls with extremely high reliability.

In December 1961, HDL began a three-month feasibility study for the Air Force on the use of fluid amplifiers for turbine engine control. It was stipulated that on 24 March 1962, a demonstration of what had been done would be given to aircraft-engine control companies invited by the Air Force. By this date, HDL had devised and made preliminary tests on a temperature sensor and on a fluid-amplifier-controlled

speed control system. In addition, a five-stage proportional amplifier with a power gain of 200,000 built by Horton and Peperone had been used to steer a jet-engine-powered vehicle mounted on large casters. In 1962, publication of technical papers began, the first being a thesis written by Forbes Brown at MIT. HDL began its series of reports on fluidics and held a symposium on fluidics, at that time called fluid amplification, in October 1962. The symposium was attended by about 200 representatives of various organizations and resulted in 24 papers.

A highlight of this symposium was Raymond Auger's paper on and demonstration of the turbulence amplifier. Because of the ease with which these devices can be staged, they aroused appreciable additional interest in fluidics.

In October 1962, the ASME also sponsored a well attended symposium at which 10 papers were presented.

Another item contributing to the expansion of the fluidics technology was the aforementioned HDL contract with Corning Glass. After they had developed the procedures and could make units, Corning Glass began to market items, initially using the HDL design and eventually modifying these designs to their own specifications; they also provided services to other companies who desired to make photoetched fluid elements. Thus for the first time, fluidic elements became available in limited supply to the general market.

Work was increased at HDL in 1962 not only on fundamentals but also on new concepts. The heart pump was developed to the point where it could be tested on dogs. The demonstration vehicle performed successfully. The feasibility of fluidic temperature sensors was shown. The effect of heat on flow in ducts—how this could be used to switch or control fluid amplifiers—was demonstrated. Tests were made on thrust vector control. A three-stage digital amplifier was built. Studies were made on the effects of the changes of the geometric parameters of bistable devices and a number of methods of fabrication were investigated, including epoxy casting, metal etching, and the glass etching under contract.

By the end of 1962, there were 10 industrial organizations making contributions of note to the technology;\* out of these organizations came new and improved components and the beginnings of theoretical foundations. By this time, other government agencies had begun to see potential uses for these devices, and funds had become available for in-house studies and for contractual efforts.

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\*Honeywell, Sperry Univac, General Electric, Johnson Service, Bowles Engineering, Bendix Research, Giannini Controls (Conrac), Corning Glass, IBM, and United Aircraft.

The Missile Command at Huntsville had begun to fund research on devices as well as the development of a missile control system. The Air Force increased its funding to include studies of vortex rate sensors and other components for use in flight-control systems. The Navy began to look into steam turbine controls, boiler controls, and sequential startup systems. Partially as a result of the interest shown by government agencies, the Bendix Corp in 1963 expanded their relatively small effort into a very substantial one.

Some of the important effort at HDL in 1963 included publication of work on static characteristics and studies of the effect of sound on jets; signals were mixed and difference frequencies obtained for the first time in fluidic devices; jet cavity resonators were investigated, and it was demonstrated that noise in proportional amplifiers could be reduced by use of tuned cavities. Several designs of amplifiers with supersonic power jets were built. Although some of this work was reported in 1963, most of it was not reported until the second fluid amplification symposium, held in May of 1964, at which 60 papers were presented.

By 1964, many government agencies had become involved in the field. In July of 1964, a meeting was held at HDL at the suggestion of Majors William Hipple and Carl Wheaton of the Air Force, and the Government Fluid Amplification Coordination Group (now the Government Fluidic Coordination Group - GFCG) was formed, consisting of representatives of agencies of the Army, Navy, Air Force, NASA, and AEC.

In 1964, efforts at HDL included the determination of transfer functions for proportional amplifiers, and additional emphasis was put on the effect of hydrodynamic instabilities.

Also, in 1964, NASA funded a study of symbology and nomenclature for this new field. The results of this study were then used by the Navy as a basis for further work to provide military standards, by standardization committees set up by the Society of Automotive Engineers, and by the National Fluid Power Association later, in 1965.

The members of the GFCG were somewhat concerned by the possibility of two different sets of standards arising from these two different standardization committees and immediately began efforts to coordinate the work of the two committees. As a result, wherever the items discussed by the two committees are the same, a mutual nomenclature and symbology has been obtained.

In its initial years, fluidics had received a great deal of publicity, and many glowing predictions had been made as to its future. As a result, every year a number of organizations made some casual investigations, but actual expansion of fluidics as a technology (in terms

of the number of active organizations) had been almost negligible.

Although the number of U.S. industrial organizations with significant programs failed to increase appreciably up to 1965,\* there had been a pronounced increase in research carried out in various educational institutions and in government, and there was an increase in foreign interest.

The government-funded studies resulted in many new and improved components that made it much easier to build large systems. Nearly all feasibility studies carried out on systems were successful, so that by mid-1965 a number of systems containing hundreds of elements had been demonstrated.

The Third HDL Fluid Amplification Symposium and the First Fluid Logic and Application Conference (also known as the First Cranfield Conference) were held in 1965. The latter was held at Cranfield, England, and was the first of a series of fluidics conferences which to date have been held at Cranfield, Cambridge, and Torino.

Some important items examined at HDL in 1965 included capillary resistance, the effect of aspect ratio on noise, and the building of a tapereader for use as a demonstration device. The theory of a temperature-insensitive oscillator and a pressure-controlled oscillator was developed, acoustic pumping was used to control fluidic devices, and a fluidic pressure regulator was conceived and tested.

Early in 1962, an internal seminar had been initiated at HDL to keep personnel aware of what was going on in fluidics in HDL and elsewhere. Written notes were distributed internally; then in 1964 at the request of the Catholic University of America, HDL revised and expanded these notes and offered a one-week seminar in fluidics in cooperation with CU in conjunction with the Diamond (75-yr) Jubilee of the Catholic University. These notes were further revised and were published in 1966 by McGraw-Hill under the title "Fluid Amplifiers."

Also published in 1966 were "Fluidics" by Fluid Amplifier Associates and "Fluidic Systems Design Guide" by the Fluidonics Division of the Imperial-Eastman Corporation.

Some of the important new work at HDL in 1966 included studies on the characteristics of the turbulent bounded jet and of the confined jet.

By the end of 1966, almost 200 patents had been issued for new or improved fluidic components and devices (nearly 100 of these in 1966 alone). The technology had developed to the point where the original

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\* Important exceptions were the companies marketing Auger's turbulence amplifier and systems depending upon it, and the formation of Fluidonics, Inc.

few difficult-to-stage components had been replaced by families of devices relatively easy to stage and, in fact, as previously stated, systems containing hundreds of units had been built. Modular and miniaturized circuit elements were being used by many organizations. Possibly even more important, theories for the devices were becoming more meaningful.

There had been a great many successful devices and systems built by and for the government. Some examples are: a very rugged temperature sensor that can be used at high temperatures and has a response time considerably shorter than that of a shielded thermocouple; a turbojet control system demonstrated on an engine in 1964; a missile control system flown in 1966; and a flight control system also flown in 1966. Devices have been shown to operate at temperatures as high as 5000<sup>o</sup> Rankine and as low as almost absolute zero using liquid helium.

However, until late 1965, industrial funding was primarily by the government or was internal. As a result of government disseminated information, the new and improved components available, and the know-how gained on government contracts, in 1966 there began a determined effort by industrial concerns to find commercial applications.

In 1967 HDL personnel helped organize the Fluidics Committee of the ASME, and together ASME and HDL cosponsored the 1967 Fluidics Symposium in Chicago. This committee has subsequently sponsored many fluidics sessions at the various ASME meetings.

An important innovation in 1967 at HDL was the design of a low-power digital fluid logic circuit element. This incorporated its own manifold and was built so as to require only a single type of manifolded element that could be modified relatively easily. The power consumption per element is some 2 mW. A computer program was developed to allow a circuit design to be analyzed, and the results were used to indicate what processes should be applied to each of the circuit elements to provide the modifications needed for any given circuit.

In 1967 and 1968, efforts were made at HDL to improve the theory of the proportional amplifier to include its dynamic effects. The effects of the vents and of the loading were considered. Also about this time, increased effort was put upon the theoretical development of the binary device. One of the things considered was the boundary layer effects along the curved wall and methods of optimizing the curvature to provide the optimum or maximum pressure recovery and the least energy loss. The theory of temperature- and pressure-insensitive oscillators was extended to lumped parameter circuits, the previous analysis having discussed the distributed parameters for a duct type of feedback. The effort on edgetone cavity coupling and how it affects the oscillators and the proportional amplifiers was also intensified.

Initial acceptance of the devices in industry was slow because of the tendency to adhere to known techniques, because the initial costs were quite high, and because the first generation of commercial devices still left much to be desired with respect to their characteristics and the ease of building them into circuits and systems.

Although the price of fluoric devices is gradually decreasing (in May of 1969, one company reduced the prices of its elements to one third of the previous price), many items are still sufficiently expensive that fluidics cannot always compete with other techniques.

The newer commercial fluidic devices are considerably improved over those of 1966. These newer components not only have eliminated many of the staging problems but are being built in modular form so as to minimize tubing and allow easy snap-on or plug-in construction.

The number of companies making or marketing fluidic components and systems has increased appreciably within the past few years. (The May 1969 Issue of Instruments and Controls lists 76 vendors.) As a result, we find today that hundreds of applications have been found for fluidics and many more are being considered. It would be completely erroneous to say that all the major problems of fluidics have been solved, but we have made considerable progress in these 10 years.

Of the practical problems we still have to tackle, the most important one is probably that of cost; it is still necessary to devise better and cheaper fabrication techniques. Some of the other problems that confront us are discussed in the rest of this paper which is devoted essentially to the present state of the art.

## 2. COMPONENTS

There are now available in no-moving-part form many devices that are fluid analogs of electrical circuit components. There are several types of proportional amplifiers, digital switches, flip-flops, various types of logic devices, and analogs of just about every other type of electrical circuit element. There are, however, two types of elements for which good fluoric analogs do not exist. These are the diode and the point-to-point capacitor.

### 2.1 Diodes

Although fluoric diodes exist, the forward-to-backward ratio (or diodicity) leaves much to be desired. Since these diodes are non-linear, the diodicity can be defined in more than one way. If we choose the definition that gives the highest ratio, the best possible is about 50 (ref 1). In arriving at this number the measurement is

made with the flow in each direction the same, and the pressure drop resulting from this flow is measured. If, on the other hand, the test is made with the pressure drop in the forward and backward directions the same, the ratios of flow obtained are about 7 to 1. Regardless of which ratio is chosen, no-moving-part diodes are not particularly good.

In many circuits what is required is not precisely a diode in the ordinary sense, but some way of keeping fluid from returning into a particular duct when the flow is reversed and still allow flow to pass out of that duct with ease. This can be done by a device that diverts the flow if it is in one direction but does not divert it if it is in the other direction. There are many ways of doing this. A simple technique is to use a biased Y-shaped flow divider. Flow entering the right arm of the Y exits from the base, and flow coming in at the base leaves from the left arm because of the built-in bias.

The diverted flow (and the associated energy) is in this case thrown away; whereas a true diode cuts off the flow rather than wasting it. A recent patent by C. Kwok (ref 2) describes a device that cuts down the supply flow and diverts it to obtain a decrease in the flow thrown away. His device is essentially a Tesla diode with bleeds.

## 2.2 Capacitors

The capacitance of a fluid is in general associated with its compressibility. This capacitance is, in effect, primarily a point-to-ground capacitance and cannot block flow. Point-to-ground capacitances are available for gases, but the point-to-ground capacitances for liquids are, in general, very small in value. A point-to-point capacitance, on the other hand, would have the effect of completely blocking dc, whereas ac would pass proportional to the frequency. At present, there is no flueric component having this property. A moving-part device approximating this sort of behavior is a thin membrane or diaphragm.

The lack of a point-to-point capacitance makes it necessary to revise certain types of circuits. For example, an integrator that uses a point-to-point capacitance feedback from the output to the input is not feasible fluerically. However, a boot-strap type integrator can be made since it uses point-to-ground capacitance. Since for liquids point-to-ground capacitance is very small, most circuits must be considered in terms of inertance and resistance. Capacitance arising from liquid compressibility is rarely used. Conventional liquid circuits often make use of a capacitance (usually denoted as compliance) that arises from elastic lines, bellows, diaphragms, and the like. It is also possible to use gas-filled tanks as capacitances for liquid systems. Where feasible, the latter may be more compatible with flueric systems.

### 2.3 Analog Amplifiers

There are several types of analog amplifiers, such as the beam-deflection (momentum interchange) device (ref 3), impact modulator, and vortex amplifier.

Commercially available beam-deflection amplifiers have listed pressure gains around 4 to 6 and bandwidths to 1000 Hz (ref 4,5). Pressure and flow recoveries from 30 to about 50 percent are possible, depending on design and loading.

Noise was a problem area of the beam-deflection amplifier in its initial years (ref 6). Dynamic ranges of 10 to 20 were prevalent. Interconnecting analog amplifiers often resulted in noise saturation in the later stage or stages. The earlier changes increased the dynamic range up to about 100 by considerably reducing the bandwidth. More recent work has resulted in dynamic ranges of over 1000 while still maintaining bandwidth (ref 7). There are now commercially available amplifiers with dynamic ranges of 200 and with a bandwidth of 1000 Hz (ref 4).

Improved noise-reduction techniques have permitted the development of operational amplifiers formed by cascading several beam-deflection amplifiers. Pressure gains of these operational amplifiers vary from 20 to 200 (ref 8) with power gains to 2500 (ref 9).

The vortex amplifier is a flow-controlled device that requires control pressures from 25 to 75 percent more than the supply pressure (ref 10) and has a turndown ratio of about 10; i.e., it varies from full flow to about 10 percent of full flow as the control is increased. Maximum pressure recovery is 95 percent resulting in power recoveries of 50 to 75 percent with bandwidths of 50 to 100 Hz (ref 11). The primary advantage of the vortex amplifier is that it is a throttling device rather than a diverting device, but it is relatively noisy and the control pressure must be higher than the power-jet pressure. Because of these factors, the vortex device is more useful as a power output device than for fine control or where staging of many elements is involved.

Important design criteria for vortex valves have been established by Mayer (ref 12), by Wormley and Richardson (ref 13), and by Bichara and Orner (ref 14).

Impact modulators are utilized as analog amplifiers with pressure gains of 30 to 50 (ref 15) but are not yet commercially available. Neither vortex amplifiers nor impact modulators lend themselves to modular-construction techniques.

## 2.4 Digital Elements

Fanout, pressure, flow recoveries, and response time are critical parameters for the binary switch. Most digital systems today use the vented wall-attachment digital amplifier. The vented amplifier has a lower pressure recovery than does the unvented amplifier (ref 16), but the vented version is more versatile because it can operate into blocked loads.

Digital amplifiers or binary switches with fanouts of 3, pressure recoveries of 35 percent, flow recoveries of 80 percent, and switching time of 1 ms or slightly less are commercially available (ref 4, 17). Fanouts up to 32 have been achieved but usually at the expense of stability. Recent studies have indicated that pressure recoveries of over 90 percent are possible by curving the offset wall in the interaction area (ref 16).

The wedge-type splitter is now rarely used with the binary switch because the cusp splitter has shown a marked superiority. Not only is the switching process sharper with the cusp-type splitter, but the vortex formed by the splitter increases the stability of the device. This permits proper operation at lower pressures and under more stringent environmental conditions.

The vortex amplifier can be designed as a digital device, but the pressure required at its controls (higher than at the supply) causes problems when a logic system is to be built requiring many elements.

The impact modulator is now commercially available as a NOR element with a fan-in of 4 and a fanout of 10 (ref 18).

## 2.5 Logic Elements

Typical active logic elements based on geometrical modifications of the fluidic bistable amplifier have approximately the same characteristics as has the amplifier. Passive AND elements exhibit about the same performance characteristics as those of the digital amplifier, with pressure and flow recoveries around 40 to 80 percent of the input.

Other types of logic elements exist, such as the turbulence amplifier (TA) and the laminar NOR elements (ref 19, 20). Both of these are low power-consumption NOR devices requiring amplification before the signal can be used to actuate a mechanical device. The attractiveness of these types of elements is the low power consumed, but they have a distinct disadvantage in that the response time is

greater than that of the higher power devices and the bandwidths correspondingly narrower. Although times as short as 1.5 ms (ref 21) have been claimed for a planar TA, the conventional TA has a time constant of about 10 ms. The time constant for the laminar NOR is around 30 ms (ref 20). However, they are useful where low power consumption is more important than speed. In a paper written by F. Siwoff (ref 22), the use of a knife edge between emitter and receiver is shown to appreciably decrease the response time of the TA.

Although no paper has appeared in the literature, a patent issued to K. Howie, Jr (ref 23) claims faster response and ability to operate at higher pressures than can the ordinary TA. To accomplish this, an additional piece of duct is inserted between output and emitter.

The conventional TA has a high fanout (around 6) and a pressure recovery of about 30 percent (ref 24). Higher pressure recovery can be obtained but only with a significant decrease in fanout capability. The laminar NOR has a fanout of 2 with a pressure recovery of approximately 40 percent (ref 20). The major advantage of the laminar NOR over the conventional TA is that it lends itself more readily to modular construction techniques although modular construction is also possible for the planar TA (ref 19).

Other devices in which transition from laminar to turbular and vice versa is used to produce a fluid device have appeared in the patent literature. E. E. Metzger (ref 25) uses one control stream to change a number of control streams from laminar to turbular. Using this principle enables him to get more than one type of logic output (OR, NOR, AND, etc ) from an amplifier.

A shroud is used with a turbulence-type device to obtain a bistable amplifier in a patent by R. C. Mott (ref 26). The shroud and an associated input to the shroud housing make it possible to cause the jet to become turbulent and remain so as long as the air entrained from the atmosphere is permitted to come in through the control into the housing. If the entrained air is cut off, the jet returns to a laminar state. According to the inventor, variation of this geometry, primarily introduction of a resistance in the input, makes proportional outputs from the turbulence device possible.

Transition from laminar to turbulent flow plus wall attachment is used in amplifiers described by H. H. Unfried (ref 27) and R. R. Schaffer (ref 28). In Schaffer's amplifier, the configuration is roughly like that of a bistable amplifier with a center dump. The device has three outlets plus two side vents and two input controls. With no input from either of the controls, the jet is normally laminar

at the operating pressures and therefore moves straight ahead into the center receiver and issues from the center outlet. If a signal is inserted at, for example, the right control, the jet becomes turbulent and attaches to the opposite (in this case the left) wall and therefore enters the left receiver and issues from the left outlet.

## 2.6 Sensors

Many types of sensors have been or are being developed for use with flueric systems. Some of these units are adaptations from older, proved designs, and some are new concepts originated by the anticipated increased use of fluid control systems due to the advent of fluerics.

Proximity detection, mechanical motion, and other hydromechanical sensors are examples of concepts adapted for fluidic systems. New concepts usually fall in the area of determining the thermodynamic properties of a moving gas or liquid. Yet, even some of these new concepts do not involve the actual sensing but relate to the matching of the sensed quantity with a flueric component and hence system. As an example, the pressure-sensing devices such as angle-of-attack sensors, shock sensors, compressor-ratio sensors, and level sensors fall into this category. The advantage of fluidics for these pressure sensors is reliability and the extreme environmental use associated with fluerics in general.

### 2.6.1 Accelerometers

A number of fluidic accelerometer concepts have been mentioned in the literature; nearly all involve a seismic mass that acts as a flapper valve or variable restrictor as it moves, changing the relative flow into one or more sets of ports that lead to the flueric controls or measuring devices (ref 29).

The only flueric concept published is that of jet deflection under acceleration. Because the deflection is dependent on the difference in density between jet and surrounding fluid, the sensitivity is very low for an air-in-air jet. The use of fluids of different densities for jet and environment (e.g., helium in air) has been suggested, but no results have appeared in the literature.

### 2.6.2 Angular Rate Sensors

Several flueric angular rate sensors have been investigated. They may be separated into those depending on (1) Coriolis force, (2) gyroscopic effect, and (3) conservation of angular momentum (vortex devices).

The Coriolis device uses a jet and two or more receivers. Rotation of the device causes the jet to deflect with respect to the receivers. The gyroscopic device uses a spinning fluid kept in motion within a sphere by tangential jets. Pressure sensors detect the movement of the axis of rotation.

Most of the effort in rate sensing has been on vortex rate sensors utilizing the velocity change that occurs as the fluid moves from the circumference to the drain. The sensitivity, threshold, and response of a vortex rate sensor are interdependent, and tradeoffs are consequently employed depending on the intended use. Examples of available characteristics for a 4-in. vortex rate sensor (ref 30) are

- (1) Sensitivity - 0.05 psi/deg/sec
- (2) Threshold - 0.2 deg/sec
- (3) Response - 10 Hz

Several papers on vortex rate sensors have indicated a low threshold, high sensitivity, and a relatively broad bandwidth. These were, however, measured at different conditions.

### 2.6.3 Temperature Sensors

Aside from the more conventional sensors, there are two types of temperature-measuring techniques associated with fluorics. The pressure-drop type sensor depends on a pressure change across a capillary resistor primarily as a result of the change in viscosity of the gas flowing through the resistor. In general, a nonlinear resistor is required in series with the capillary (essentially linear) resistor.

The other type fluoric thermometer is an oscillator that changes in frequency as the temperature changes because the speed of wave propagation varies with temperature. Both external feedback and internal feedback (cavities) have been used. Of these, the cavity device has received most attention (ref 31). When operating with choked flow, it has very little pressure sensitivity. The sensor has been used as a temperature probe in extreme environments because of its small size and ability to operate with a fast response at extreme temperatures. The characteristics of the sensor depend on the gas and temperature of the gas being sensed as well as on the size of the device. In addition to the response time resulting directly from a sudden change in temperature, there is a time constant resulting from thermal lag due to the heat transfer from the gas to the body of the sensor. Methods of compensating for or minimizing this effect include the use of insulating layers of material (where feasible) and the addition of lead circuits in the output.

#### 2.6.4 Thread or Other Small Object Detector

A jet at low Reynolds numbers is very sensitive to disturbances—a property fundamental to operation of the turbulence amplifier, which makes it possible to sense the presence of small objects such as a thread (which will trigger turbulence). This device can be used to detect the breakage of a thread or to count small objects. Impact modulators have been used in a similar fashion where advantage is taken of the fact that a boundary layer surrounding a rapidly moving thread increases its apparent diameter.

#### 2.6.5 Stall Sensor

A stall sensor developed by Warren and Swartz (ref 32) shows great promise. In developing this device, the ordinary binary switch was found to have some problems. The conventional binary switch has a pressure lower than ambient at its controls so that it tends to suck in air from the atmosphere. Since it is better for the air to flow out the controls rather than in (to prevent dust intake in the stall-sensing system), the binary switch was altered. By a connecting passage from the power nozzle input to the control nozzle input, part of the flow from the power jet is channeled off into the control inlet. This causes flow out of the control instead of into it. The operation of the sensor depends on the fact that when the flow is attached to the upper side of the airfoil, it causes the pressure in a small tube just above the airfoil to be less than it is if the airfoil stalls and the jet detaches. The change in pressure resulting when the flow separates is used to flip the amplifier.

### 3. INTERFACE DEVICES

As flueric devices and systems gain wider acceptance, more emphasis is being placed on hybrid systems that include mechanical and/or electrical components. Thus interface devices that convert one type of energy to another are increasing in importance. Interfaces are also used between two systems operating at greatly different pressure levels or using different fluids, and finally we can also class as interfaces the various types of input devices and output (display) devices.

Aside from the more or less conventional devices that have been around for some time (such as pressure transducers), most devices to date have been built for specific systems and relatively few are commercially available. Patents are, however, appearing and a few papers have been published dealing with interface techniques.

#### 3.1 Mechanical to Flueric

A bistable device of the HDL type can be flipped by closing

one of the control ports by placing a finger over the opening. This is a simple type of mechanical-to-flueric conversion.

An immediate extension of this is to bring the various controls of a system of flueric amplifiers out to a single panel so that inputs may be made to any desired amplifier by merely closing off with a finger the proper hole on the panel. Some improvement in finger comfort and in precision is obtained at the sacrifice of simplicity if spring action keys (similar to typewriter keys) are used to cause the necessary closing of the ports. A pneumatic keyboard was first patented by W. G. Wadey in 1962 (ref 33).

Further extensions of this concept are to punched card and tape readers (ref 34, 35). An eight-hole tape reader was discussed in 1965 by Norman A. Eisenberg (ref 34). Coded information punched onto the tape was passed through a logic system, and the output was used to drive a typewriter.

Details on the head of a tape reader that uses back pressure sensing are given in the 1967 paper of Cant and Rosenbaum (ref 36). As the authors point out, back-pressure sensing may be slightly slower but it minimizes the risk of dust contamination.

Mechanical motion can be used to restrict the flow into the controls or to cause back-pressure signals not only in the ways mentioned but by variations such as discs that can be turned to expose a hole or slit (or rotated to form a signal generator), wobble plates (ref 37), and turnable balls with drilled-through holes that can be aligned with the control ducts. A similar but slightly different concept is involved in mechanically aligning a jet pipe with a control port (ref 38).

A different concept uses the motion of pistons in hollow cylinders (ref 39) connected to the control ports to produce a transient flow to cause switching. Reeds and tuning forks (ref 40, 41, 42, 43) have been used to synchronize oscillators by covering or partially covering the controls during their vibration.

### 3.2 Electrical to Fluid

Electrical techniques are of several types. The most obvious is the use of electromagnetism to cause the mechanical motion necessary to open or close the control port. An example is the use of a solenoid (ref 44). A variation is to use an electromagnetic field to control the motion of a reed or plate (ref 45, 46, 47, 48). Displacement of the reed opens or closes the port. By connecting one of a pair of ducts to each of the controls and bringing the duct openings opposite

each other, the reed motion can be caused to close one duct and open the other.

Variations of the above include making the reed itself a movable wall of the amplifier and thus directly deflecting the power jet (ref 49), and using an electrically positioned jet pipe placed within the power nozzle (ref 50). Electrostriction or magnetostriction may also be used to bend a reed to close or open a port. A second electrical technique is to use heat generated by electrical energy either to cause a mechanical motion (for example using a bimetallic strip to cover or uncover a port) or to affect some flow parameter, usually viscosity (ref 51). A third method is to cause a conducting fluid to deflect by means of a magnetic field (ref 52) or to cause its viscosity to change by a magnetic field (53). Certain dielectric liquids (such as kerosene) can be deflected in an inhomogenous electric field.

Control is also possible using an acoustic field to change the turbulence of the eddy-shedding characteristics of the power jet (ref 54, 55, 56). The acoustic field is usually obtained from an electromagnetically driven diaphragm or from a piezoelectric crystal. The difference in entrainment as the degree of turbulence changes results in pressure variations, which can be used for control purposes.

DC flow can be produced from an acoustic signal by rectification. This d-c flow can then be used for control (ref 57, 58). Electric sparks have also been used to switch fluoric devices (ref 59, 60, 61).

### 3.3 Fluoric to Mechanical or to Electrical and to Higher-Power Devices

The output of fluoric device may be used to move a piston (ref 62, 63), a spool valve (ref 64, 65), or a diaphragm in more or less obvious ways. The resultant motion can be used for actuation or control of a higher-power device that uses a high-pressure gas or liquid (ref 64). The mechanical motion can be used to display the output (ref 66), and the motion can be used to close or open an electric circuit; it has also been used to generate electricity in a piezoelectric crystal (ref 67) or in a conductor in a magnetic field.

## 4. CIRCUITS AND SYSTEMS DESIGN AND ASSEMBLY

There are several important problems related to building a system from components. These are concerned with matching (i.e., minimizing reflections), stability, obtaining the necessary bandwidth (or response time), minimizing noise, ease of fabrication, size and weight of the system, and power consumption.

Ideally, it should be possible to build these systems without knowing a great deal of fluid dynamics. Thus, it is desirable to devise techniques allowing characterization of fluidic components as black boxes and putting them together purely on the basis of their inputs and outputs with no concern for internal operation.

The simplest items to work with are a set of compatible modular items that can be easily connected (by plugging into a board or by stacking). A number of companies are presently marketing modular components of both stacking and plug-in variety. Plug-in modules in general require the use of some type of quick disconnect, which, typically, may consist of a spring-loaded ball that closes off the inlet until it is opened by insertion of the plug (ref 68).

A type of stacking module consisting of a laminar NOR element and an associated manifold has been designed by Trask (ref 69, 70). This device has the advantages of low power ( $\sim 2$  mW) and identical modules. It has the disadvantages that its response is relatively slow and each module must be altered to produce the required logic circuit. Iseman and Trask have minimized this latter disadvantage by devising a computer program that allows the circuit desired to be fed into the computer and then reads out the modifications necessary for each module and the order in which they should be stacked (ref 20). This program could also be used to feed an automatic machine tool that would make the necessary changes.

Although the modular approach is working out very well, to obtain a high degree of flexibility in designing fluidic circuits, particularly with analog devices, a fluid-circuit theory is needed so that one can analyze circuit response and ultimately synthesize networks to obtain desired responses. Although at present this task seems far beyond our capabilities for the most general case, analysis is being done for many specific cases.

#### 4.1 Fluid Circuit Theory

There are no analogs of Kirchoff's circuit equations that hold for the general case of fluid flow. The difficulties are that the Navier-Stokes equations are nonlinear and a general theory must account at least for momentum, temperature, and turbulence effects. When compressible flow is considered, the continuity conditions necessary for a proper analog for current are satisfied only by mass flow. Then since the analog of the voltage must satisfy the energy equation, one must use that equation to determine it.

Unfortunately, purely thermodynamic considerations alone are insufficient to supply the proper definition since all energy available

in a thermodynamic sense is not in general mechanically recoverable.

This is not the only problem involved in attempting to obtain a general fluid-circuit theory. Another difficulty is that analogs of voltage and current are not sufficient to specify the flow conditions since it is also necessary to take momentum into account. This means that the circuit properties of the fluid must be expressed by a function having both vector and scalar properties and that the conventional parameters of an electrical circuit (capacitance, inductance, and resistance) are not sufficient for a fluid circuit. Not only must one generalize the electrical parameters but additional ones are needed. For example, besides something to express energy loss and energy storage, we have to be able to express the fact that the fluid may change in direction as it does in a tee or an elbow.

Upon considering the above along with the problems associated with accounting for turbulence, we may conclude that the task is almost hopeless; however, we are also forced to conclude that solving the set of fluid equations (Navier-Stokes, momentum, and continuity) for each particular control system or circuit cannot be any easier. It therefore does seem worthwhile to attempt to develop circuit techniques despite the discouraging outlook.

Certainly some of the other concepts associated with circuits and control systems and which require the use of the above analogs can (where they can be applied) very much ease the problem of fluid circuit analysis and synthesis. We refer to the fact that it is not necessary to consider the entire system, but that portions can be analyzed separately and considerable simplification obtained by use of the concepts of impedance, characteristic curves, etc.

Many of these concepts are already being applied.

For the particular case when  $v^2 \ll \int \frac{dp}{\rho}$ , which corresponds to  $v^2 \ll a^2$ , where  $a$  is the speed of sound, i.e., for low Mach number flow, the momentum effects and the nonlinear terms in the fluid equations become negligible and the resultant equations turn out to be essentially identical with the electrical equations so that all of electrical theory becomes applicable to fluid circuit theory (ref 71, 72, 73, 74). One can develop transfer functions, transfer matrices, and all other mathematical tools that normally go with linear systems (ref 75, 76, 77).

Where the velocity is sufficiently high or when temperature changes are sufficient to cause appreciable changes of density in the circuit, volume flow and pressure are not even approximately the proper analogs to use. Primarily because measurement techniques and the

present theories allow little alternative, we find these same variables being applied even when their use is improper and the meaning of the results questionable. However, in many cases of interest, the linear assumptions hold and it is possible to derive transfer functions for fluid amplifiers (ref 76, 77) and to analyze circuits with good agreement between theory and experiment (ref 75, 78). Although no general circuit theory exists, when nonlinearities must be taken into account, well known results of unsteady flow are being applied in considering matching of fluid elements and effects of branches. In many cases the assumption of inviscid flow and the method of characteristics allow at least rough solutions for the cases of interest (ref 79). For example, one of the important problems that has been considered in this way is that of impedance matching, i.e., the process of obtaining minimum reflection of a wave and maximum energy into the next element or next portion of the circuit.

Another area of interest which concerns finite amplitude waves or where the momentum must be considered is in the case of the tee. S. Katz (ref 80) has examined the steady-state aspects of the tee, and J. Iseman (ref 81) has looked into the dynamic characteristics of the tee. The dynamic characteristics are of particular interest because a tee forms a kind of differentiator. If a step input is applied to the arm of a tee, the output from the base will be a pulse. Iseman's experiments have shown that the tee in many respects actually approximates an RC differentiation circuit. There are undoubtedly some differences; and some preliminary unreported experiments carried out some time ago by S. Katz have shown that if a sinusoidal wave is used as the input, the phase shift between the input and the output is not necessary approximately 90 deg but depends on the direct current that may be present.

Let us now return to the cases for which the fluid equations become linear, i.e., the cases for which the Mach number is relatively small, less than, say, 0.3. Under these conditions, it is possible to solve a number of problems. One of these is that of obtaining an oscillator insensitive to temperature. Using linear equations, it has been shown that temperature-insensitive oscillators are possible; this has been experimentally confirmed (ref 82, 83, 84).

The equations have also been used to show how the frequency of an oscillator can be made to depend linearly on pressure (ref 82).

We also repeat for emphasis that the linearized equations are applicable in many fluidic control systems and that transfer functions for fluid amplifiers have been developed and computing circuits of various types (summing, differentiating, integrating, etc) built.

## 5. EFFECTS OF ENVIRONMENT

The statement that flueric systems can operate in extreme environments has, unfortunately, often been interpreted to mean that flueric systems are unaffected by the environment. Actually, however, even as far back as 1962 (ref 85), an environmentally affected limitation was pointed out when a minimum Reynolds number below which the wall attachment bistable amplifier does not operate was discussed. Since it depends on the viscosity, the Reynolds number is a function of temperature and consequently the effect of temperature is important.

The use of sound to control a digital amplifier was reported in 1964 (ref 54). Thus the effect of an acoustic environment is obviously important. Initial work on the effect of environmental changes consisted of limited tests on a component or system. These tests considered only complete failure, and neglected performance changes. To the knowledge of the authors, no shock and vibration tests, which commonly cause failure in mechanical and electrical systems, have produced any flueric failures.

Recently, tests have been performed that consider the effect of temperature and sound more completely.

### 5.1 Temperature Effects

Since strong wall attachment is obtained only in the turbulent flow regime, if the Reynolds number decreases until transition to laminar flow occurs, the wall attachment becomes weak. This minimum Reynolds number (about 50) can easily be obtained when small units are considered. The loss of wall attachment will seriously affect the performance.

If the input and output characteristics change with temperature, the performance of an individual component in the system could degrade to the extent that it would not be able to properly control the subsequent components. Then failure could occur although the affected component would still operate under some tests. As an example, if the system is designed so that a bistable amplifier requires a fanout of two and, if as temperature increases the component's fanout capability decreases to one, the system will fail when used to drive two units although the amplifier would still exhibit bistability.

Recent tests on digital and analog amplifiers show this component degradation (ref 86, 87). The analog amplifiers tested were more sensitive to temperature than were the digital amplifiers and, as expected, the effect was more pronounced for the smaller units. The same tests showed that minimum Reynolds number varied significantly with temperature.

These tests showed that the splitter design was a critical factor and that a bistable amplifier with a cusp-type splitter would operate under conditions where one with a wedge-type splitter would fail.

No tests have been reported on the dynamic effects of temperature, but one would expect that switching times will change. It is obvious that the material of the fluidic system must be able to withstand the temperature. Present commercially available units are limited by their material to a temperature range of a few hundred degrees. High-temperature fluidic systems are presently costly due to the expensive fabrication techniques necessary for the more exotic materials.

## 5.2 Acoustic Effects

The initial work at HDL on the effect of sound on units (ref 54) spurred considerable interest. Work has progressed in two directions, experimental and theoretical. The theory has been slow in developing because of lack of technical literature on the interaction of turbulent flow with an acoustic field.

The effect of a sound field on a laminar jet has been known for many years. A laminar jet, being extremely sensitive to sound, breaks up rapidly into turbulence even at low sound intensities. Thus, it is dubious whether a turbulence amplifier can be used in an environment where an acoustic field is present. Since the laminar jet is much more sensitive to certain frequencies than to others, it may be possible to design a component to operate in a sound field if the frequency spectrum of the field is known. However, it does not appear likely that devices operating with laminar flow jets will have widespread use where sound levels are high.

A limited amount of experimental data is available on the effect of sound on a device with a turbulent jet as a power source. A visualization study has shown that in general a turbulent jet has a greater spreading rate in an acoustic field (ref 88). This effect is sensitive to a range of frequencies. Thus, it would be reasonable to conclude that an analog amplifier would lose pressure recovery and exhibit a reduction in gain if subjected to an acoustic field. This conclusion has been verified to a limited extent by results obtained by subjecting analog amplifiers to an intense noise field (ref 89).

The increase in jet spreading rate should also affect digital amplifiers and logic devices, resulting in reduced pressure recovery and decreased stability; the reported tests (ref 87) showed that some bistable devices could be made to oscillate in a strong acoustic field.

Information on acoustic effects is still limited and except for components operating with sound-sensitive jets, the effects are appreciable only at intense sound levels.

## 6. INDUSTRIAL APPLICATIONS

The year 1966 was critical as far as industrial applications were concerned. Until then, almost all work in fluidics was oriented toward government uses. Feasibility studies had been shown for such things as sensing of turbine-inlet temperatures; some of the controls for turbine engines had been replaced by fluidic devices; aircraft-stabilization feasibility studies had been made and proper operation obtained.

Although there had been a few isolated cases of commercial application prior to 1966, it was during that year that a number of companies in the field began vigorous programs seeking applications in the commercial field. As a result, packaged systems as well as kits of components began to appear on the market, and today many useful items are available as off-the-shelf equipment. Special systems built for particular applications are now in use.

For example, fluidics has been used for the controls of a new box-sealing machine for Commando Packaging Machinery Co. The features of the machine are automatic adjusting to seal cartons with a 5-to-1 variation in length, height, and/or width and sizing sealing up to 1000 cartons per hour. This random case sealer control system was designed in less than one month with standard off-the-shelf hardware. Fluidic controls are being used to regulate the filling of large containers with a talcum-like powder. The control was designed by Frontier Fluidics. Using fluidic sensing and controls, engineers of Ranco, Inc have come up with a device that measures the frosting on the coils of a refrigeration system and defrosts when necessary. As the frost builds up on the coils, resistance to air flow over the coils increases, cutting down the flow. This decrease in flow is sensed; and when a critical point is reached, the defrosting process begins.

In Scandinavia, a fluidic control system is being used in a punch press to determine when the work piece is correctly located on the punch table. This system prevents the press from being actuated unless the work is properly positioned. The control system was developed for Excenter Press, Kalmar by Forsviks Brukas A B in cooperation with ABMECMAN, Stockholm, Sweden. The Jarrett Compressor and Equipment Co. has build a sensing system for the Arrow Converting Equipment Co., which is used with photographic film to sense the surface position of a movable rewind roll in relation to a fixed idler roll. One of the advantages of this system is that it eliminates physical contact with the film.

Link Engineering has built a fluid system for a Japanese industrial concern, which controls a coil winder. Grinding machines are being controlled in Italy by fluidic air gauging. Fluidic devices are being used in candy filling machines, where fluidic sensors determine whether the box is completely filled. Engineers at High Speed Checkweigher have built and delivered a fluidically controlled scale for accurately weighing explosives in an arsenal.

Other applications of fluidics that have appeared in the literature include that of actuating trimming knives incorporated into sewing machines at the Langridge Ltd factory in England; operating a semiautomatic crimping machine made by Amphenol Corp; a high-speed glass press at Corning Glass; paper-making machinery at Bertrams, Ltd. in Edinburgh; a punching machine developed by Heathway Engineering Co. Ltd. (to automate the punching of hinge holes in refrigerator doors); for liquid level control at a sewage pumping station, Orinda, Calif; and in bottle casing machines at a Pepsi Cola plant.

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