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NASA CONTRIBUTIONS TO FLUIDIC SYSTEMS

A SURVEY

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Foreword

Fluidic systems are being used in increasing numbers to control manufacturing operations and for a wide range of sensing, logic, amplification, and control functions. These applications take advantage of a fluidic system's ability to function solely by employing the fluid dynamic phenomena associated with a flowing stream of gas or liquid. Fluidic systems can be designed to operate with neither moving parts nor electrical components, although many designs incorporate these more conventional parts. NASA has investigated fluidic systems ranging from aircraft autopilots and rocket control systems to a fluidic clothes washer for zero-gravity operation. Most fluidic systems in use today, however, are for monitoring and controlling industrial processes and operations and for environmental control of large buildings. Interesting medical applications have been studied and commercial medical equipment employing a fluidic system has appeared on the market.

This book describes how specialized requirements of NASA and others have influenced the evolution of fluidic systems from a laboratory curiosity known as a fluid amplifier in 1959 to operational systems employing hundreds of fluidic devices and fluidic integrated circuits. In addition to describing the contributions sponsored by the various NASA Centers, this book points out that a dynamic and growing fluidics industry has sprung up which is now independent of government sponsorship, although the industry continues to support NASA, DOD, and AEC fluidics requirements. This book also offers suggestions on how to apply fluidics to new uses and how firms not presently familiar with this growing new technology may evaluate its worth and start to exploit its many advantages. As they do, new uses will be added to the current long list of weighing, measuring, counting, temperature sensing, and control functions already in being.

This publication is one of a series sponsored by the NASA Technology Utilization Office to help industry benefit from research and development in the aerospace field. It is part of a program to identify, collect, organize, and disseminate aerospace developments that may have value for industry, education, and Federal, State and local Government agencies. References and a bibliography are provided to aid those who wish to obtain further information on specific topics for potential applications.

Director
Technology Utilization Office

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Contents

CHAPTER 1

Introduction

A *fluidic system* is one in which some sensing, signal processing (logic), control, and/or amplification functions are performed through the use of fluid dynamic phenomena, without relying upon moving parts or electrical components. The word fluidic was derived from the combination of the words fluid and logic. The role of fluidics in the evolution of fluid systems is analogous to the role of electronics in the evolution of electrical systems. A fluid system with one or more fluidic devices is called a fluidic system just as an electrical system with one or more electronic devices is called an electronic system. Similarly, a fluidic system may also contain moving-parts devices or electrical components, in which case it is sometimes referred to as a hybrid system. The term flueric is often used to identify a fluidic system that contains neither moving parts nor electrical components.

Today fluidic systems are in use throughout the world. Heated arguments can develop as to whether the best research or the most imaginative applications are found on the North American continent, in Europe, or behind the Iron Curtain. A significant lesson in selecting those applications best suited to a fluidic system may be taken from the observation that fluidics appears to be most vigorously applied in Europe by those countries where electronic sophistication is least developed. Where an electronic or electromechanical system is already doing a job satisfactorily, it is seldom prudent to replace that system with a fluidic system.

Applications of fluidic systems in the United States may be found in fields ranging from aerospace to medicine. Fluidic systems are presently controlling machining, painting, measuring, filling, packaging, mixing, sorting, and inspection operations in a wide variety of industrial and commercial production activities. In most cases the fluidic system is performing those functions cheaper, safer, more reliably, more accurately, and/or faster than would a nonfluidic control system. Chapter 3 describes examples of ways in which fluidic systems are being applied to aerospace, medical, industrial, and commercial problems. Why aren't they in even wider use, and where does NASA fit into all this? That is what this book is about.

SCOPE OF THIS SURVEY

This survey is a state-of-the-art review of fluidic technology. It is oriented towards systems applications rather than theory or design. It draws heavily upon work performed or sponsored by NASA in support of the space program and aeronautical research and development (R&D).

When a technology is no more than a dozen years old, as in the case with fluidics at this writing, the state-of-the-art is indeed a fleeting thing. Fluidics is generally considered to have had its birth in 1959 at the U.S. Army Harry Diamond Laboratories (HDL) in Washington, D.C. (then called the Diamond Ordnance Fuse Laboratory). The new technology was enthusiastically pursued by both industry and Government in the early 1960's. It was rather badly oversold as a potential panacea to many control systems ills in the mid-1960's. It has been a disappointment to some and a very successful boon to others in recent years. Now appears to be an excellent time to take stock and see where fluidic systems seem to best fit into the overall scheme of things.

Applications are emphasized in this survey because it is hoped that the examples described and the criteria presented for evaluating the suitability of fluidics to new applications will be of value to potential users of fluidic systems. This survey of the fluidics industry suggests some of the means whereby a company may use a fluidic system effectively either to manufacture a product or as part of the end product.

The emphasis upon Government-sponsored contributions to the technology, particularly those of NASA, serves to benefit those who are in or are contemplating entering the fluidics industry per se. Virtually all successful manufacturers of fluidics hardware have some patent, license, or proprietary technique position. The long list of fluidics-related patents grows daily. The patents and disclosures by NASA, the Department of Defense (DOD), and the Atomic Energy Commission (AEC) are readily available for exploitation. Some of the NASA-sponsored contributions to fluidics technology have received relatively little publicity heretofore and could well provide the basis for significant new commercial developments.

This survey also includes a glossary of fluidics terminology and symbology, and a selected bibliography that can aid in understanding fluidic systems.

HOW DO FLUIDIC SYSTEMS WORK?

Our initial definition stated that fluidic systems can perform sensing, signal processing (logic), control, and/or amplification functions using only fluid dynamic phenomena without necessarily having moving parts or electrical connections. Fluid dynamic phenomena can include a great many things, so just what are we talking about when we say fluidics is based upon fluid dynamic phenomena? Since most fluidic systems are control systems, it is convenient to use the terminology of the controls engineer. A control system is comprised of a number of control elements. As a control element, a fluidic device (or fluid amplifier) may be considered to have four functional parts: a supply port, an output port, a control port, and an interaction region. In the case of a simple vacuum tube these would be, respectively, the cathode, plate, control grid, and interelectrode region.

Most fluidic devices have only one or two supply ports, but the number of control and output ports increases with the complexity of the control function that the device is called upon to perform. The distinguishing characteristic by which we classify fluidic devices, however, is the particular fluid dynamic phenomenon that is employed in the interaction region to make the device work. The various fluid dynamic phenomena or mechanisms may be divided into three basic categories (ref. 1):

1. Jet interaction–where a supply jet is essentially unconstrained by surfaces (other than the top or bottom plates) in the interaction region and the control flow directly modulates the supply flow (fig. 1).
2. Surface interaction–where the presence of an adjacent surface is essential to the control action. This includes the well-known wall attachment or Coanda effect type of device (fig. 2).
3. Vortex flow–where the existence of a vortex field, or the tendency for one to form, is essential to the device function (fig. 3).

These phenomena, and how particular fluidic systems work, are described in chapter 6. Names of the devices include wall attachment, beam deflection, impact, turbulence, and vortex amplifiers.

WHAT CAN FLUIDIC SYSTEMS DO?

A few years ago discussions of fluidic applications centered mainly about what might be done. Most of the documentation was related to feasibility studies, research, or laboratory tests on "breadboard" systems. By comparison, table 1 lists only complete systems that have been placed in operation. This list is by no means all-inclusive, but serves to represent what has been accomplished to date. Table 2 is much longer, and includes a large number of potential applications for which technical feasibility has been shown, but for which no documented examples of operational application were available. Chapter 3 describes a number of different applications selected to demonstrate different functions that fluidic systems can perform well. Table 3 is a partial list of these functions.

WHERE DOES NASA FIT INTO THE FLUIDICS PICTURE?

Fluidics has interested those responsible for this country's space and aeronautics programs ever since the first use of fluid amplifiers was announced in early 1960. A few applications showed immediate promise for fluidics, such as controls for the NERVA nuclear rocket engine where a very high radiation environment presents serious problems for electronic control systems. Fluidics also offered a potential means for controlling the temperature of the coolant in an astronaut's flight suit, and for providing attitude control for Vertical Takeoff and Landing (VTOL) aircraft. Chapter 2 describes fluidics developments that have been started at various NASA centers. The

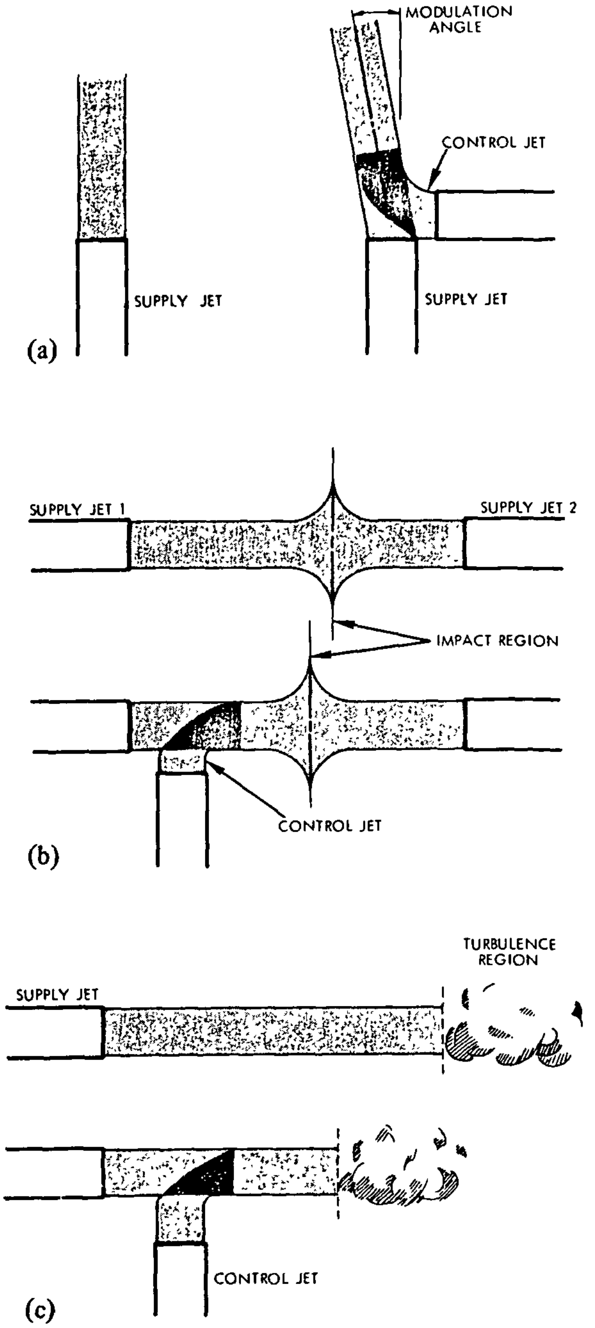


FIGURE 1.–Jet interaction phenomena (ref. 1). (a) Beam deflection; (b) impact modulation; (c) controlled turbulence.

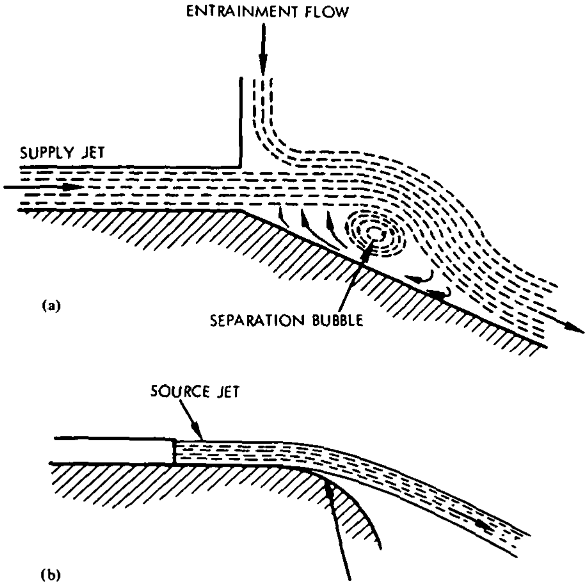


FIGURE 2.–Surface interaction phenomena (ref. 1). (a) Coanda effect (wall attachment); (b) separation effect.

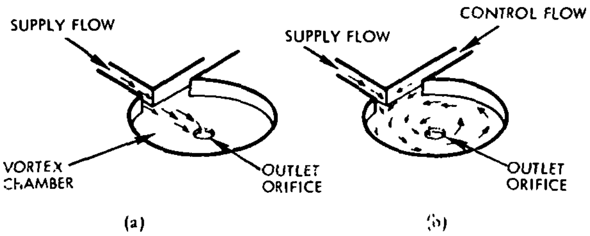


FIGURE 3.–Vortex flow phenomenon (ref. 1). (a) No control flow; (b) with control flow.

following items are representative of the manner in which NASA-sponsored fluidics work has influenced present applications of this technology.

NASA Program Introduces Fluidics to an Industrial Firm

In November 1964, at NASA Lewis Research Center in Cleveland, Ohio, a technology utilization conference included a brief description of several fluidic devices. D. R. Imhoff, Chairman of the Board of Bardons & Oliver, Inc., a Cleveland machine tool manufacturer, believed then that fluidics would be too costly for machine tool control. But in June 1965 he saw a fluidic element cast into the nozzle of a rocket, and realized that there was a great potential for low cost fluidics. The decision to develop a fluidic control system for an automatic turret lathe was subsequently based on an analysis showing reliability, simplicity, ruggedness, environmental tolerance, and cost advantages over electronic control. In the sum-

TABLE 1.—*Fluidic Systems That Have Been Placed in Operation*

Automatic turret lathe sequencing
Automatic sealing of random-sized boxes
Measurement and control of frost buildup on refrigerator coils
Punch press work positioning
Photographic film winding control
Gaging for automatic grinding machines
Candy box filling machine control
Scale control for weighing explosives
Sewing machine trimming knife actuation
Controlling a semiautomatic crimping machine
Controlling papermaking machinery
Automatic punching machine operation
Sewage pumping station liquid level control
Soft drink bottle casing
Thread, wire, or rod diameter measurement
Bow thruster for boat or ship
Breathing assist device
Automatic boiler control
Noncontact position measurement or proximity switching
Counter systems (predetermining and cumulative)
Disc memories for computers
Automated paint spraying
Alphanumeric displays
Leak testing of automobile gasoline tanks
Pallet loading of different size boxes and conveyor control
Newspaper materials handling machine controls
Ordnance round assembly tolerance inspection
Machining and assembly control of live mortar rounds
Inspection and classification of automotive pollution control valves
Liquid drum filling monitoring and control
Scrap metal baler control
Metal tapping machine control
Steam turbine governor
Gas turbine or jet engine overspeed limiter
Broken tool detector
Moving belt edge guide control
Bin level control for liquid, powder, and small parts
Environmental control in large buildings
Industrial air motor governors
Life test cycling of heart pump check valves
Automatic cold saw cutting-angle setting
Monitoring and control of vacuum in tiremaking equipment
Filter bag cleaning controls in tiremaking equipment
Paper splice detection for papercoating machinery
Lip-seal inspection using moving-part logic
Life test cycling of postage meters
Coil winding machinery controls
Acid vaporizer controls for textile processing
Irrigation channel switching
Fluidic lawn sprinklers
Tachometers for diesel motor ships
Transistor lead bender

TABLE 2.—*Fluidic Systems for Which Feasibility Has Been Shown*

Sensing turbine inlet temperatures
Locating supersonic jet engine intake shock waves
Aircraft wing stall sensing
Light aircraft autopilot
Spacecraft proportional attitude control
Tape readers
Flight suit temperature control
Liquid rocket engine start sequencing
VTOL aircraft attitude control
Jet engine thrust reversal
Tactical missile roll control
Rocket secondary injection thrust vector control
Massaging shower head
Fluid velocity monitoring over wide ranges (free and in ducts)
Artificial heart pump
Artificial heart and heart assist device control
Lawn sprinkler control
Leakage control for mechanical diverter valves on VTOL aircraft
Automobile engine carburetion
Nuclear reactor control rod positioning
Steam turbine speed control
High temperature gas temperature control
Sounding rocket attitude control proportional thruster
Very high temperature gas flow modulation
Liquid rocket tank pressurization
Jet engine fuel controls
Digital navigation computer
Ordnance timers
Shift registers for automatic warehouse conveyors
Assembly machine sequence timers
Gyros
Fluidic toothbrush
Helicopter stability control
Automobile engine exhaust gas diverter valves
Fluidic interferometry height gaging
Acoustic curtains for personnel safety
Breakdown testing of keyboard postage meters
Die protection for press operations
Fluidic accelerometer
Turbine speed control
Heart massage machine control
Measurement of molecular weight of a gas
Measurement of humidity of a gas
Pneumatic stepping motor control
Tank gun control
Ram jet spike positioning
Sounding rocket roll control
Self-nulling fluidic probe for wind tunnels
Miniature fluid pulse counter for ordnance
Fluidic sun sensor for spacecraft
Automatic air compressor shutdown
Astronaut maneuvering control
V/STOL emergency roll control
Nuclear rocket engine chamber pressure control

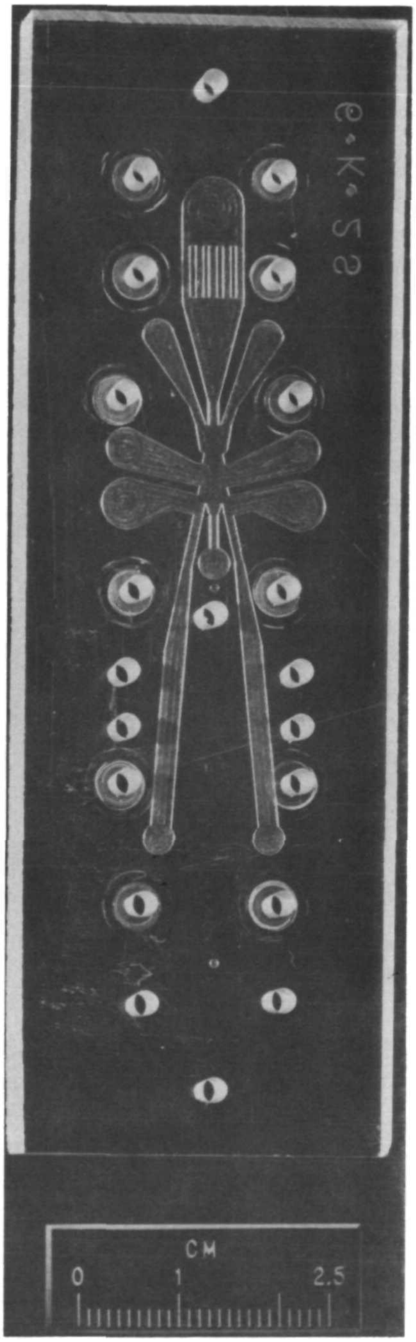


FIGURE 6.–A proportional amplifier.

6. The experimental demonstration of a no-moving-part electrically switched bistable fluidic valve (which requires substantial electrical power to operate) (ref. 36).

7. The experimental demonstration of a very low-power electrically switched fluid amplifier that uses an electromagnetic relay or torque motor (ref. 32).

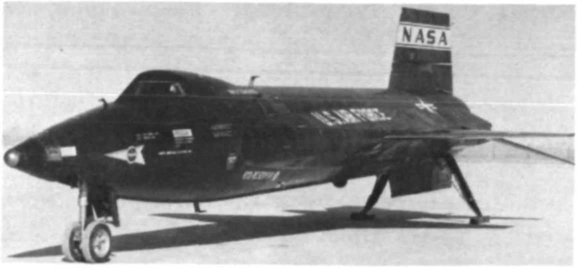


FIGURE 7.–X-15 research airplane.

8. Experimental scaling study of fluid amplifier elements (fluidic devices) (ref. 37).

9. Development at Langley Research Center of a monolithic precision casting technique (see chapter 5). This process permits fabrication of low-cost-per-unit complex fluidic components or fluidic integrated circuits; design changes may be made easily.

The device mentioned in item 7 is so sensitive that a demonstration setup driving a pneumatic actuator has been made at Lewis Research Center that may be switched back and forth using only the power generated by shining a flashlight from a distance of several yards onto a single solar cell of the type used on spacecraft power systems.

DEVELOPMENTS TO MEET SPECIFIC NASA REQUIREMENTS

The adage that "necessity is the mother of invention" has been demonstrated many times in the history of aerospace. The advances in the state-of-the-art of fluidics technology have been like many in cryogenics, rocketry, and telemetry. Listed below are a few of the fluidic developments resulting from particular NASA requirements.

Temperature Sensing for the X-15

The very high speeds attainable with the X-15 rocket plane (fig. 7) resulted in aerodynamic heating that exceeded the capacities of conventional resistance thermometers and shielded thermocouples for reliable measurements. In an attempt to reduce the measurement errors in total temperature at Mach numbers greater than 1, and to improve the structural integrity of sensors at high Mach numbers, a fluidic oscillator temperature sensor developed by HDL and

Honeywell, Inc., was used that had shown promise of satisfactory operation at stagnation temperatures in excess of 1667°K. (3000°R.) (ref. 38). Reference 39 describes the fluidic temperature sensing system (fig. 8) that was mounted in the upper vertical fin (fig. 9) of the X-15-2 airplane. On October 3, 1967, this installation recorded total temperatures in excess of 1667°K. (3000°R.) when an aircraft was flown to a Mach number of 6.70. Reference 39 describes the test installation made by personnel at NASA's Flight Research Center and the flight test results; reference 40 describes the development of the fluidic temperature sensor itself.

Pneumatic Actuator Controls for Nuclear Rockets

The combined factors of having high-pressure hydrogen readily available at the nuclear reactor and the difficulty of protecting an electronic control system from the severe environment of a nuclear rocket have led to several interesting developments in fluidic control systems for nuclear rocket engines. An early study (ref. 41) showed the feasibility of using fluid amplifiers for reactor rod control. A potentially ideal system was considered to be a high-speed fluidic control system mounted directly on the pneumatic actuator. A pneumatic stepping motor and a proportional fluidic control system were fabricated (ref. 42) and further improved (ref. 43). The breadboard fluidic control system (fig. 10) initially developed at Lewis Research Center for this application (ref. 43) was further advanced with the design and fabrication of two fluidic integrated circuits for this system (ref. 44). One of these integrated circuits is shown assembled in figure 11 and as an expanded schematic in figure 12. These efforts not only demonstrated the feasibility of using fluidics for nuclear rocket engine control systems, but also yielded new criteria for the development of fluidic integrated circuits. For example, it was shown to be most practical when dealing with a new development to use integrated circuits only in a modularized form to facilitate (1) incorporating design changes and (2) cleaning in the event of system contamination. Although today's miniaturized circuits make the one shown in figure 11 look large and cumbersome, this program remains one

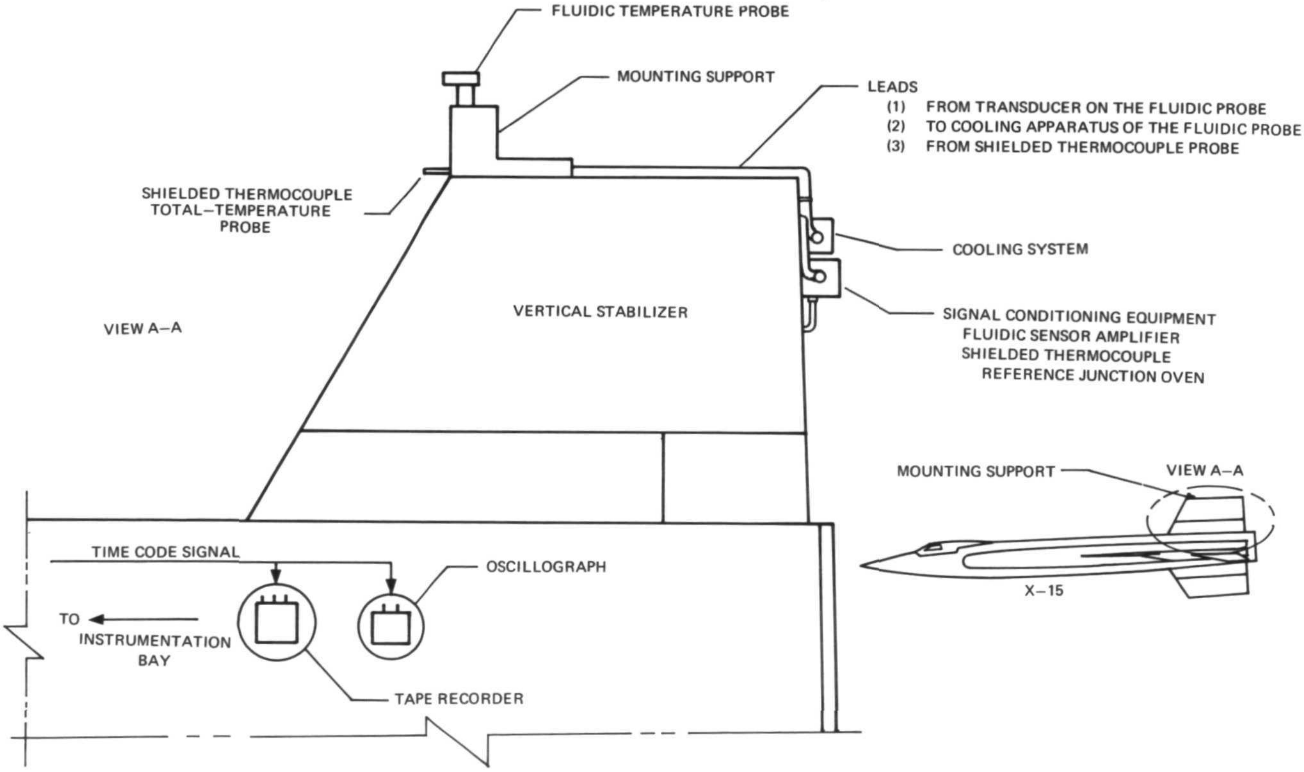


FIGURE 8.–Total temperature flight system installation on X-15 (ref. 39).

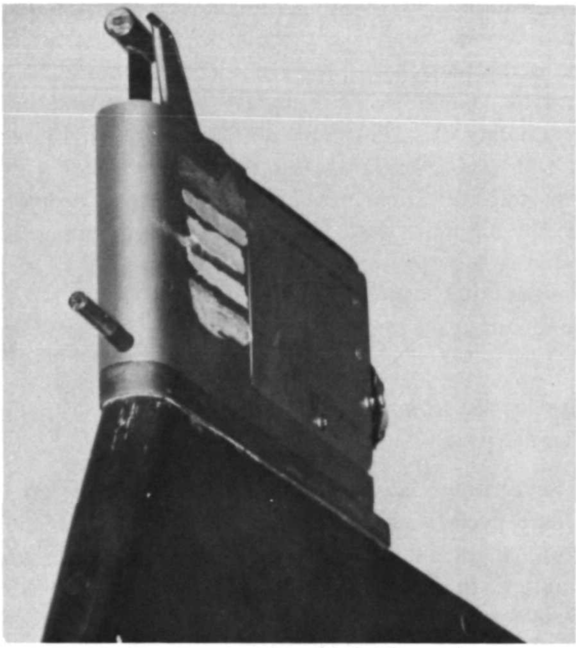


FIGURE 9.–X-15 vertical fin with fluidic total temperature probe installed (ref. 39).

of the best-documented descriptions of the problems encountered in making a fluidic integrated circuit from a breadboard device. (Some of the problems associated with selling breadboarded fluidic systems to managers and customers are discussed in ch. 7.)

Another series of related studies for nuclear rocket engine applications centered about the use of fluidic servovalves to operate with room temperature nitrogen or on hydrogen at temperatures ranging from 56°K. (100°R.) to 333°K. (600°R.) (ref. 45). These fluidic servovalve designs had the challenging requirement of having to operate with a supply pressure of 148 N/cm^2 (215 psia), but with a maximum control pressure of only 48.5 N/cm^2 (70.4 psia). These fluidic servovalves used a combination of jet-interaction devices and vortex devices (ref. 46).

Temperature Control of Space Suit Liquid Coolant

NASA experience in recent years showed liquid cooling of astronaut space suits to be superior to earlier gas cooling techniques. Liquid cooling, how-

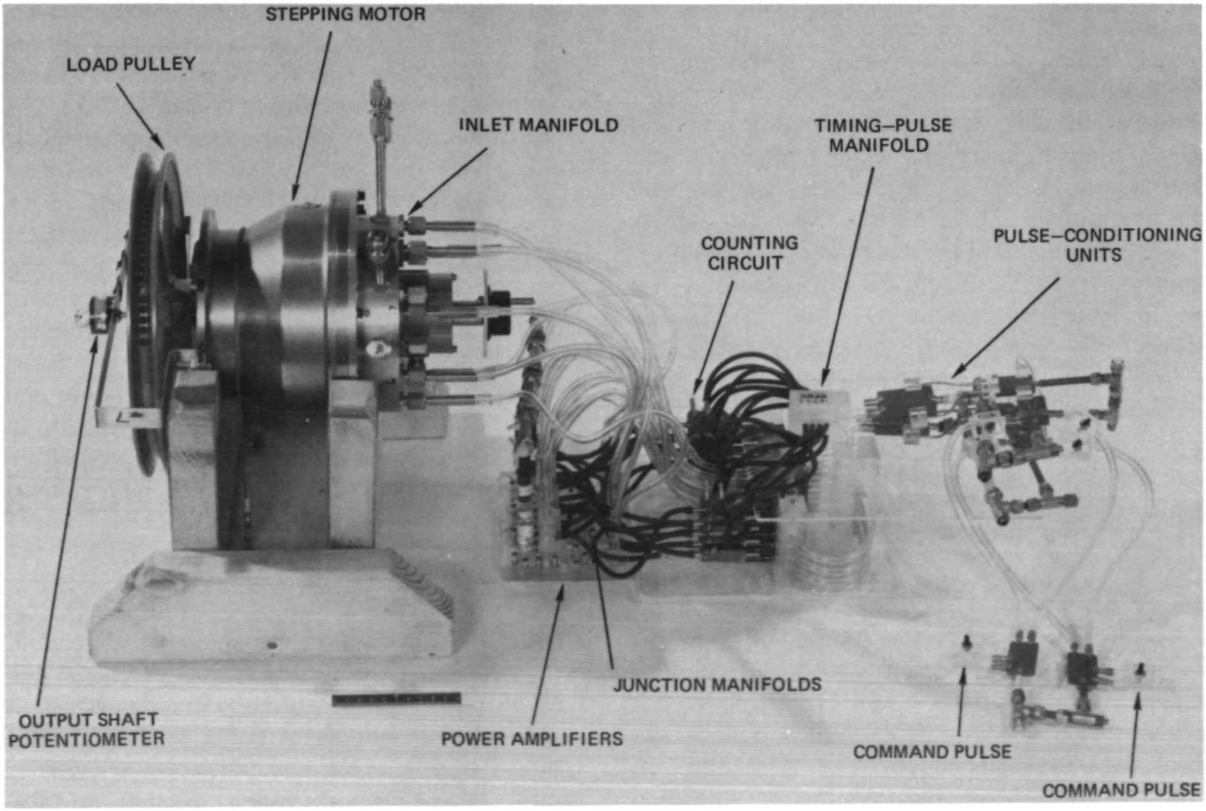


FIGURE 10.–Breadboard actuator system (ref. 43).

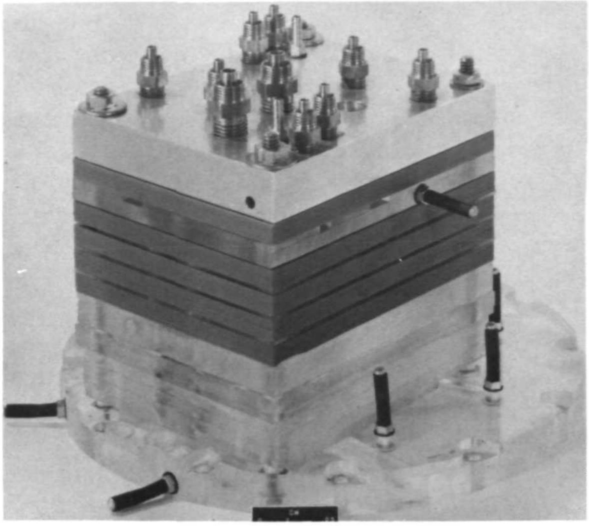


FIGURE 11.–Fluidic integrated circuit mounted on power amplifiers and bellows distribution plate (ref. 44).

ever, requires modulation of the coolant inlet temperature for maximum subject control. Fluidic control of the coolant temperature can provide this control without running extra recirculating lines from the suit to the pumping equipment or adding electrical controls to the suit itself. A system was developed (refs. 47-49) that used the existing supply and return conduits to transmit manual or automatic signals from the space suit to the pumping system. This system was developed to permit use even with the long umbilical used for extra vehicular activity (EVA). Limitations of mixture ratio possible with the fluidic mixing valve used in the initial control system led to an optimization program (ref. 50) that employed flow-visualization techniques showing flow patterns within the fluidic device. The NASA-sponsored development of fluidically controlled liquid-cooled space suits was an extrapolation of earlier Navy-sponsored work on fluidic temperature control of liquid-cooled flight suits (ref. 51).

Zero Gravity Clothes Washer

A half-scale demonstration model of a clothes washer using fluidic principles to provide washing action was developed for NASA Manned Spacecraft Center (ref. 52). Although the bistable wall attachment fluid amplifiers employed are essentially conventional, it was necessary to design them to accommodate water at the flow rates typical of this application. These fluid amplifiers were incorporated in a vertical stack in the center of the washer tube, replacing the conventional mechanical agitator. These bistable amplifiers were so staged as to provide an alternating, pulsating series of flow surges that gives the necessary washing action in the wash water. This particular development is of interest not only because of the nature of the application, but also because it represents an example of appropriately sized fluidic devices that can perform both logic and control functions at the same time.

Sensing Molecular Weight and Humidity of Gas Mixtures

Space power generation systems that operate on a closed cycle, such as the Brayton cycle, are sensitive to changes in the molecular weight of the gas mixture. In the study of one such system at Lewis Research Center, it was desired to monitor molecular weight of the working fluid continuously (refs. 53-55). Similarly, in another test program at Lewis Research Center, researchers needed to measure the humidity of the hydrogen-steam mixture in a hydrogen-oxygen fuel cell system resulting when the water produced was removed from the cells in vapor form by a recirculating hydrogen steam (refs. 56, 57). In both instances, Lewis researchers applied fluidic oscillators as the central element in the design of instrumentation to monitor molecular weight of the gas or vapor, using the principle that the oscillator frequency will vary with changes in the molecular weight of the gas. In the case of the humidity sensor, humidity is in turn determined from the molecular weight of the hydrogen-steam mixture. It was necessary either to maintain constant temperature and constant pressure drop across the oscillator, or to correct for variations in levels of these factors. Figure 13 shows both the oscillator and the humidity sensor schematically.

Aircraft Flight Control Systems

NASA has applied fluidics to aircraft flight control systems in two separate but related programs. The first of these was a relatively ambitious effort to design, develop, and flight test a fluidic autopilot system (ref. 58), which was one part of a review of avionics requirements for general aviation (ref. 59). NASA's Flight Research Center at Edwards AFB,

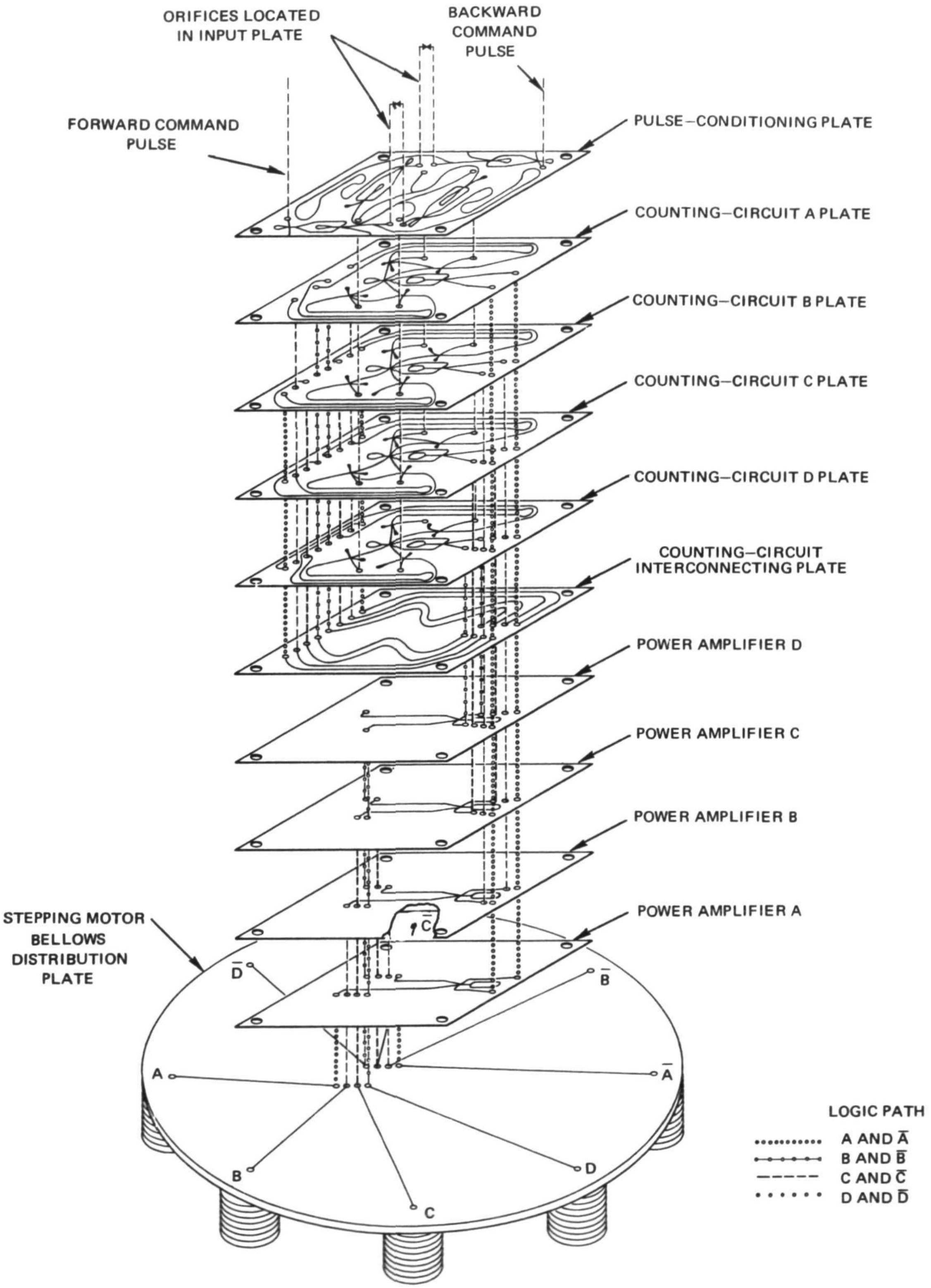


FIGURE. 12.–Expanded schematic diagram of fluidic integrated circuit (ref. 44).

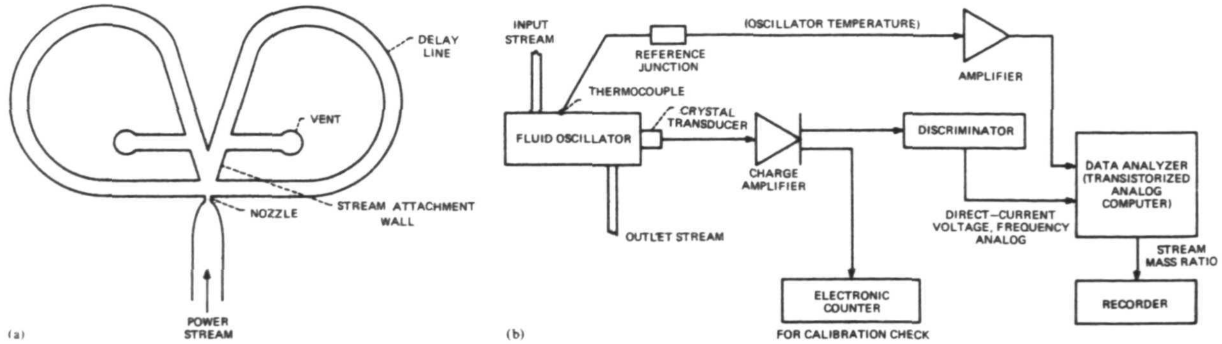


FIGURE 13.–Humidity sensor based on fluidic oscillator (ref. 57). (a) Schematic of fluidic oscillator; (b) complete humidity sensor.

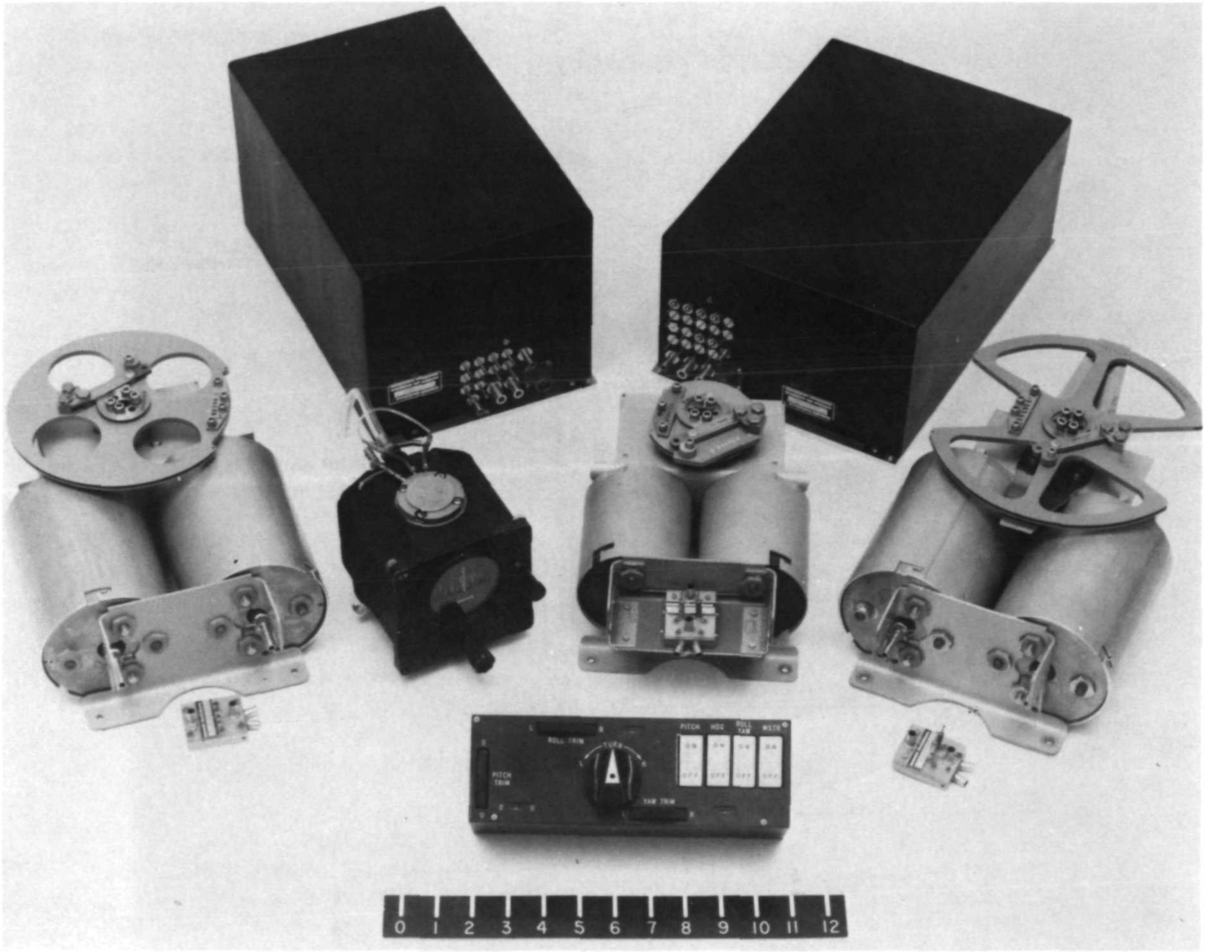


FIGURE 14.–Components of fluidic autopilot system.

California, contracted with Honeywell, Inc., to design and build the three-axis fluidic autopilot to provide wing-leveling, heading hold, and altitude hold capabilities. This equipment (fig. 14) was designed for and installed in an Aero Commander 680 FP airplane operated by the Flight Research Center (fig. 15). The flight test program for this system consisted of 30 flights extending over 1 year, with emphasis on

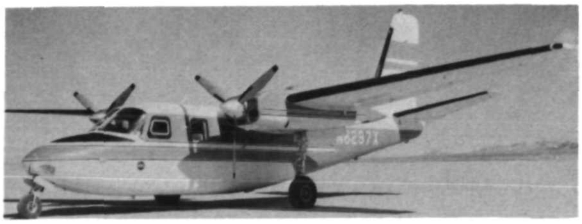


FIGURE 15.–NASA Aero Commander airplane used for fluidic autopilot testing.

cruising flight at 1524- and 3048-m (5000 and 10 000-ft) altitudes. This study demonstrated that a system of this type can be mechanized for light aircraft application. The high reliability of the fluidic elements with no moving parts was demonstrated. (The only system failures occurred in the mechanical fluidic components.) The high power consumption of the nonminiaturized fluidic system showed the need for further improvements before a complex, multifunction fluidic system of this type could be incorporated economically on such an aircraft.

More recently, Langley Research Center has been studying the problem of light aircraft stability augmentation. This in-house project began with a study of a simple wing-leveler stability augmentation system patterned after commercially available systems. The idea was to use a Langley-developed cast plastic vortex rate sensor as a substitute for the rate gyro normally employed, and to use cast plastic fluid amplifiers for matching the rate sensor to the bellows-type control servos. The small signals put out by a vortex rate sensor need high-gain, low-noise (high signal-to-noise ratio) signal amplifiers for use in such a system. A significant result of this effort has been the development by Langley researchers of a laminar-flow proportional fluid amplifier with a very high signal-to-noise ratio. Figure 16 shows examples of the plastic amplifiers and rate sensors developed at Langley, as well as a general layout of the system in an airplane. Another interesting aspect of the fluidics work at Langley is the emphasis that has been placed on improved fabrication techniques. Low power consumption is another key factor. Langley fluidic avionic devices are designed to work with only 10.16 cm (4 in.) of mercury pressure differential. Simpler, more reliable and less expensive fluidic components for the light plane market should result from this Langley effort.

Attitude Control Thruster for Sounding Rockets

A study (ref. 60) at Ames Research Center showed a need for developing a proportional thruster system to provide smoother and finer control of the attitude of an Aerobee-type sounding rocket during the critical part of its flight path when the rocket must be kept pointing in a particular direction relative to the sun while scientific observations are made (fig. 17). Conventional "bang-bang" systems use discrete bursts of thrust from roll, pitch, and yaw reaction jets controlled by solenoid valves. A fluidic proportional thruster patented by D. M. Chisel of Ames (ref. 61) was subsequently developed by GE (refs. 62, 63). The system has proven to be very accurate and eliminates the characteristic "limit cycle" (how fast a solenoid valve can be signaled to open and then close again).

This proportional thruster concept has also been used to design a flight control system for emergency use for attitude control of Vertical or Short Takeoff and Landing (V/STOL) aircraft at Ames (fig. 18). It is designed to provide backup control protection against emergency conditions such as excessive gust disturbances, primary control failures and wing stall during takeoff and landing. The emergency control is fluidic and provides torque proportional to an electrical input control signal. The torque is independent of the aircraft power plant and aerodynamic control surfaces. All the functions, including the gas generator power source, are contained in a single, bolt-on module. The input is an electrical control signal, and the output is thrust proportional to the input signal. The system operates with either a hydrazine or a solid propellant gas generator power supply. In addition to V/STOL, this emergency control has other applications including: (1) stall control for high "T" tail aircraft, (2) gust simulation on research aircraft, (3) stability control for seat ejection systems, (4) control for shuttle vehicles and (5) emergency protection for helicopters in case the tail rotor malfunctions. In other VTOL stability control programs, Ames researchers have experimented with other fluidic devices for attitude and thrust control, such as large tristable flip-flops and very large diverter valves (fig. 19).

Low-Speed Airspeed Indicator

Another V/STOL aircraft requirement is that of accurately measuring air velocity relative to the

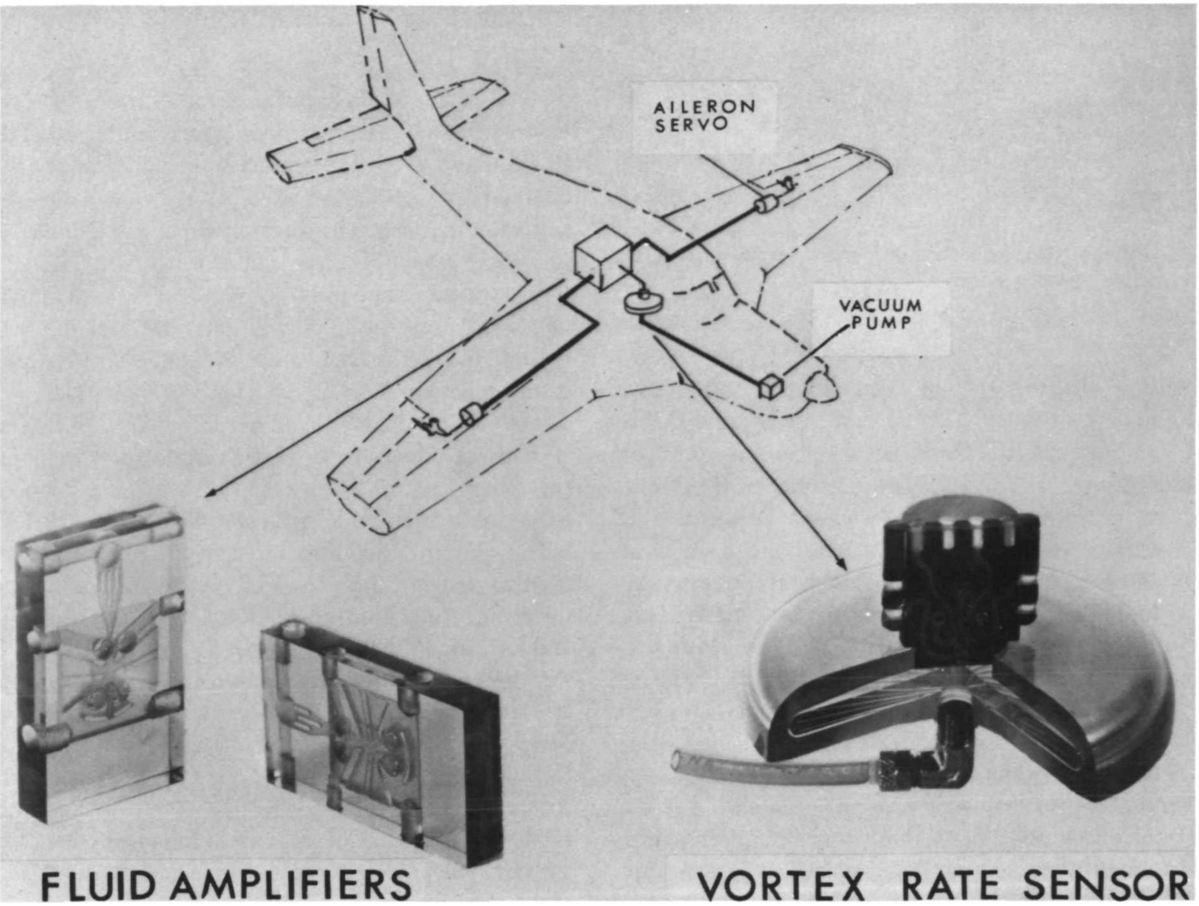


FIGURE 16.–Fluidic wing leveler.

aircraft at very low forward speeds. It was this requirement that resulted in NASA's Electronic Research Center contracting with Bowles Fluidics Corp. to develop the fluidic wind sensor (refs. 64-66) mentioned in chapter 1 (fig. 5). Actually, two different devices were developed. One was a parallel flow sensor and the other a crossflow sensor (fig. 20) (ref. 67). The parallel flow device has a more linear response and provides a differential pressure output over the velocity range of 0.1 to 50 m/sec (0.3 to 160 ft/sec). This sensor development has proven so promising that Langley Research Center is continuing improvement of it and other agencies are evaluating its application to such diverse areas as meteorology, air and water pollution control monitoring, and mine safety.

Locating the Shock Wave in a Supersonic Jet Engine Inlet

For supersonic inlets that have a high degree of internal contraction, refined control systems are required to maintain inlet pressure and flow recoveries at optimum levels. At the same time, the system must prevent the internal normal shock wave from being expelled out the front of the inlet. A program was instituted at Lewis Research Center to develop a reliable shock wave position sensor. The selected approach considered both electronic and fluidic schemes for making a digital comparison of a series of static wall pressure tap readings (ref. 68). The fluidic system was built and tested. The program resulted in descriptions of the design approaches and data on the fluid amplifiers to permit other re-

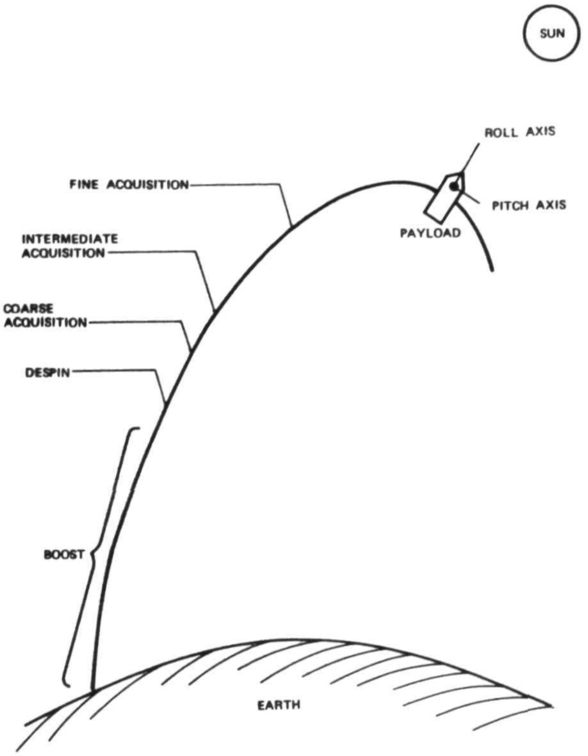


FIGURE 17.–Solar-pointing sounding rocket trajectory (ref. 62).

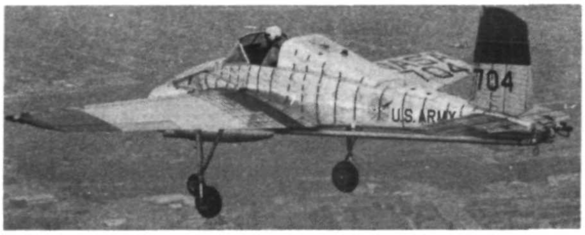


FIGURE 18.–NASA-Ames/U.S. Army X-14B VTOL experimental aircraft.

searchers to design even more accurate and reliable fluidic systems for sensing the position of normal shock waves. The problems associated with contamination of the fluidic devices during this program served to emphasize the problems facing the designer of similar systems for flight operational systems. This program also used discrete fluidic devices plumbed together into a system. The results supported the growing conclusion that much more efficient systems could be achieved from the use of fluidic integrated circuit techniques.

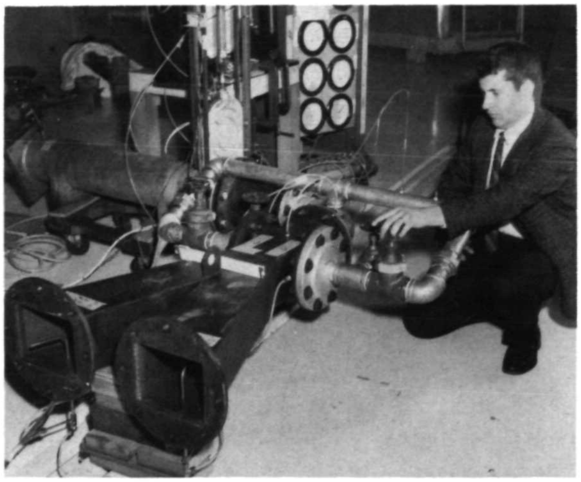
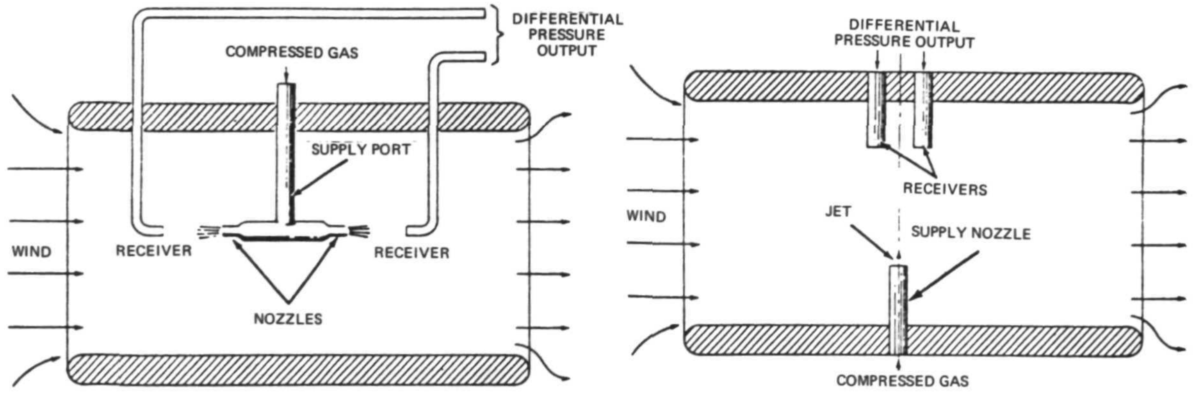


FIGURE 19.–Large diverter valve used in VTOL aircraft research.

Fluidic Displays Without Moving Parts

The potentially high reliability and low cost of fluidic logic offers interesting possibilities for the generation of an interface between sensors or computers and displays, especially if moving parts can be eliminated from the display (ref. 69). Accordingly, the Electronics Research Center contracted with Martin Marietta Corp. to develop means of achieving such no-moving-parts displays. This effort resulted in both fluidic-thermochromic and plasma-fluidic hybrid display systems being proven feasible. The fluidic-thermochromic display uses thermochromic materials; i.e., those which change color upon exposure to heat and revert to their original color when cooled (refs. 70, 71). This not only eliminates requirements for any moving parts, but also provides a display readily observable under high ambient illumination levels, because the color change in the materials is due to differential reflection rather than to light emission. The plasma-fluidic hybrid display employs fluidic logic elements to control the firing or extinction of selected cells in a plasma matrix having a common and constant electrical power supply (ref. 72). An interesting innovation that resulted from the Martin work with displays is an interface device, or transducer, between the electrical signal-inducing system and the fluidic display system (ref. 73). This interface is accomplished with piezoelectric ceramic elements cemented together in such a manner that one plate contracts and the other expands as voltage



(a) (b)

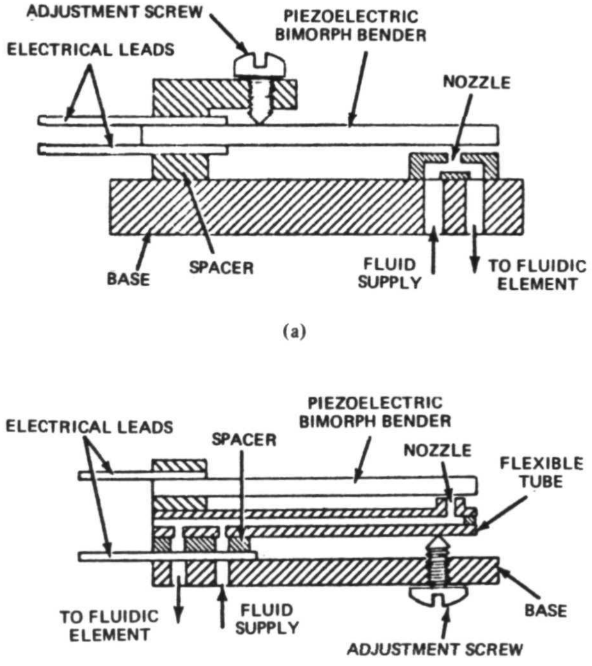
FIGURE 20.–Two configurations of low-velocity wind sensor (ref. 67). (a) Parallel flow wind sensor; (b) cross-flow configuration.

is applied across the bender (fig. 21). When supported as a cantilever beam, the bender will bend or deflect in response to the applied voltage and vary the resistance to flow from the nozzle in either of the two configurations shown in figure 21.

Vortex Technology from a Variety of Requirements

If there is any one aspect of fluidics technology that has profited from research to satisfy NASA requirements, it is that associated with devices which use vortex flow phenomena. Both vortex valves for flow control and vortex rate sensors for detecting angular displacements have been the subject of extensive investigations. These two applications have been pursued strongly in support of NASA programs, although there are other equally important vortex devices such as the vortex diode and vortex pressure amplifier. The following is a brief listing of some of these vortex device developments:

1. The fluidic autopilot system tested at the Flight Research Center (fig. 14) used a vortex rate sensor in each of three axes.
2. The Langley Research Center vortex rate sensor shown in figure 16 incorporates significant advances in the state-of-the-art of pickoff design.
3. Bendix Research Laboratories, Southfield, Michigan, developed and tested a vortex valve for controlling the flow of solid rocket exhaust gas at 3038°C. (5500°F.) under contract to Langley Research Center (fig. 22) (refs. 74, 75).
4. Bendix also applied vortex amplifiers to liquid rocket engines for Lewis Research Center as a means of controlling hot gas for secondary injection thrust vector control (ref. 76). (Secondary injection is a means whereby the direction of thrust from a rocket engine is changed by injecting a gas or liquid into the side of the rocket nozzle, causing the main stream of exhaust gas to be deflected away from the rocket's centerline.)



(a)

(b)

FIGURE 21.–Fluidic display transducer using bimorph piezoelectric device (ref. 73). (a) Nozzle in base; (b) nozzle in adjustable tube.

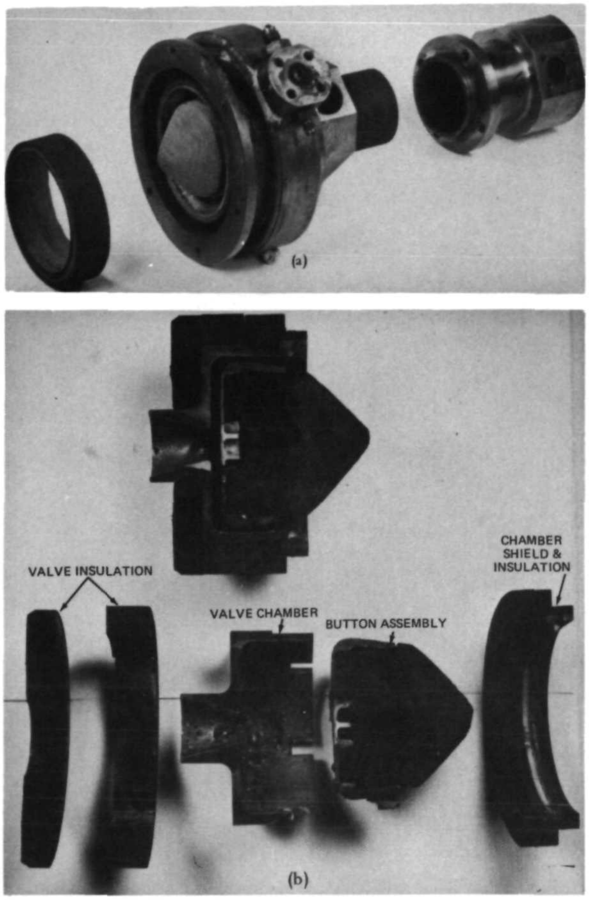


FIGURE 22.–Vortex valve for controlling solid rocket motor thrust. (a) Post-test partial disassembly of a hot gas vortex valve; (b) hot gas vortex valve post-test section.

5. Marshall Space Flight Center contracted with Bendix to develop the vortex servovalve shown in figure 23. Two of these vortex servovalves demonstrated the feasibility of performing push-pull control of a hydraulic servoactuator in tests on a Saturn SI-B gimbal actuator (ref. 77).

6. As part of other research for NASA, F. R. Goldschmied of Auburn Research Foundation, Inc. patented a high-pressure hydraulic amplifier comprising a high-pressure vortex amplifier power stage controlled by the output of a low-pressure vortex shear modulator (ref. 78).

7. Lewis Research Center also investigated fluidic servovalves using vortex devices through a series of contracts with Bendix (refs. 79-81). Several advances in the state-of-the-art of vortex valves and vortex amplifiers resulted, particularly for increased stability of operation.

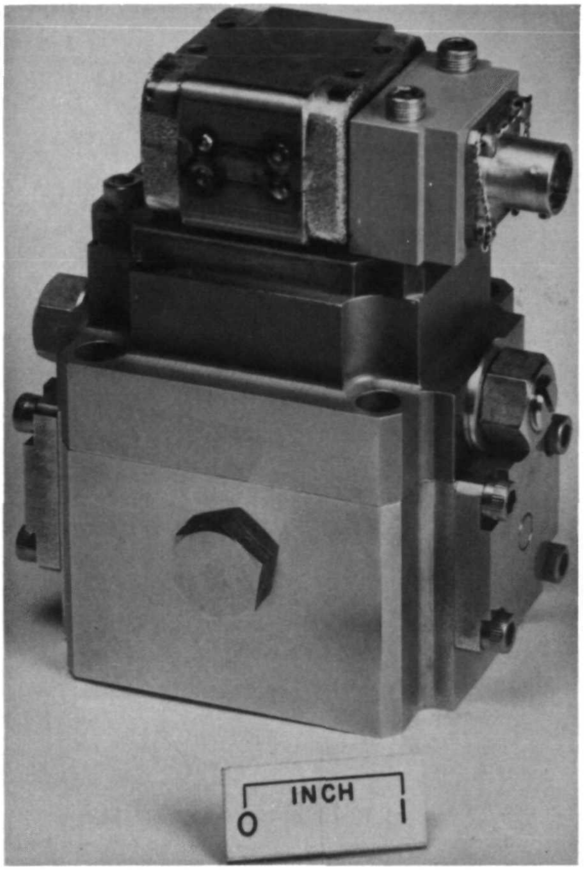


FIGURE 23.–Vortex servovalve for high-pressure hydraulic application.

8. Under joint NASA-AEC sponsorship, Aerojet Nuclear Systems Co. developed several vortex valves to control turbine inlet conditions for the NERVA nuclear rocket engine (ref. 82). This effort included development of scaling laws accounting for variations in type of gas, temperature, pressure, and geometry, as well as development of a computer program to predict vortex valve performance.

Fluidics for Gyros (Fluidic Accelerometers)

In addition to developing vortex rate sensors to replace gyros in some applications, NASA has found applications where it is desirable to retain a mechanical gyro, but to pick off the signals fluidically rather than electrically. Under contract to Marshall Space Flight Center, GE developed a two-axis fluidic rate gyro incorporating closed-loop, force-balance type accelerometers (refs. 83-86).

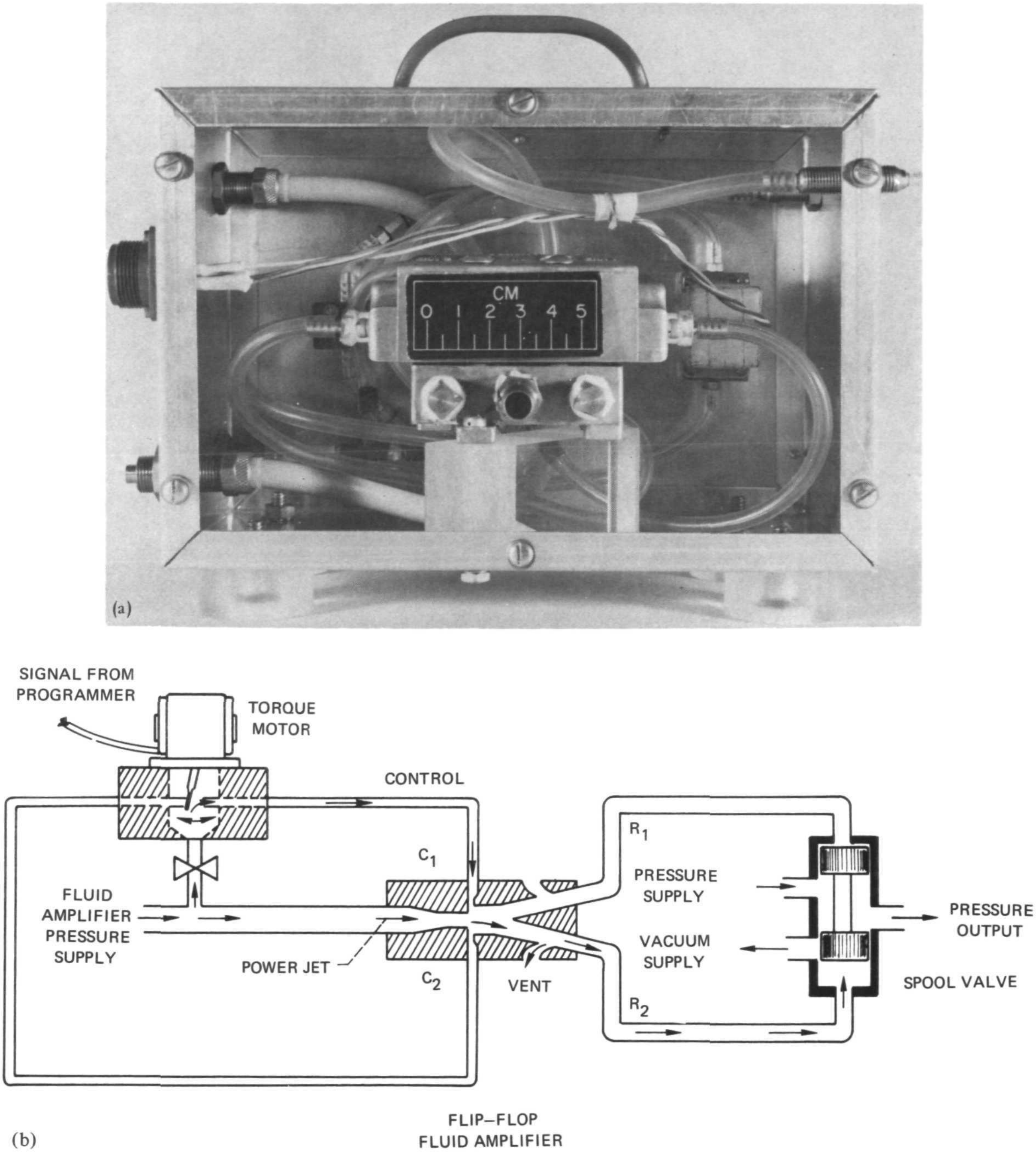


FIGURE 24.–Pneumatic switching valve for cardiac assist pump driving system (ref. 87). (a) Switching valve assembly; (b) pneumatic switching valve diagram showing flip-flop fluid/power amplifier.

NASA FLUIDICS TECHNOLOGY APPLIED TO MEDICAL RESEARCH

A specific example in which NASA's aerospace use of fluidics technology has been exploited as part of the Technology Utilization Program may be found in the work of two researchers at Lewis Research Center. John A. Webb, Jr., and Vernon D. Gebben used NASA experience in fluidics to design and evaluate a pneumatic control system to drive a wide variety of cardiac assist pumps and artificial hearts (ref. 87). A cooperative program for artificial heart research was developed between NASA and the Department of Artificial Organs at the Cleveland Clinic Research Foundation, Cleveland, Ohio. Other investigators had previously attempted to develop a small, lightweight pump that could be implanted to assist the failing heart temporarily, or to replace the pumping function of the natural heart permanently. An early suggestion made by NASA engineers was to use compressed air as an energy transmission medium for driving an artificial heart. The pneumatic heart designs subsequently developed by the Cleveland Clinic showed considerable promise as compared with earlier electric motor or solenoid-driven pumps. Figure 24 shows the pneumatic switching valve and illustrates the manner in which the flip-flop fluid amplifier serves as a power amplifier to drive the spool valve. This spool valve in turn provides the necessary systolic (positive pressure) and diastolic (negative pressure or vacuum) heart pumping actions.

THE ROLE OF GOVERNMENT IN GENERAL AND NASA IN PARTICULAR

Except for the reference to some of the historical work at the Harry Diamond Laboratories and reference to a few military or AEC efforts that were directly related to particular NASA programs, this chapter has not covered contributions that other Government agencies have made to the growth of fluidics. Some of the more interesting examples will be mentioned later, but no comprehensive summary of these efforts is attempted here. It is appropriate at this point to try to define Government's role, particularly that of NASA, in the evolution of fluidics as a technology in the United States.

Fluidics is such a natural way to accomplish some fluid control functions that it is probably safe to say that sooner or later the technology would have been developed even without Government sponsorship. When and at what rate this would have happened is difficult to say. Certainly if the pioneering work in fluid amplifiers at HDL had not been performed and publicized, the start would have been both later and slower. Commercially profitable fluidics products have become a reality only within the last few years. Had private industry found it necessary to perform all the basic R&D necessary to conceive and mature the technology, it would almost certainly have found the cost prohibitive. As with so many other technologies, however, the pressures of weapons systems development or the needs for design improvement in satisfying the challenges of the space program have warranted the expenditures for such R&D work.

Technically, the NASA-sponsored efforts are of particular interest because so many of them deal with the more knotty problems of proportional control. Proportional fluidic systems are only starting to appear on the commercial fluidics market, and many fluidics manufacturers indicate that they will stick to the simpler digital fluidics for some time to come. It is reasonable to expect that the first commercial applications of proportional fluidics will come from those companies that have gained experience while performing NASA contracts. The greatest value of NASA's contributions to fluidics, however, rests in the fact that the great bulk of the work has been documented in unclassified publications and, except for those applications which used items that were already patented or proprietary to the supplier, the results are largely in the public domain.

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CHAPTER 3

Examples of Fluidic Systems

This chapter looks at some of the fluidic systems that have been placed in operation. Some have not progressed beyond an experimental feasibility demonstration model, whereas others are in large-scale production. The emphasis here is on the wide variety of examples for which there is at least some documentation. Because of the large number of these different fluidic systems applications, they are simply categorized and the references describing them are listed. Chapter 5 considers the selection factors involved, listing some of the tradeoff studies that can provide insight into the analytical processes used.

The fluidic systems listed in the tables of this section represent only a portion of the many functions already performed by fluidics. The dynamic state of the fluidics business today is such that an author who endeavors to publish a "complete list of fluidic applications" is almost certain to omit the favorite example of several fluidic equipment manufacturers.

AEROSPACE AND MILITARY EXAMPLES

Table 5 lists some fluidic systems that have been developed for aircraft, spacecraft, rocket, missile, and associated applications. Many of these have been described in chapter 2. There are relatively few military examples listed, which may at first seem strange in view of the strong fluidics programs that the services have mounted. Many reports and papers have been published by military research organizations, especially the Army's Harry Diamond Laboratories (HDL). Much of this material is directed towards basic research. As soon as it becomes applied to a particular weapons system, such as an artillery shell fuse, it usually becomes classified. This chapter is concerned primarily with complete, end-item fluidic systems applications; hence, relatively few military examples are cited. However, several of the aerospace applications are briefly described.

Inspection and Assembly in Munitions Manufacture

The U.S. Army, largely through the efforts of HDL researchers, has applied fluidics in a number of arsenals. The applications are particularly appropriate because of the obvious explosive hazards. Fluidics either eliminates electrical controls or permits these controls with their attendant spark potential to be remotely located and shielded. These installations are of interest because their production line nature bears many similarities to industrial operations. Mr. Lyndon Cox of HDL cited the following examples of installations in operation in mid-1971:

1. Badger Arsenal in Baraboo, Wisconsin, uses 25 packaged fluidic systems to control sequence presses for removing water from nitrocellulose.

2. Indiana Arsenal in Charlestown, Indiana, employs fluidic systems for weighing 81-mm and 175-mm projectiles.

3. Lake City Arsenal in Independence, Missouri, uses essentially the same high-speed check weigher and fluidic control system.

4. Milan Arsenal in Milan, Tennessee, uses automatic assembly machines with complete fluidic control provided by four identical 100-gate fluidics systems per machine.

5. Twin Cities Arsenal in Minnesota is equipped with 100 fluidic systems for detecting the presence or absence of vent holes in cases.

6. Tooele Army Depot in Tooele, Utah, has employed a primer height sensor developed by HDL. This fluidic system features an interruptible jet sensor which can locate pin height to within 0.013 mm (0.005 in.) and will automatically shut down the machine if the primer has been improperly installed in the artillery shell.

TABLE 5.–*Aerospace and Military Examples of Fluidic Systems*

Example	Status	Reference
Airplane Flight Controls		
Three-axis autopilot system	Flight Tested	58, 88
Hybrid fluidic yaw damper	Flight Tested	89
Rate and attitude control system	Flight Tested	90
Helicopter Flight Controls		
Three-axis stability augmentation	Flight Tested	91, 92, 123
Fluidic yaw damper	Flight Tested	93, 94
Missile or Space Vehicle Flight Controls		
Sounding rocket attitude control proportional thruster	Experimental	60, 61, 62, 63, 114, 126
Reentry vehicle roll control system	Experimental	95
Missile roll control	Flight Tested	90, 118
Aircraft Cabin Pressure Control System	Experimental	96
Aircraft Fluidic Stall Sensor	Experimental	97
Aircraft Hydraulic System Fluidic Circuit Breaker	Experimental	98
Turbojet Engines		
Supersonic inlet shock position locator	Experimental	68
J–79 engine control	Experimental	99
Turbine inlet temperature sensor	Experimental	100
Afterburner light-off detector	Experimental	101
Compressor bleed control	Experimental	102
Fuel control valve	Experimental	103
Thrust reverser		104
Navy carrier aircraft approach power compensator	Flight Tested	123
Space Suit/Flight Suit Temperature Control	Experimental	47, 48, 49, 105, 148
Nuclear Rocket Engine Controls		
Fluidic servovalve	Experimental	45, 80, 106
Pneumatic stepping motor	Experimental	42, 43, 44
Vortex turbine throttle	Experimental	82, 107
Pneumatic nutator actuator motor	Experimental	108
Analog-to-pulse frequency converter	Experimental	109
Fluidic chamber pressure control	Experimental	110
Liquid Rocket Engine Controls		
Hydraulic gimbal actuator control	Experimental	77
Vortex control of hydraulic servovalves	Experimental	79, 80, 81
Secondary injection thrust vector control	Experimental	76
Solid Rocket Motor Controls		
Vortex throttling valve	Experimental	74, 75, 111, 112
Spacecraft Sensors		
Fluidic sun sensors	Experimental	114, 115, 116
Fluidic inertial sensors (gyros and accelerometers)	Experimental	83, 84, 86, 117, 119, 120, 121, 122
Naval Motor-Generator Speed/Load Controller	Experimental	124
Military Miniature Fluid Counter	Experimental	125

Fluidic Stall Sensor

Figure 25 shows the operation of a fluidic stall sensor developed by HDL for use on either airplane wings or helicopter rotors (ref. 97). It was noted that when a wing or other aerodynamic surface stalls, the phenomenon is similar to the flow in a wall attachment fluid amplifier upon being detached and attaching to the opposite wall (see ch. 8). In both cases the attached flow encounters an adverse pressure gradient and then detaches.

In the stall sensor, a small probe similar to a pitot tube is positioned just above the boundary layer on

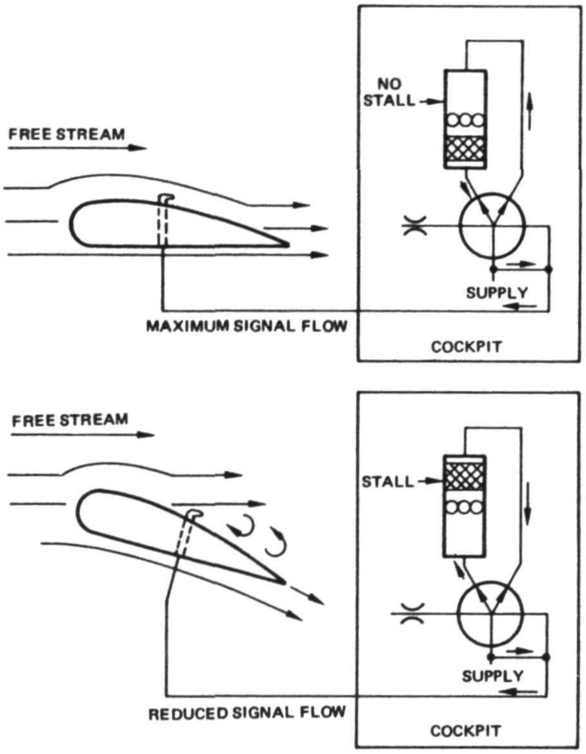


FIGURE 25.–Fluidic stall sensor indicating both the stall and no-stall conditions (ref. 97).

the wing. The tube faces about 15° aft of perpendicular to the flow. The attached flow aspirates air from the sensor. As shown in figure 25, the flow aspirated from the sensor prevents foreign matter from entering the system. When stall occurs, the flow over the sensor becomes highly turbulent and then reverses. Flow is no longer aspirated from the sensor but is resisted. Some of the flow from the bias slot enters the control and the bistable fluid amplifier is switched. This operates a red plastic piston in the cockpit of the plane. A row of indicators is attached to a row of sensor systems on the wing. As the red line appears to lengthen, it indicates to the pilot that his lift or margin of safety is decreasing.

COMMERCIAL AND INDUSTRIAL APPLICATIONS

Table 6 lists examples of commercial and industrial applications of fluidic systems and gives an indication of the extent to which each had matured by the time the cited references were published. These examples range from automotive applications, most of which have not advanced beyond the experimental stage, to Johnson Service Company's well-established line of fluidic environmental controls for large buildings.

TABLE 6.–*Commercial and Industrial Examples of Fluidic Systems*

Example	Status	Reference
Process Controls		
Document handling	Developed	152, 153, 154
Mail singulation and cancelling	Developed	154, 155
Glass press control	In Use	156
Papermaking machinery control (Scotland)	In Use	6
Pyrotechnic flare charge manufacture	In Use	157
Acid vaporizer controller	In Use	158
Batch process control, monitor, and display	In Use	150, 151
Control and monitoring of filter bag cleaning in tire manufacture	In Use	177
Vacuum monitor and control in tire manufacture	In Use	177
Papercoating operation; paper-splice detector	In Use	180
Sequence and Function Control of Machines		
Automatic turret lathe sequencing	In Use	127, 150, 180
Newspaper stacking, compensating and labelling	In Use	143, 177
Folding door hanger pin manufacture	In Use	128
Eight-gun paint spray system	In Use	143, 180
Pump unloading system		129
High-speed assembling machines	Developed	130, 141
Numerically controlled chucker	In Use	150
Coil winding	In Use	6
High-speed die casting	Developed	140

TABLE 6.–*Commercial and Industrial Examples of Fluidic Systems*–Continued

Sewing maching controls	In Use	6, 146, 147
Grinding operations (Italy)	In Use	6
Hole punching operations (England)	In Use	6
Liquid Level Control and Container Filling		
Carbonator pressure tank	Developed	134
Boiler feedwater	Developed	135
Sewage pumping station level control	In Use	6
Level and density control	Developed	136, 137
Filling and Packaging		
Automatic bottle filling	In Use	132, 133, 159
Drum filling by weight	In Use	160, 181
Bin filling (liquid, powder, or small parts)	In Use	
Gunpowder net-weight filling of artillery shells	In Use	161, 178
Hair tonic bottle wrapping (in six-packs)	In Use	161
Food wrapping film alignment check	In Use	161
Case palletizing machine	In Use	181
Address label stacking and boxing	In Use	179
Candy box filling	In Use	6
Random-size box sealing	In Use	6, 131, 143
Soft drink bottle casing	In Use	6
Test and Inspection		
Automobile gas tank leak detector	In Use	138, 141
Miscellaneous gaging and classifying	In Use	160
Cylinder height gaging and sorting	In Use	162
Postage meter life cycle testing	In Use	143
Event counting and display systems	Commercially Available	180
Lip seal inspection (moving-part logic)	In Use	181
Noncontact Sensing and/or Control		
Acoustic sensors	Developed	139, 148, 162
Proximity gaging	In Use	141, 144, 145, 149, 150
Vaporized metal measuring	Developed	142
Die protection	In Use	143, 163
Sewing machine controls	In Use	146, 147
Edge or end-of-stock sensors	In Use	
Yarn, rope, or wire diameter gaging	In Use	148
Broken tool detector	In Use	
Photographic film winder	In Use	6
Paint spray target analysis	In Use	143
Labelling machine	In Use	150
Flow Diversion Applications		
Test equipment burner cooling	In Use	164
Irrigation water-switching	In Use	159
Bow thruster for yachts, barges, etc.	In Use	159
Home and commercial building ventilation	In Use	165
Refrigeration defroster control	Developed	6, 148
Automotive Products		
Fluidic carburetor	Experimental	148, 166, 170
Automatic transmission control	Conceptual	166
Two-cycle engine fuel conservation	Experimental	166
Consumer Products		
Fluidic lawn sprinkler	Available in Quantity	159
Pulsating shower head	Trial Sales	159
Environmental Control		
Heating and air conditioning controls for large buildings	In Use (large quantities)	150

TABLE 6.–*Commercial and Industrial Examples of Fluidic Systems*–Concluded

Home and commercial building ventilation	In Use	165
L 1011 cabin ventilation control	Developed	165
Fluid Mixing		
Large-scale hot and cold water mixing	Experimental	167
Radioactive slurry emergency feed system	Experimental	168
Rotating Equipment Speed Control/Monitoring		
Air motor fluidic governor	In Use	151, 169
Steam turbine fluidic governor	In Use	151
Gas turbine fluidic governor	Developed	151
Fluidic tachometer for diesel-driven ships	In Use	151

Several representative examples of commercially available fluidic systems will be described briefly in this section. The emphasis here is not on how the fluidics of the system works, but on where fluidics fits into the system to which it is being applied.

One Approach to Fluidic Gaging

Johnson Service Company has applied the same basic impact modulator fluidic devices used in their environmental control systems to various other functions that fluidics can perform well. The following examples of fluidic gaging systems have been drawn from the company's application bulletin. It illustrates how one manufacturer uses one basic controller (fig. 26) to perform a number of different gaging jobs with sensors that operate on the same principle.

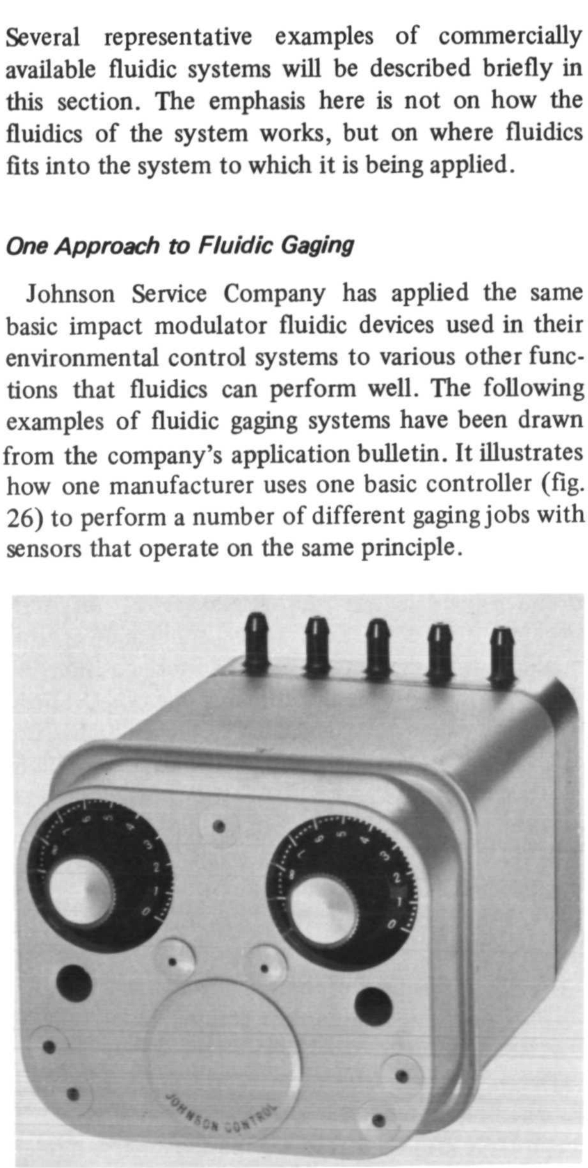


FIGURE 26.–Gaging controller with exposed set point.

These controllers operate on the process variable input range of 3 to 15 psig and all have two adjustable reference pressures. The reference pressures are determined by a pair of set point regulators within the controller. The input signal is compared to the reference pressures through a pair of summing impact modulators (SIM's), which are also enclosed within the controller. The result of this comparison determines the specific fluidic outputs. The comparison of the input to the reference pressure is accurate to less than 1 percent.

A back pressure sensor is sometimes used in conjunction with the gaging controller. The back pressure sensor is a fluidic sensor particularly suitable for gaging applications. For example, the Fluidic Position Transmitter in figure 27 used a back pressure sensor in conjunction with a fluid amplifier and feedback bellows to provide a signal pressure linearly proportional to dimensions.

The back pressure sensor (fig. 28a) consists of an upstream metering orifice, an output tap, and a downstream leakport. The output pressure is dependent upon the sensing distance (x), which is the distance between the leakport and the sensed object.

The characteristics of the sensor can be changed by modifying the leakport size and metering orifice size. Varying the level of these sensor parameters (leakport size and metering orifice size) can provide a wide range of sensor characteristics. The sensor characteristics (fig. 28b) show the pressure output versus sensing distance (x) for a leakport of 0.040 in. I.D., for three different metering orifice sizes.

1. *Gaging indication system.*–A gaging controller and a back pressure sensor can be combined to provide a useful system for checking tolerances. The reaction speed of the controller allows test specimens to be checked at rates as high as 1800/min.

The gaging indication system operation begins with

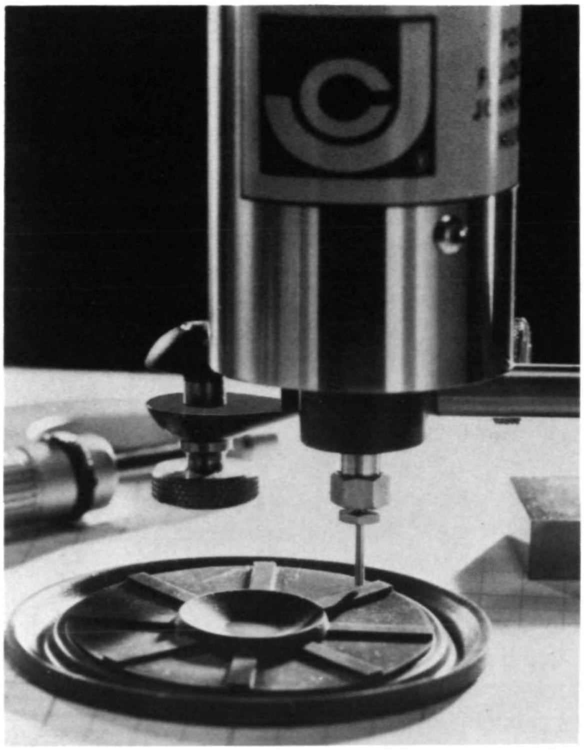


FIGURE 27.–Fluidic position transmitter.

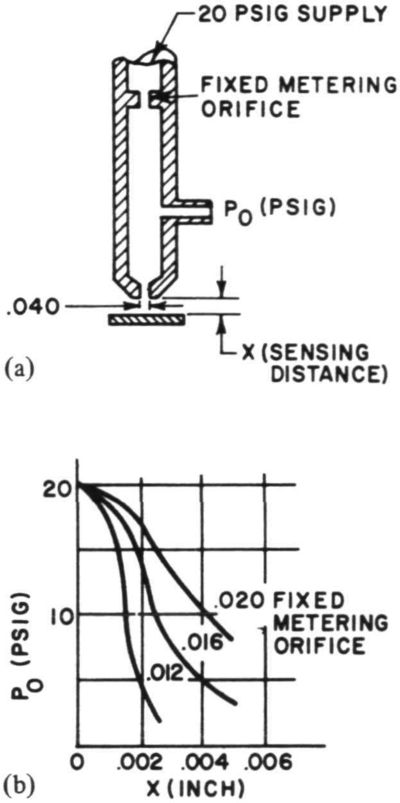


FIGURE 28.–(a) Back pressure sensor; (b) back pressure sensor characteristics.

the setting of the test specimen into the gaging fixture (fig. 29). The supply pressure is turned on and the resulting back pressure is compared to the reference pressures set on the controller. The low reference pressure set point is adjusted to correspond to the low tolerance of the part, and the high reference pressure set point is adjusted to correspond to the high tolerance of the part. The two selectable tolerance levels are adjusted and function independently of one another. If the test specimen is within tolerance, the ACCEPT fluidic indicator (II) will turn on and the REJECT fluidic indicator (III) will be off. If the test specimen is out of tolerance, whether low or high, the REJECT fluidic indicator (III) will turn on and the ACCEPT fluidic indicator (II) will be off. The REJECT fluidic indicator (III) will turn on continuously during the absence of a test specimen.

The indication system can be upgraded by employing a READ button, as indicated in figure 29. Installation of the READ button eliminates the annoying on-off sequence of the REJECT fluidic indicator due to the placement and removal of a test specimen, and allows the tolerances of the test specimen to be checked upon command of the operator. With the button in the normal position, an output is emitted from the normally open (N.O.) port which will cause both the ACCEPT (II) and REJECT (III) outputs of the gaging controller to be off. With the READ button depressed, the N.O. port closes and no signal is supplied to port I of the gaging controller. With no input at port I, the gaging controller will function in a normal fashion.

2. *Gaging control system.*–This system (fig. 30) shows the same controller as the first system. However, in this system there is automatic "control" and not mere "indication" of acceptable and rejectable test specimens. Operation of the gaging control system is almost identical to that of the indication system. The system differs in that a conveyor takes the place of the gaging fixtures and the reject cylinder replaces the REJECT fluidic indicator. The operation of the controller itself and the use of the ACCEPT

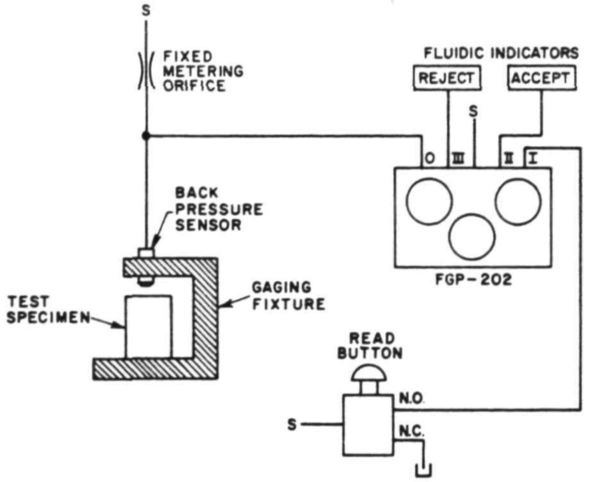


FIGURE 29.–Gaging indication system.

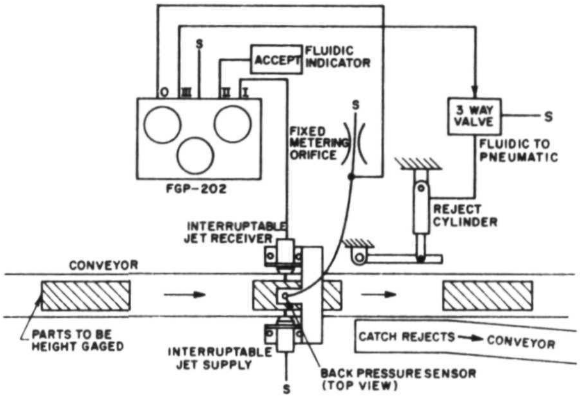


FIGURE 30.–Gaging control system.

fluidic indicator is not affected. Whenever a test specimen is absent from beneath the back pressure sensor, an interruptible jet supply and receiver prevent the controller from initiating a REJECT port (III) output, which in turn prevents the extension of the reject cylinder. This interruptible jet supply and receiver perform the same function as the READ button in the gaging indication system.

3. *Orifice gaging system.*–Orifice gaging is accomplished with the gaging controller by simply using a metering orifice in series with the test orifice (fig. 31). If the metering orifice is smaller than the test orifice, a very accurate system can be developed. The pressure between these orifices is fed to the gaging controller and pressure set points are selected. The low reference pressure set point is adjusted to correspond to an orifice which is at the low pressure end of the tolerance spectrum. If the test orifice is within tolerance, the CORRECT fluidic indicator output (II) will turn on. If the test orifice is too small, the SMALL fluidic indicator output (III) will turn on. If the test orifice is too large, the LARGE fluidic indicator output (I) will turn on. Only one fluidic indicator output is on at a time.

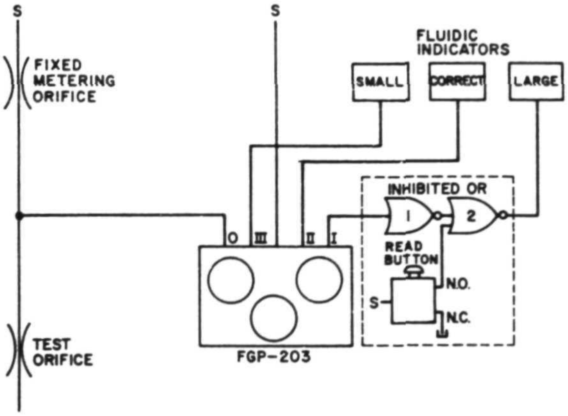


FIGURE 31.–Orifice gaging system.

Also, whenever a test orifice is absent, the LARGE fluidic indicator will be on. The placement and removal of the test orifice will cause a possibly annoying on-off sequence of the LARGE fluidic indicator. A READ button, and two NOR gates arranged in an inhibited OR logic pattern, placed in series with the LARGE fluidic indicator will eliminate the possible annoyance. As illustrated in figure 31, placement of an inhibited OR in the LARGE fluidic indicator line permits a readout upon command from the operator. With the READ button in the normal position, no signal will reach the indicator. With the READ button depressed, a signal will reach the indicator whenever an output from the controller is present. By proper selection of a metering orifice and reference pressure set points, variations in orifice diameter of less than 0.001 in. can be detected. The reaction speed of the controller allows test orifices to be checked at rates as high as 1800/min. This system can also be used as a leak detector for pressure tight vessels.

4. *Comparative gaging system.*–These controllers are designed to accept remote set point settings. One or both of the reference pressures can be supplied from an external source. This external source may be (1) an external regulator mounted at the central panel

or at another remote location, (2) an output from some other process controller, or (3) a reference pressure established by some reference part or condition.

Thus, it is possible with these controllers to perform comparative gaging. The schematic in figure 32 shows how comparative gaging can be accomplished by using a reference part to establish the low and high reference pressure levels for a mating part. When the parts match within the tolerance spectrum established by the remote low (II) and high (III) reference pressure set points, the PARTS MATCH fluidic indicator output (O) will turn on. When the parts do not match, that is they fall beyond the limits of the tolerance spectrum, the PARTS MATCH output (O) will be off.

The comparative gaging system may be used for comparison of two dissimilar parts which when used together are part of an assembly. For example, one might wish to compare the interior of a wheel cylinder and the exterior of a brake shoe to ensure that the mating of the two pieces falls within specified tolerances. Other uses of remote set point systems are for (1) on-off control with adjustable hysteresis, (2) remote set point applications where controller and operator are in different locations, and (3) time proportioning systems where percent of cycle is varied with the hysteresis.

5. *Proportional control process temperature with digital override.*—Pneumatic process controllers convert a controlled variable into the 3 to 15 psig pressure range. They can be used as limit detectors because they can be directly interfaced with these process controllers.

Limit detection can be used to indicate, to provide on-coast-off control, or as a digital override on a proportional system. The schematic in figure 33 shows a system using a controller as a digital override on a proportional process control system.

Operation of the temperature control system begins with the proportional process controller. The process controller accepts a signal from the temperature sensor and proportionally controls the mixing valve in accordance with the offset, or deviation from the set point.

Fluidic Displays and Counters

A line of counters and timers produced by Pitney-Bowes Fluidic Controls (fig. 34) is one of the first examples of a totally fluidic system marketed on a functional basis rather than as a part of a system. Figure 34 shows some of the fluidic accessories such as sensors and output devices which are offered in conjunction with the units. Both cumulative and predetermining counter and timer versions are offered at prices competitive with conventional electronic devices.

The alphanumeric readouts used in these counters and timers are an interesting example of fluidic display technology. Pitney-Bowes has expanded on the idea of a simple pop-up indicator (fig. 35) to make the alphanumeric readout device shown in figure 36 (ref. 182). The tiny pistons in the indicators are the only moving parts in the entire counter-timer system. No electrical components are included, al-

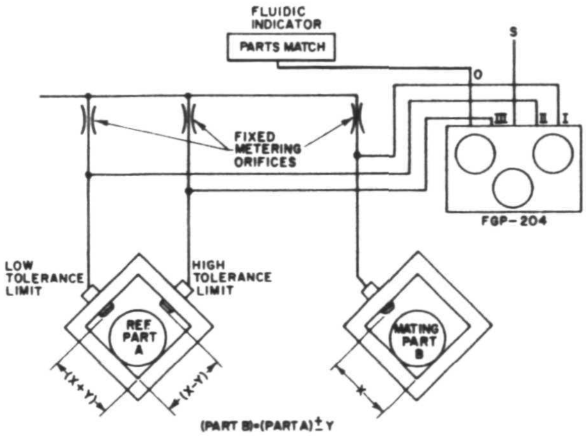


FIGURE 32.—Comparative gaging system.

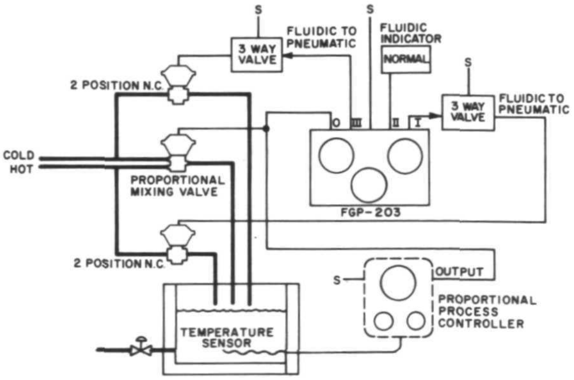


FIGURE 33.—Proportional control of process temperature with digital override.

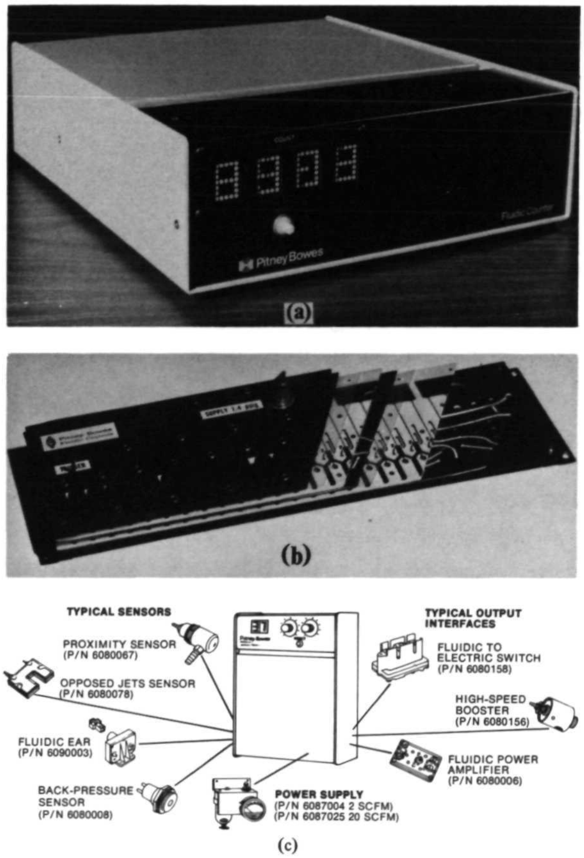


FIGURE 34.–Commercially available all-fluidic counters or timers. (a) 4-decade cumulative fluidic counter; (b) cutaway of FLOWBRICK fluidic integrated circuit; (c) optical accessories.

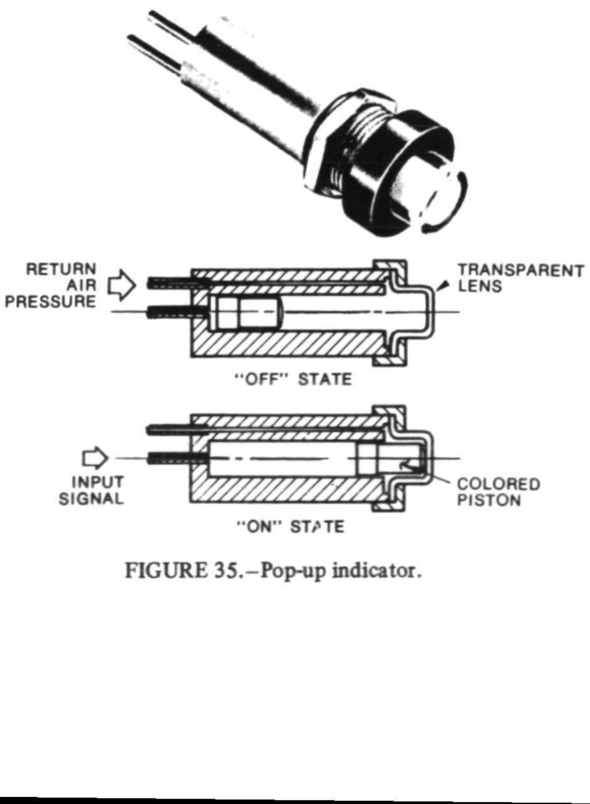


FIGURE 35.–Pop-up indicator.

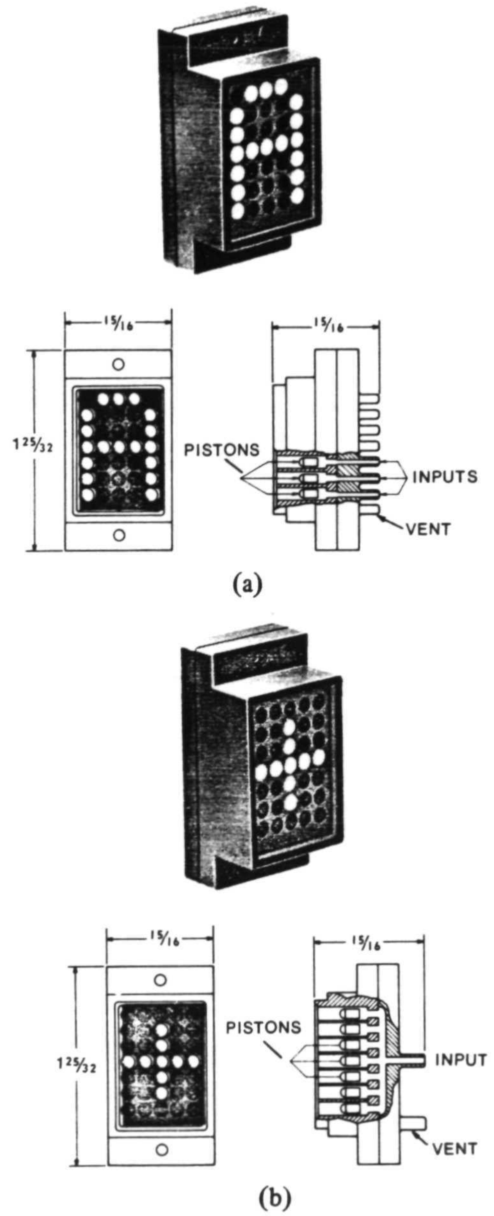


FIGURE 36.–(a) Alphanumeric fluidic readout; (b) single character readout.

though some applications naturally require electrical interfaces. The integrated circuits comprising the logic of this series are described in chapter 5.

Inspecting Yarn or Wire Production

Figure 37 illustrates a system developed by General Electric (GE) for continuously evaluating the quality of fiber or filament. According to GE, this on-line

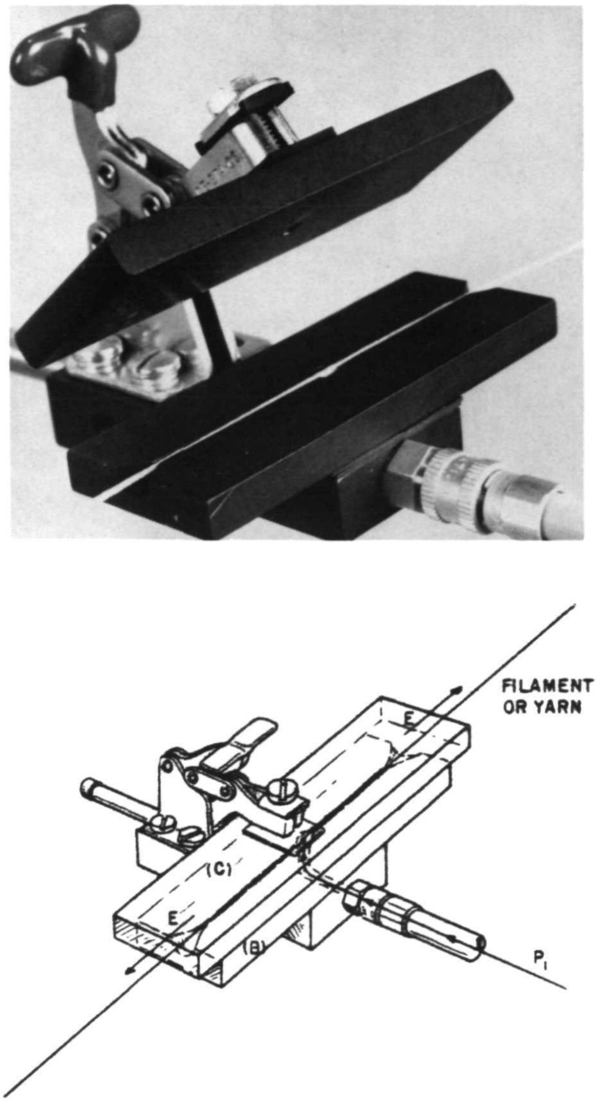
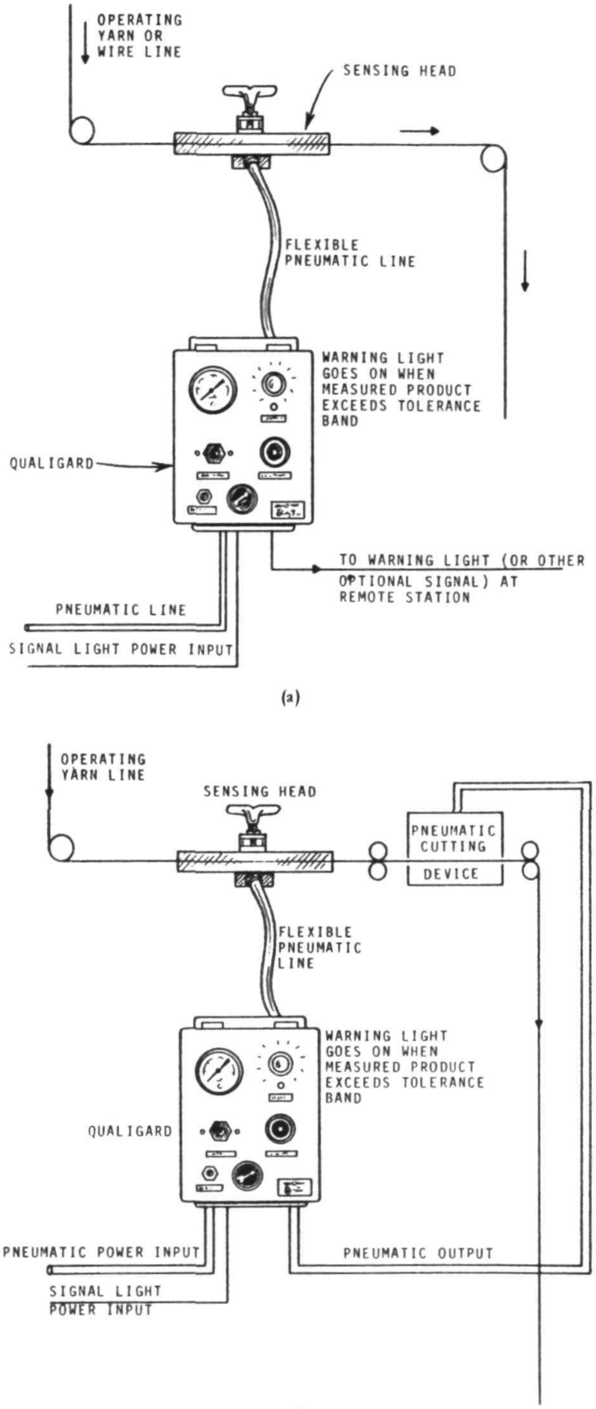


FIGURE 37.—Yarn sensing head.

system can measure yarn or wire diameters, fiber porosity, pile height, or insulation thickness at accuracies better than ± 1 percent at production speeds exceeding 1500 m/min (5000 ft/min). The sensor consists of a top cap (C) and a slotted bottom plate (B) through which the material to be tested is drawn. Air is introduced into the sensor at pressure P_1 and escapes through the ends of the slot (E). The tested material presents a resistance to the flow of air, which must pass by the filament or through the fiber bundle to reach atmospheric pressure. Changes in pressure P_1 resulting from change in density or diameter of the



(a)

(b)

FIGURE 38.—Three fluidic fiber quality monitoring systems. (a) Simple warning device; (b) warning system with cutoff provision.

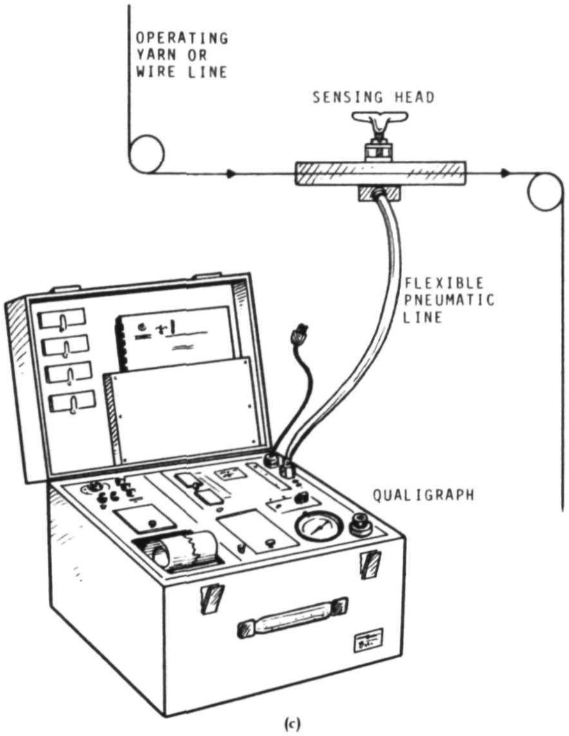


FIGURE 38.– Concluded
(c) graphical quality recorder.

measured material modulate the input to the monitoring system.

The monitoring system may take the form of either a simple "off-spec" warning light or other signal (fig. 38a), a warning system coupled to an automatic stop or filament cutter (fig. 38b), or a continuous graphical recorder (fig. 38c).

Two interesting aspects of this filament quality monitor are:

1. No attempt has been made to make the unit all-fluidic. The warning light or other signal and the graphical recorder are conventional electrical units.
2. The fluidic logic employed is analog or proportional rather than digital, although the output of the simple warning system is digital.

MEDICAL EXAMPLES

Table 7 lists examples of fluidic systems applications to the medical field. With the exception of the Mine Safety Appliances Company breathing assistor (fig. 39) for which Bowles Fluidics Corporation manufactures the fluidic control device, medical uses of fluidics are still in the introductory stages. The potentials associated with fluidics' high reliability,

TABLE 7.–*Medical Examples of Fluidic Systems*

Example	Status	Reference
Artificial Hearts and Heart Assists		
Cardiac assist switching valve	Developed	87
Extra corporeal pulsatile blood pump	Developed	171
Implantable artificial heart	Proposed	172
External cardiac compressor	Experimental	171
Respirators and Breathing Assists		
Fluidic breathing assistor for emphysema patients	Commercially Available	159
Artificial respiration apparatus (Russia)	Experimental	173
Volume-cycled respirator	Experimental	171
Pressure-cycled respirator	Developed	171
Electric wheelchair control for quadriplegics	Developed	174
Hospital Equipment		
Bedrocking device for immobile patients (England)	Developed	175
Carbon dioxide concentration sensor	Experimental	176
Anesthesia equipment for animals	Developed	159
Blood sample preparation equipment	Developed	159

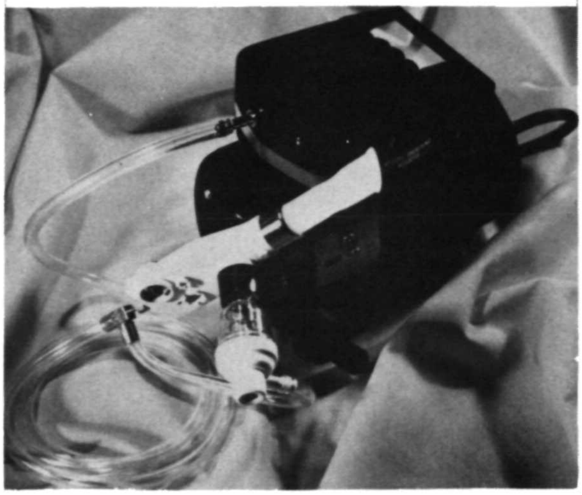


FIGURE 39.–Fluidic breathing assistor.

lack of shock hazard, and maintenance simplicity are expected to result in rapid expansion of this list in the near future.

The simplicity of operation of the fluidic breathing assistor shown in figure 39 is typical of what can be accomplished with a fluidic no-moving-part device. With the assistor connected to a 20-cm H_2O air pressure supply (such as the motor-driven compressor that comes with the unit), the user simply inserts the mouthpiece, seals it with the lips, and inhales slightly. The slight negative pressure created by inhalation starts the pressure breathing cycle. The delivery of air continues until the preadjusted pressure is reached, at which point the unit cuts off and pressure drops to zero, awaiting another slight inhalation to restart the cycle.

CHAPTER 4

Applying Fluidic Systems

In this chapter we will discuss briefly the considerations and selection criteria which influence the approach to answering two basic questions: Can fluidics do the job? If so, should fluidics be used?

PRIOR LOOKS AT APPLYING FLUIDIC SYSTEMS

A great deal of effort has gone into ascertaining whether fluidics is the best way to do a large number of jobs. The newcomer to fluidics who chooses to ignore this work and sets about directly to establish his own criteria for fluidics applicability to his requirements will certainly have the benefit of a fresh outlook. On the other hand, odds of his not repeating at least a portion of a prior analysis are slim indeed. Table 8 summarizes some of the early application feasibility studies, tradeoff studies, and application recommendations and analyses to provide a starting point for those who would like to review them. The effectiveness with which the titles of these references convey the actual content and its value to the researcher varies. Most of these references, however, will give the researcher insight into the level of sophistication (both high and low are included) of these studies.

CRITERIA FOR APPLYING FLUIDICS

One benefit of the unfortunate overselling of fluidics in the mid-1960's has been nearly universal concurrence by successful fluidics manufacturers, users, and application specialists (often manufacturer's representatives) that fluidic systems should be specified only when they would result in a definite advantage, never simply for their novelty. Fluidics offers so many possibilities, that once feasibility for an application was established, all too often a fluidic system was incorporated without proper analysis of whether fluidics should be used for the job. Most of this chapter is devoted to the factors which can enter into making that important judgment.

Let us first dispense with the easy question, "Can fluidics do this job?" If the function to be performed involves sensing, logic (or signal processing of some sort), control, or signal amplification, it is reasonable to assume that fluidics can do the job if a flow of fluid can be provided. If the job requires none of these functions, or if there is no means of providing a flow of gas or liquid, fluidics may be inappropriate. This obviously leaves a great many potential applications for consideration.

Where fluidics can do the job, the next question is, "Should fluidics be used here?" The first and rather obvious step is to ask yet another question, "Can anything other than fluidics do this job?" In the very rare event that the answer is negative, one can proceed directly to specifying the fluidic system needed (see ch. 7). If the situation fits into the category that accounts for probably 99 percent of all potential applications for fluidic systems, however, we are faced with trading off one or more potential fluidic systems with other candidate means of getting the job done.

Check List of Key Fluidics Application Criteria

The factors to be considered in the selection of fluidics for a control system application vary widely. The items that are presented below may be considered as a minimum check list applicable to virtually any potential fluidic installation.

1. Is there a ready supply of gas or liquid under pressure?

Experience with industrial applications has shown that it is seldom worthwhile to provide a source of pressurized fluid only for a fluidic control system. In some applications, such as portable equipment like

TABLE 8.–*Some Representative Studies and Articles Concerning Applications and Tradeoffs With Fluidics*

Survey or Application Reference Title	Reference
General Fluidics Application	
A Practical Look at Some Aspects of Fluidics	203
The Application of Fluidics to Low-Power Logic Circuits	193
Fluid Amplifiers Go Where it's Hot, Dirty, Unsafe, or Just Crowded	177
Applying Fluidic Operational Amplifiers	191
Future System Applications for Fluidics	200
Making it With Fluidics	180
Making it With Moving-Part Air Logic	181
A Brief Survey of Fluidics in the U.K. and Some Comments on Problems Encountered in Developing Fluidic Circuits	216
Far-Out Fluidics is Exotic Compared With Commercial	148
Fluidic Control Devices and Systems	233
Fluidics Applications: Analysis of the Literature and Bibliography	229
A Systems Approach to Applying Fluidic Controls	230
Fluids Selection for Fluidic Systems	
On Combined Use of Pneumatic and Hydraulic Components in Fluidics	217
The Use of Liquids in Gas-Operated Fluidics	209
Fluidic Elements in Hydraulic Oil	194
Fluidic Gas Power Sources	222
Hydraulic Fluidics	231
Liquid Fluidics–Problems and Potential	232
General Control and Instrumentation Applications of Fluidics	
Survey of Recent Developments in Semifluidic Proportional Control Systems	205
Application of Pure Fluid Elements to Control Systems	198
Fluidics for Control and Instrumentation	189
Air-Operated Display Fluidics	182
Fluidic Devices and Application to Fluid Power Systems	219
High-Speed Computing Techniques Applicable to Fluidic Digital Computation	220
Fluidic Displays	69
Fluidic Temperature Sensor Investigations for High Gas Temperatures	211
A Fluidic Ammeter for Measuring Current in Bridge Wires	234
Fluid Ammeter	235
A Simple Fluid Viscometer	236
Aircraft Applications of Fluidics	
A Review of Avionics Requirements for General Aviation	59
Rate and Attitude Stabilization for Aircraft and Missiles	90
Fluidic Cabin Pressure Control Systems for Military and Civil Aircraft	96
A Fluidically Controlled Aircraft Fuel Transfer System	184
A Fluidically Augmented Artificial Feed System for High Performance Aircraft	185
New Developments in Fluidics for Aircraft High-Pressure Hydraulic System Applications	186
Application of Fluidics to Automatic Flight Control	196
A Comparison of Avionics System Requirements and Fluidic Technology Capabilities	199
A Study of Applications of Pure Fluid Devices to Aircraft Hydraulic and Pneumatic Systems	221
Hydrofluidic Flight Controls	183
A Fluidic Approach to Control of VTOL Aircraft	226
Spacecraft Applications of Fluidic Systems	
Fluidic Attitude Control System–Solar Probe	113
Study of a Fluidic Attitude Control System for a Solar Probe Spacecraft, Phase I	21
A Survey of Potential Applications of Fluidics to Spacecraft Attitude Control	20
Advanced Valve Technology, Vol. II Nonmechanical Controls (No Moving Parts)	19
Advanced Valve Technology, Mechanical Controls, Nonmechanical Controls, and Technology Support	18
Performance Tradeoffs in Fluidic Attitude Control Systems	187
Rocket and Missile Applications of Fluidic Systems	
Fluid Amplifier Application Studies	9
Feasibility Study–Application of Fluid Amplifiers to Reactor Rod Control	41
Study of Fluidic Roll Control for Sounding Rocket Applications	63
Investigation of a Vortex Valve to Control Chamber Pressure in the NERVA Engine	82
Fluidic Heading Reference System	218
Fluidic Gyroscopes	214
Fluidic Inertial Sensors for Space Applications	117
Fluidic Inertial Instruments	188
Fluidic Applications to the Manufacture and Inspection of Missile Components	141, 192
Fluidics in the Control of Advanced Ramjet Engines	213
Fluidics in Liquid Propulsion Controls	227
Pneumatic Logic Rocket Engine Sequence Control	224
Jet Engine and Gas Turbine Applications of Fluidic Systems	
Fluidic Gas Turbine Controls	206
Fluidic Signal Processing Techniques for Aerospace Propulsion Control Systems	210
Fluidic Gas Turbine Engine Controls	212
Fluidics Has a Future in Jet Engine Control	223
Military Applications of Fluidic Systems	

Survey or Application Reference Title	Reference
A Fluidic Application Study–Weapon Safety and Arming	207
Development Aspects of a Miniature Fluidic Counter	125
A Flueric Oscillator for Military Timer Applications	195
Naval Fluidic Applications–Present and Future	123
A Review of the State-of-the-Art of Fluidic Annunciators	197
Fluidic Gas Power Sources	222
Process Control Applications of Fluidic Systems	
Fluidic Process Control Systems	137
The Application of Fluidics to an Automatic Weighing System	174
Application of a Digital Fluidic System to Monitor and Control a Fluid Metering Unit	208
Applying Fluidics to Control Systems: Digital and Analog	228
Machine Tool Applications of Fluidic Systems	
Designing High-Speed Machine Circuits With Fluidics	131
Air Logic Techniques for High-Speed Assembly Machines	130
Industrial Sequencing With Fluidics	129
Fluidic Applications to Machine Tool Automation	128
Why Fluidic Machine Control?	190
Troubleshooting a Fluid Logic Control System	204
Other Commercial and Industrial Applications of Fluidic Systems	
Applicability of Fluidic Controls to a Rankine Cycle Automotive Engine	22
Fluidic Control for Reliability in Packaging	179
The Application of Fluidics to the Detection of Burst Fuel Elements in Nuclear Reactors	201
A Fluidic Absolute Measuring System	202
Medical Applications of Fluidic Systems	
Independent Respiratory Support System	215
Design and Performance of a Heart Assist or Artificial Heart Control System Using Industrial Pneumatic Components	87
Undersea Applications of Fluidic Systems	
Underwater Hovering Control with Fluidic Amplifiers	225

the Bowles/MSA breathing assistor, or the portable version of the GE graphical filament quality recorder, a self-contained air pump is a reasonable accessory. In the great majority of cases, however, lack of an available working fluid is cause to question the applicability of fluidics at the start. Missile applications can pose even more difficult problems (ref. 222).

2. Is there suitable provision for venting, draining, or recirculating the fluid?

In most industrial "shop air" installations this is no problem at all. It does become a major consideration on applications such as spacecraft where mass conservation, venting thrust cancellation, and center of gravity control enter the picture (ref. 227).

3. Is the application a completely new product or installation, or does it comprise modification or replacement of an existing system?

The present consensus of opinion on this question appears to be, "If something else is already doing the job *satisfactorily*, it will not pay to switch over to fluidics." This recalls the example in chapter 1 of Bardons & Oliver's development of fluidic control for a new series of automatic turret lathes which they were introducing to their product line. The application proved to be a natural for Bardons & Oliver, but it could possibly have proven disastrous for a company with an established line of automatic turret lathes to convert them to fluidics. In one case the entire automatic control capability had to be established. In the second case, the fluidics capability would have to be developed in addition to the existing electromechanical capability. The benefits would not necessarily justify the additional investment.

A sound guideline relative to this criterion might be: If the new application is a completely new item, consider fluidics most carefully; if it represents a change from an existing or similar in-use system, fluidics will likely be worthwhile only if there is an overriding advantage in terms of safety, marketability, economy, etc.

4. Does the unit on which the fluidic system is to be applied require other power for performing other functions?

If electrical power, especially if associated with any computer-operated equipment, is going to be used on the application anyway, it further shadows the desirability of installing fluidics on the same unit. Certainly fluidics would still work, but the advantages may be more than offset by the necessity for providing two or more different inputs and outputs. If fluid power has to be provided to the machine for some other nonfluidic function (i.e., pneumatic actuators), the presence of electrical power also is further reduced in importance.

5. Is there a specific need for which fluidics can provide a uniquely superior answer?

Here we are concerned with the *overriding* need for fluidics, the kind of need that can convince a customer or board of directors that a higher price is justified. Such items which fluidics is uniquely well prepared to satisfy include:

- Safety in explosive environments
- Environmental insensitivity to radiation, temperature (some applications), shock, vibration
- Survivability (a gross overpressurization will blow some plastic tubes from a conventional industrial fluidic system, but will not harm important system elements in the way an overvoltage surge can burn out out an electronic system)
- Moderate operating speeds (electronic systems are faster, but electromechanical systems are slower)
- Volume (envelope) and weight (again, fluidics falls between electronic and electromechanical systems)
- Electromagnetic interference (EMI) (fluidics are great here because no spurious electrical or magnetic signals are emitted by most fluidic systems)

6. What are the economic advantages (both short term and long term) of using fluidics over alternates?

Chapter 5 treats this subject. In the 1960's the biggest gripe from industrial "pioneers" who tried incorporating fluidic systems was that the engineering costs were excessive. Since then the economic advantages of fluidic systems have improved remarkably.

7. Is the particular fluidic technology to be employed within the current state-of-the-art of the manufacturer and the user?

Rapid progress is being made in analog fluidics, but at present most manufacturers of commercial fluidic systems are sticking with either digital fluidics or very basic analog (proportional) systems with which they have experience. It is important that the buyer of a fluidic system have a firm understanding of what he is buying. Equally as important is how well the manufacturer understands what he is selling. Fluidics is a constantly evolving technology and will remain so for a number of years. Naturally, it will have many applications that stretch the state-of-the-art. The important thing is that the buyer who is sponsoring such advances should know what he is doing.

The preceding items all deserve careful analysis when evaluating fluidic systems and comparing them with nonfluidic means of performing the requisite system functions. This discussion makes no attempt to optimize the fluidic system. This emphasizes one of the perennial knotty problems of control system preliminary design tradeoff.

For example, consider an application where a relatively standard fluidic industrial control system appears very promising in most respects except that the power consumption is so great that additional shop air facilities would be required. This makes the fluidic system less economically advantageous than a conventional electromechanical system. A logical approach would be to study the fluidic system with an eye towards improving the power consumption, such as going to miniaturized devices or using fewer devices driven to work at higher fan-outs. The former would tend to increase price and increase the probability of system problems from contamination. The latter would inherently decrease reliability by reducing the design margin for the system, increasing the probability of system malfunction especially with marginal power available. Whatever the ramifications of any design changes would be, it is important that they be considered thoroughly.

The most competitive fluidic system for the particular application is the one which should be compared with the alternative means of doing the job. Naturally, the same is true of the nonfluidic candidate systems. It is certainly inconsistent to decide to install a carefully optimized modern fluidic system as a replacement for an obsolescent electronic system if full consideration has not been given to the capabilities of a modern state-of-the-art electronic counterpart.

Further observations on deciding whether and how to use fluidics may be found in chapters 7 and 8.

CHAPTER 5

Economics of Fluidic Systems

Why are economics considered in a Technology Utilization Survey describing NASA contributions to the state of an art? The usefulness of fluidics or any other technology to the private sector of the economy is inseparably tied to its cost effectiveness. Fluidics has been touted for its potential cost savings. Unfortunately, many of the pioneers watched profits evaporate while efforts were made to debug the early systems, but the situation has improved markedly in the last few years.

RECENT CHANGES IN THE COSTS OF FLUIDICS

Three factors have been paramount in lowering the cost to the user of fluidic systems:

1. Advances in the technology, increased experience with real applications, and a far better understanding of why fluidic systems behave as they do, have made design, installation, and startup of fluidic systems, especially simple digital systems, a relatively straight-forward, predictable business. This reduction in engineering cost per installation is still improving. An interesting example was reported in mid-1969 (ref. 237). In a 4-week period, Unadynamics/Phoenix developed a fluidically controlled machine to perform 15 individual, complex, synchronized operations. Because the machine's function was to pin tail cones to the shell body of live illuminating mortar rounds, fluidics proved to be a natural choice.

2. The coming of age of fluidic integrated circuits (IC's) has reduced the price of volume-produced fluidic systems significantly. Unlike the one-of-a-kind example of the mortar shell fin attacher, fluidic systems that are sold in quantity lend themselves to the use of IC's. These may take the form of the Pitney-Bowes FLOWBRICK (fig. 34) which is simply a stack of "flowboards," each containing 26 identical NOR gates employing flow mode (turbulence) control principles. Alternatively, they may take the form of highly specialized circuits such as some of those made experimentally at Langley Research Center (ref. 238). Fluidic integrated circuits are still a long way from achieving the efficiencies of power, size, and weight that have been accomplished with electronics. The economics of integrated fluidic circuits compare very favorably with separately plumbed devices for some applications, but definitely not all (see ch. 7).

3. Finally, the cost of individual fluidic devices (a value which is usually referred to as "cost per gate") has begun to drop significantly. Whereas a few years ago it was difficult to purchase most discrete fluid amplifiers for less than $20 per gate, some of the simpler ones may now be bought for about $1 apiece in large quantities (ref. 160). For example, one manufacturer has sold scores of a $75 introductory fluidics kit that includes 12 NOR gates (the basic transverse impact modulator used widely in their control systems), three display indicators, fixed and variable resistors, and mounting and interconnecting hardware.

In the area of digital fluidic elements, the 1969-1970 time period has seen prices for some fluidic devices reduced to one-half (ref. 160) or even one-third (ref. 6) of earlier prices.

THE INFLUENCE OF MANUFACTURING METHOD ON COST

Table 9 lists some of the many ways in which fluidic devices are made. The NASA-sponsored study of fluidics for spacecraft (ref. 18) included a comprehensive summary of fabrication techniques which it is appropriate to review here.

Basic Elements

Fluidic devices can be made by a wide variety of processes, and from almost any type of rigid material.

TABLE 9.—*Fabrication Methods for Fluidic Devices*

Fabrication Method	Reference
Chemical etching of photosensitive glass	239
Plastic injection molding	239
Soldered brass tubes	239
Brass tubes cast in plastic	239
Monolithic precision cast plastic	238, 247
Photoetched stainless steel, diffusion bonded	240, 241, 242
Chemical etching photosensitive plastic	243
Glass drawing (for subminiature devices)	244
Dry-film adhesive bonding	245
Ultrasonic bonding of injection-molded thermoplastics	246
Epoxy molding	239, 242
Steel welding (large size)	242
Concrete molding (large size)	242
Photoetching, ultrasonic machining, and electron beam machining of ceramics	18
Chemical milling, electrical discharge machining, electroforming, die casting, and powder metallurgy forming of metals	18

Techniques for the fabrication of these devices are well known and not difficult. The most important consideration is that the performance and characteristics of a fluidic device are closely related to its geometric shape; therefore, intricate shapes must be held to precise dimensions. Because of the wide diversity in the sizes, quantities, tolerances, and materials used, there is no single best fabrication technique.

The environmental tolerance required in a fluidic element is a consideration in selecting a fabrication process. More important is the choice of material. Fluidic devices are subjected to both structural and fluid dynamic forces, so that materials must have sufficient strength to withstand these forces without undue distortion. Surface hardness of the material must also be considered, particularly if the working fluid carries abrasive particles. Wear in stream-interaction devices is critical in the nozzles and on the splitter. Other factors, such as operating temperature and compatibility with the working fluid, also enter into the selection.

Injection molding of thermoplastic material appears to offer the cheapest method of fabricating large quantities of fluidic elements. However, these elements are limited to operation at near room temperature conditions and with noncorrosive media. In industrial application, injection molded devices should provide long term reliable operation, particularly in digital systems.

Several fabrication methods are suitable for use in making elements.

Precision Casting

A system of monolithic precision casting has been developed at Langley Research Center for fabricating economical complex multilayer fluidic circuitry. To fabricate a circuit, each layer is first laid out on a design drawing. An actual size negative is made from the drawing. The negative is then used on a photosensitive plastic (a process conventionally used for printing) to provide three-dimensional walls or raised surfaces that have the silhouette of the desired channels. The photosensitive-plastic process is also used to produce another plate having raised pads that match surfaces on the original plate to provide channels or connections from one layer of circuitry to another. The two plates are placed in an aluminum housing strong enough to withstand the pressures of a water soluble wax that is injected between the plates. This wax forms a water-soluble laminae. In a similar manner the other layers of the circuitry are formed in water-soluble wax, each layer having one side laced with the exact channels of the desired circuitry and the other side containing the holes or channels for interconnecting layers. These laminae are stacked together and pinned in another aluminum housing. Insoluble pattern wax is then injected to form a composite. The water-soluble layers may now be washed away in a solution of hydrochloric acid. The pattern wax core is next placed in a mold and an epoxy resin is poured around it. The pattern wax is then washed away in kerosene at high temperature. The desired circuit remains in one piece of epoxy plastic (ref. 247).

Compression Molding

This is perhaps the most economical production method for manufacturing parts from thermosetting materials. Tolerances can be held as close as required for most fluidic elements. Fillers are used to add stiffness, control shrinkage, and reduce the coefficient of thermal expansion. Maximum operating temperature is about 200°C. (400°F.) for the best filled thermosetting plastic elements; filled epoxy elements are limited to about 150°C. (300°F.).

Photoetching Ceramics

This process was originally developed by the Corning Glass Works to prepare substrates for electronic circuits and has been adapted to the manufacture of fluidic elements. A high contrast negative is placed on a thin sheet of Fotoform glass, which is a silicate glass containing a photosensitizing ingredient such as the cesium radical, Ce^{+3}. In the presence of ultraviolet light, the exposed glass absorbs the ultraviolet radiation, creating a contact print in depth. The glass is then heated to about 650°C (1200°F.), so that colloidal particles of crystallized lithium metasilicate are formed in the exposed areas of the glass, which appear as a white opaque image. When the glass sheet is immersed in a hydrofluoric acid bath, the exposed areas dissolve 20 to 30 times faster than the clear unexposed areas of the glass. Further processing converts the Fotoform glass to a higher strength, partially crystalline material called Fotoceram.

The finished Fotoceram elements offer several important advantages that are normally associated with ceramic material, i.e., high dimensional stability, low moisture absorption, good shock resistance, and operating temperatures approaching 550°C (1000°F.). This process can produce intricate two-dimensional elements down to a nozzle width of 0.13 mm (0.005 in.). An important consideration in circuit fabrication is that both the Fotoform and Fotoceram plates can be thermally laminated to form a monolithic structure.

Photoetching Metals

This process has recently become very important in the manufacture of fluidic elements. Initially used for aerospace applications, several manufacturers such as GE, Norgren, and Bendix use it for most of their industrial fluidics as well. Essentially, the process removes metal by the chemical etching of preferentially exposed surfaces. The process is presently limited to metal sheets no thicker than about 5 mm (0.020 in.), because the dimensional tolerances that can be achieved change with increasing metal thickness. A channel 0.13 mm (0.005 in.) wide can be cut through 0.025 mm (0.001 in.) thick stainless steel with a width tolerance of 0.013 mm (0.0005 in.) or about ± 10 percent. This same 0.13 mm channel would have a tolerance of ± 40 percent if cut through 0.13 mm (0.005 in.) thickness of the same material.

In the fabrication of two-dimensional (thin) fluidic elements, several laminations of etched sheets are required to provide the required aspect ratio (channel height to channel width ratio). Photoetching can be used with the following metals, in order of increasing difficulty: copper, nickel, carbon steel, stainless steel, aluminum, titanium, and molybdenum. Operating temperature depends primarily on the metal used and/or the method used to seal the laminated devices.

A major investigation into the technology of fabricating metal fluidic devices was performed recently for the Air Force Materials Laboratory (AFML) at Wright-Patterson AFB by GE. At this writing, the final report for this effort (AFML Contract F33615-68-C-1700, "Fabrication of Integrated Fluidic Control Systems") is not available for inclusion in the references of this survey. Earlier related AFML and GE studies are noted here (refs. 240, 241).

Other Methods

Many new methods are being considered for the fabrication of fluidic elements. Techniques such as electron and laser beam machining may eventually make it possible to pack 1000 fluidic elements into one cubic inch (16 cc). Coining techniques may soon make it possible to manufacture interconnected fluidic elements by indexing a die and stamping in the right location. However, much work still needs to be done in the sealing of fluidic elements, particularly those for use with high temperature working fluids. To date, diffusion bonding and furnace brazing have been used with success in the sealing of photoetched metal elements. Sealing remains the most closely guarded proprietary art of those manufacturers who have mastered it.

One way of overcoming the sealing problem is a ceramic molding process, in which a polystyrene mold is made from a metal master. Ceramic is then molded around the polystyrene and fired at about 1100°C. (2000°F.). The polystyrene is vaporized, leaving a one-piece ceramic device. Although the process is complex, it eliminates the basic problem of sealing a two-dimensional element with a cover plate.

Integrated Circuits

The interconnection of fluidic elements with fittings and tubing is not suitable for all applications.

Consequently, one trend is to group circuit elements on a functional basis in rectangular or circular two-dimensional planar arrays or modules. This allows the incorporation of the maximum number of interconnections in the module. Power supplies, vent connections, and interconnections between modules can be made by interspersing manifolds between the modules. The number of circuit modules that can be stacked is limited, since supply and exhaust ports as well as the circuit interconnections must all be canted through the stacked circuit blocks.

Another method is to bring all the connections out to the edge of the module. Modules can then be stacked on edge between manifolds that provide the fluid power supplies and circuit interconnections. This makes for a convenient arrangement in that a sensor, interfaces, and compensating volumes can be located close to the circuit modules.

For small fluidic circuits, it may be more convenient to fabricate the manifold and interconnections in a single block. Then, the fluidic elements, sensors, and interfaces are attached externally to the manifold block. This method is more convenient for prototype applications and allows the modification or replacement of circuit elements, if required.

This last item can be a key to the economic employment of integrated circuits. Integrated circuits can lose their economic appeal if it becomes necessary to throw away an expensive circuit only because a minor change in the characteristic of one gate is required or if a portion becomes contaminated. Bowles Fluidics Corporation's experience has shown that industrial customers are unwilling to throw away integrated circuits costing \$100 or \$200 (ref. 159). Reference 159 suggests that the most economical maintenance procedure is to use \$10 to \$25 integrated circuit modules that can either be replaced or removed for cleaning.

INFLUENCE OF ENGINEERING EXPENSE

The difficulties of obtaining satisfactory results with early commercial fluidics installations often resulted in excessive engineering costs. This was usually due to the need to develop and debug the system on the site. Fortunately, the amount of engineering effort required for any given application appears to be going down drastically as the technology matures. The important thing to determine in estimating the cost of using fluidics in any given application is whether the application is within, or just beyond, the state-of-the-art for manufacturers.

LONG-RANGE COST–THE SYSTEMS APPROACH

The cost of a potential fluidic system should be compared with the cost of alternatives over the entire anticipated life of the system. Whether the purchase price is higher or lower is only a small part of the analysis. Assuming that a review of the criteria discussed in chapter 4 has indicated that fluidics appears to be the way to go, a cost analysis should consider:

1. Installation cost–Engineering, hardware, installation, including facilities such as a larger shop air system, safety equipment.
2. Maintenance cost–Who takes care of it–plumbers or electricians?
3. Operating cost–Operator skill level, training, power (even bleed air on a turbojet is not really free), anticipated downtime
4. Useful life–How long will it last?

CHAPTER 6

Components of Fluidic Systems

The components of any given fluidic system may be classified and identified by their functions and by their design characteristics. The scope of this survey does not permit analysis of the complete array of devices and auxiliary components from which the fluidic systems designer may choose today. An up-to-the-minute listing would be obsolete within weeks of publication, so rapidly is the field growing. Fortunately, a relatively recent (July 1970) NASA compilation of advanced valve technology concepts (ref. 18) provides an excellent introduction into components of fluidic systems. This compilation summarizes the results of a series of programs performed by TRW Systems for NASA Jet Propulsion Laboratory under the sponsorship of the NASA Office of Advanced Research and Technology and the following descriptions of fluidic devices have been excerpted in large part from it. Reference 18 also contains performance data and design details which are not included here.

FLUIDIC DEVICES–FLUID AMPLIFIER NAMES

The term fluidic device is most commonly applied to amplifiers such as those described below and defined in the glossary. Confusion often arises in the minds of those not familiar with the technology about whether a particular device is to be called an amplifier, a sensor, or an interface device. Some common devices, such as a wall attachment bistable flip-flop, could serve as any one, depending upon the application. For this reason it is common practice to identify devices by their characteristics when considering them out of context, and by both characteristic and application when related to a system application.

For example, a vortex amplifier is called just that when treated by itself or when its purpose in the system is strictly one of signal amplification. If the application differs, however, it may become a vortex rate sensor or a vortex pressure regulator.

BASIC DEVICE PHENOMENA

Most fluidic devices have at least four basic functional parts: a supply port, an output port, one or more control ports, and an interaction region (fig. 40). These parts have been compared respectively to the cathode, plate, control grid, and interelectrode region in a vacuum tube. The supply jet (fluid stream) in the fluidic device is introduced into the interaction region and directed toward the output port or receiver. The degree of pressure and flow recovery in the receiver is influenced by the details of the device configuration. Control flow is directed into the interaction region to modify the direction and distribution of the supply flow so that a change in output results at the receiver. Useful amplification occurs, because the change in output energy is usually achieved with a much smaller change in control energy.

Fluid interaction phenomena as presently used in fluidic devices can be divided into the three basic categories listed in chapter 1–jet interaction, surface interaction, and vortex flow–and depicted in figures 1, 2 and 3.

Jet Interaction

In jet interaction devices, control action is achieved through the direct impingement of control flow on the free source (supply) jet. The interaction mechanisms included in this category are beam deflection, impact modulation, and controlled turbulence.

Beam deflection is achieved by installing one or more control ports perpendicular to the supply jet (fig. 1a). The vector direction of flow from the

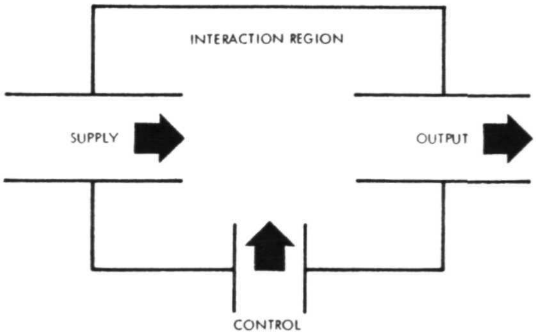


FIGURE 40.–Basic fluidic device (ref. 18).

supply jet is then varied by flow from the control jet. The angular deflection or modulation angle of the supply is essentially a linear function of the control momentum for the small modulation angles normally used in practical fluidic devices. Therefore, for a properly designed receiver, the beam deflection effect can be used to develop a linear proportional amplifier.

Two axially opposed supply jets are used to achieve the impact modulation effect. When the momenta of the two supply jets are equal, a planar impact region is established midway between the two supply jets (fig. 1b). The shape and location of the impact region can be varied by modifying the momentum of one of the supply jets. This is accomplished by introducing a control flow directly into or transversely across one of the supply jets. This will either increase or decrease the momentum of the jet such that the impact region is displaced axially. When an appropriate receiver is located near the impact region, the transverse radial flow from the impact region into the receiver can then be modulated by the control action.

When a laminar supply jet flow is ejected from a nozzle into a disturbance-free medium, the jet flow will remain laminar for a considerable distance downstream from the nozzle and then abruptly become turbulent (fig. 1c). Controlled turbulence is achieved by introducing a control flow near the exit of the supply jet. This flow disturbs the supply jet causing the point of turbulent breakdown to move axially upstream toward the supply jet nozzle. A receiver or output located between the uncontrolled turbulence point and the controlled turbulence point will sense a significant change in energy level, because the energy recoverable from the supply jet is much greater in the laminar region than in the turbulent region. Because the flow mode changes from laminar to turbulent, this type of control is often referred to as flow mode control.

Surface Interaction

Many fluidic devices depend upon the influence that a nearby or adjacent surface has on the supply flow to perform their function. The most important effects are: (1) the attachment of a stream to a surface and (2) separation of flow from a curved surface. In each case, the control function is provided by a control flow although the surface supports and is essential to the device operation.

The mechanism of wall attachment is a fluid dynamic phenomenon called the Coanda effect. To understand this effect, consider a supply jet emerging into the area bounded on one side by a wall perpendicular to the jet and on the other side by another wall angled approximately 30° from the supply jet centerline (fig. 2a). The emerging jet entrains ambient fluid because of high shear at the edge of the jet. On the angled wall side of the jet, the entrained fluid is not easily replaced by ambient fluid so that a transverse static pressure gradient is formed across the jet that bends the jet and forces it to attach to the angled wall. Upon attachment, a low-pressure vortex region (or bubble) is formed between the jet and the point of attachment which is returned to the mainstream by entrainment near the supply nozzle. The attached jet may be detached from the angled wall by injecting control flow into the low-pressure separation bubble so as to reverse the transverse pressure gradient. The stability of the wall attachment plus the ability to attach and shift the jet makes this an extremely useful effect in digital fluidic devices.

The separation effect (fig. 2b) is based on the tendency of a fluid stream to follow an adjacent gradually curved surface as long as the pressure gradient is larger than the momentum vector. When the radius of curvature of the surface is sharply reduced, momentum will predominate at some point downstream and the flow will separate from the surface. The point of separation can be influenced by injecting control flow upstream of the normal separation point. This reduces the pressure gradient across the jet and thus changes the angle at which the flow leaves the curved surface. Several fluidic devices use this effect to modulate the source flow in one or more receivers located downstream of the controlled separation region.

Vortex Flow

To understand this effect, consider a supply flow introduced radially at the centerline of a shallow cylindrical chamber (fig. 3). The supply flow enters the vortex chamber and proceeds radially inward with minimal resistance and flows out through the centrally located outlet orifice. The supply port is generally much larger than the outlet orifice so that the outlet flow rate is determined by the area of the exit orifice and system pressures. As control flow is injected tangentially into the chamber, the supply and control flows combine and the resultant flow develops a degree of swirl, dependent on the relative magnitudes of the supply control flow momenta. A forced vortex field is developed within the chamber that varies the pressure gradient across the chamber such that the magnitude as well as the pattern of the supply flow is altered. Since the vortex field is essentially a variable resistance, it can substantially reduce or throttle flow and thus provides a unique control function in fluidic devices. In sensor applications no control flow is applied, but inertia of the supply flow combines with rotation about the exit orifice centerline to induce a vortex field.

WALL ATTACHMENT AMPLIFIER

The configuration of a basic two-dimensional wall attachment amplifier is shown in figure 41. This device has two walls set back from the supply nozzle, control ports, and channels that define two downstream outputs. Because of the Coanda effect, the device is bistable, i.e., a turbulent free jet emerging from the supply port can be made to attach stably to either wall downstream of the control port. The switching mechanism in the bistable wall attachment device is illustrated in figure 42. Presuming the supply jet is initially attached to the lower wall, fluid is injected through the lower control port into the vortex bubble. When the rate of injected fluid exceeds the rate at which fluid is removed by entrainment, the pressure on the lower edge of the jet will increase. As this pressure becomes greater than the pressure of the upper edge of the jet, the pressure differential is reversed and the jet will detach, cross over to, and attach to the upper wall and remain attached even after the lower control flow is removed.

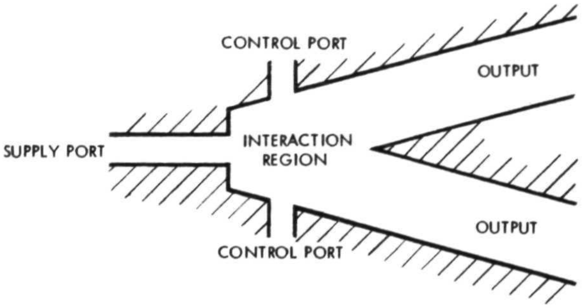


FIGURE 41.–Basic wall attachment device (ref. 18).

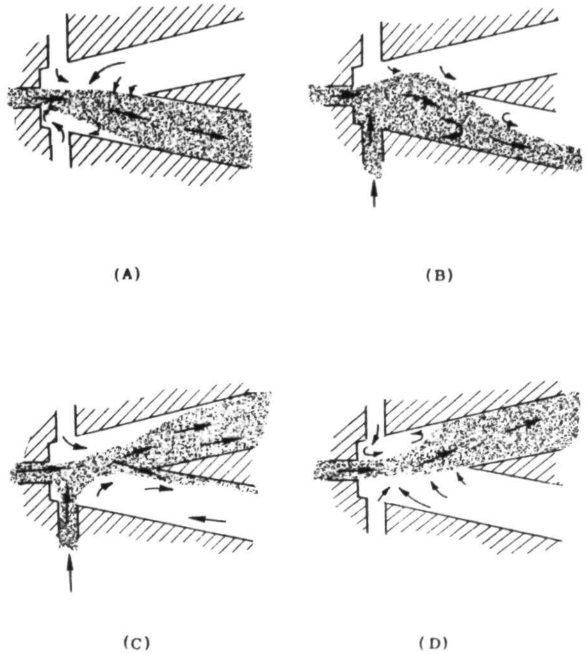
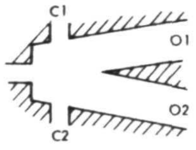


FIGURE 42.–Switching mechanism in bistable wall attachment device (ref. 18).

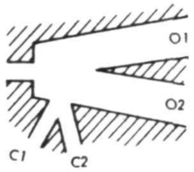
A few examples of the many logic elements that employ wall attachment are shown in figure 43. Some of these devices use a combination of wall attachment and beam deflection (discussed next) to perform logic functions. The digital states of each device can be followed by referring to the accompanying truth table. Operation of the flip-flop or bistable wall attachment device was explained in the preceding sections. In the OR/NOR gate the interaction region is physically biased so that the supply flow will stably attach only to the adjacent wall leading to output 2. When control flow is introduced at either or both of

(a) FLIP-FLOP



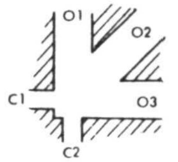
C1	C2	O1	O2
1	0	0	1
0	0	0	1
0	1	1	0
0	0	1	0

(b) OR-NOR GATE



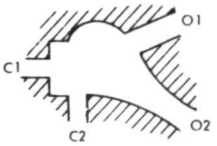
C1	C2	O1	O2
0	0	0	1
1	0	1	0
0	0	0	1
0	1	1	0
0	0	0	1
1	1	1	0

(c) AND GATE (PASSIVE)



C1	C2	O1	O2	O3
1	0	0	0	1
0	1	1	0	0
0	0	0	0	0
1	1	0	1	0

(d) HALF-ADDER (PASSIVE)



C1	C2	O1	O2
0	0	0	0
1	0	0	1
0	1	0	1
1	1	1	0

FIGURE 43.–Wall attachment logic elements (ref. 18).

the control ports, the power stream is shifted to output 1 by beam deflection, and when the controls are removed, the power stream returns to output 2.

The AND gate and half-adder shown in figure 43 are passive elements, i.e., devices that operate on the signal power alone. In the AND gate, control 1 will appear at output 3 only if control 2 is not present, and control 2 will appear at output 1 only if control 1 is not present. These stable output states are achieved by wall attachment in the respective output ducts. When controls 1 and 2 appear simultaneously (presuming equal control pressures) they combine by beam deflection to produce a signal at output 2. Operation of the half-adder differs from the AND gate in that both controls appear at output 2, control 1 by wall attachment and control 2 by deflection in the opposite cusp. When applied simultaneously, the two controls combine to produce a signal at output 1.

BEAM DEFLECTION AMPLIFIER

In the beam deflection amplifier (fig. 44), the supply jet emerges into and flows across the interaction region and is divided downstream at the splitter. When there is no control flow or when the pressures and flows from each of the two control ports are equal, the supply jet remains axially centered and equal flows issue from each output port. Control flow is directed into the interaction region from nozzles on each side of the supply jet which are approximately perpendicular to its centerline. If one control force is made stronger than the other, the supply jet is deflected away from the centerline in the direction of the weaker force and a greater portion of the jet enters the output receiver on that side. In a properly designed amplifier, the change in output power is greater than the change in the input control power.

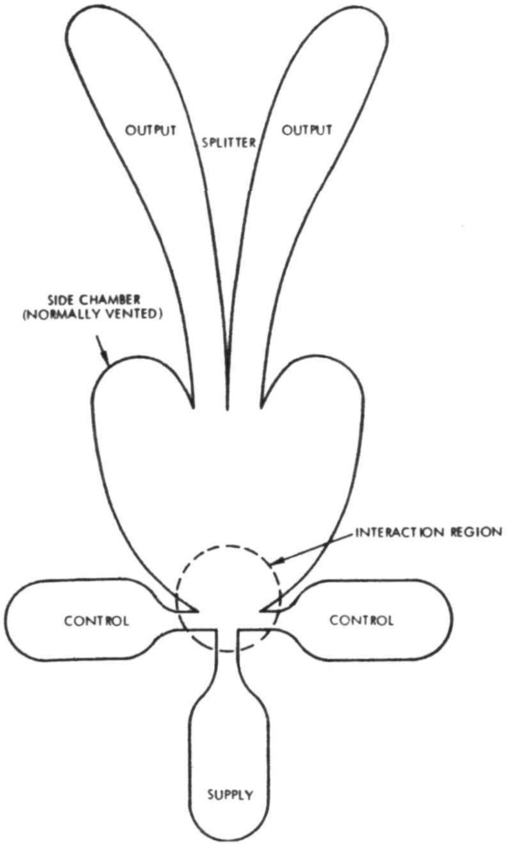


FIGURE 44.–Beam deflection amplifier configuration (ref. 18).

The deflecting force provided by the control streams may be either a pressure or momentum force; both forces are present to some degree in all beam deflection amplifiers. Momentum forces will normally predominate when the controls are set back several supply nozzle widths from the supply jet, and pressure forces will predominate when the control nozzle is close to the edge of the supply stream. For proportional operation the static pressure across the supply jet downstream of the interaction region must be zero. To accomplish this, beam deflection devices are specifically designed to prevent wall attachment and the cutouts or side chambers on both sides of the power jet are vented to atmosphere or, in some cases, to a constant pressure reservoir. The vents also provide overflow ports for the excess fluid in the supply stream and for backflow due to output port loading. Many beam deflection amplifiers also incorporate a vent (or centerdump) between the two output ports (fig. 45). Although a considerable portion of the supply jet power is lost in this centerdump, it provides several advantages including increased stability with blocked loads and repeatable zero balance conditions (differential output pressure equal to zero) over a wide range of power jet pressure, which is a necessity in high-gain staged units.

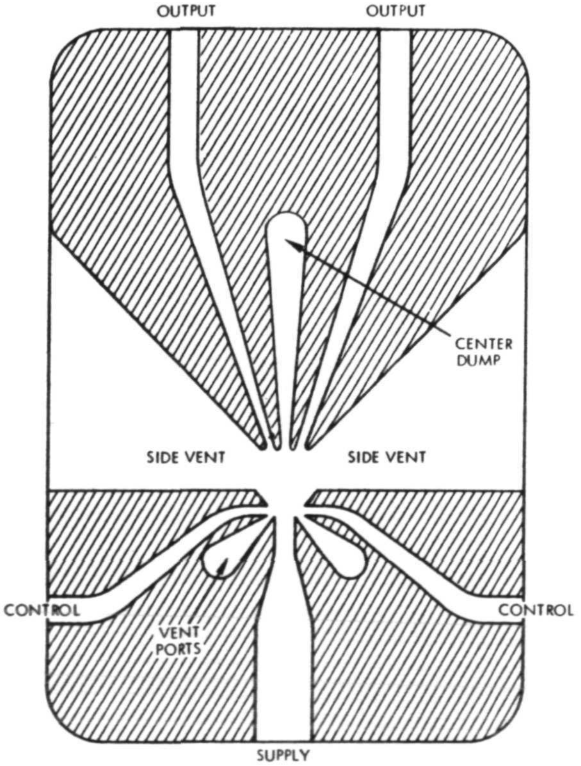


FIGURE 45.–Center dump proportional amplifier (ref. 18).

VORTEX DEVICES

The operation of vortex devices relies upon the amplification mechanism derived by the conservation of angular momentum in a vortex field. This amplification takes place in a shallow two-dimensional vortex chamber as shown in figure 46. Swirl may be imparted to a radial supply flow by a tangential control jet which is introduced at the periphery of the vortex chamber. The degree of swirl and the specific method used to generate it depend on the particular device used. As the combined flow proceeds toward the center of the vortex chamber, the tangential velocity of the fluid molecule (fig. 46) must increase, since the angular momentum must be conserved. The velocity increase is then inversely proportional to the radial location of the fluid molecule so that if the ratio of the outer-to-inner radius is very large, the corresponding increase in the tangential velocity will also be great. In practical vortex devices operating on real viscous fluids, the maximum amplification in the flow field is limited by nonlinearities or flow distortions, such as those caused by the degradation of the tangential velocity in the boundary layer at the end walls of the vortex chamber.

Vortex Diode

A typical vortex diode (fig. 47) has a circular chamber with a tangential inlet and an axial sink at the center of the chamber. Flow through the tangential inlet produces a high pressure loss because of the swirling flow in the vortex chamber. In the reverse direction, flow enters through the axial sink and

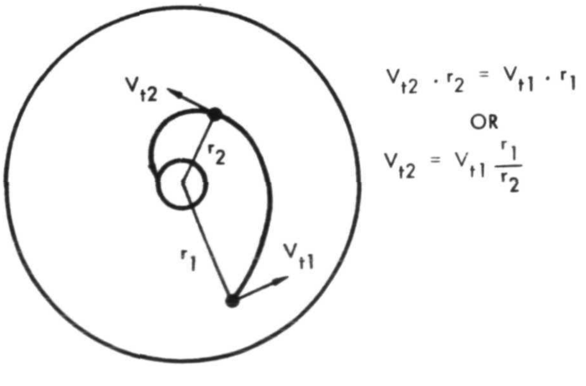


FIGURE 46.–Two-dimensional vortex chamber (ref. 18).

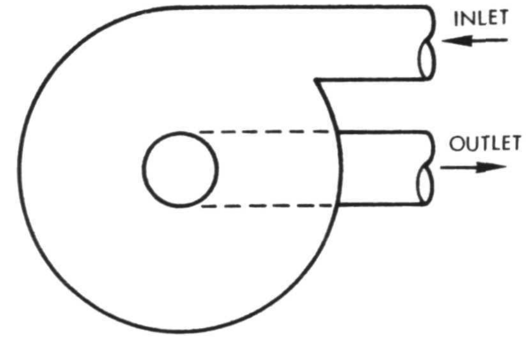


FIGURE 47.–Vortex diode (ref. 18).

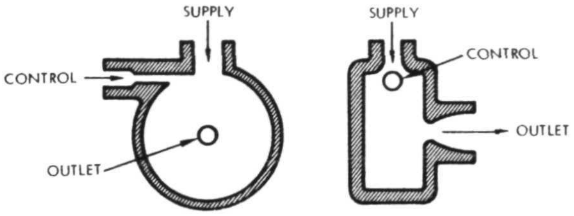


FIGURE 48.–Basic nonvented vortex amplifier (ref. 18).

passes through the vortex chamber without swirl so that the pressure loss is much lower.

Nonvented Vortex Amplifier

The nonvented vortex amplifier in its simplest form is shown in figure 48. It is similar in construction to the vortex diode except that a third opening has been added for a supply stream, while the original supply port becomes the control port. This configuration is easily constructed in two-dimensional form and, although performance is not optimized, it is adequate for many applications.

The performance of the basic nonvented vortex amplifier with a single supply and single control inlet is not optimum because of the asymmetry of the device. For optimum performance, the supply flow can be introduced into the vortex chamber around the circumference of a button-shaped unit as shown in figure 49. Control flow is introduced at several points to ensure axisymmetric mixing of the supply and control flows. The control ports must be within the supply flow annulus to prevent the control momentum from being dissipated by a free expansion into the vortex chamber before mixing occurs. This construction is considered rather complex, and, consequently, is normally made in a three-dimensional configuration.

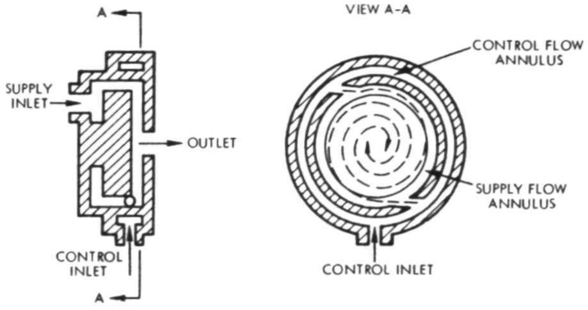


FIGURE 49.–Nonvented vortex amplifier button configuration (ref. 18).

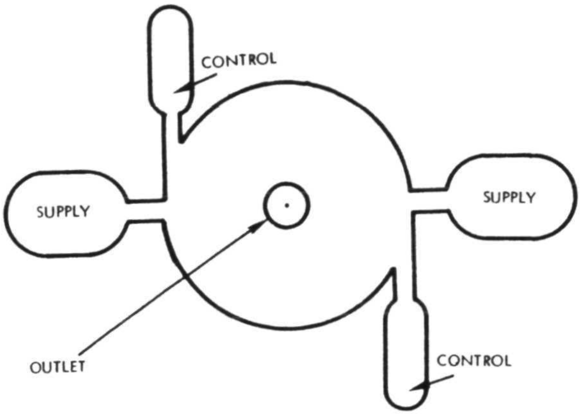


FIGURE 50.–Dual nonvented vortex amplifier configuration (ref. 18).

A practical compromise is a dual inlet, dual control configuration as shown in figure 50. The two controls and two supplies are connected externally or manifolded together in a cover plate. This device can be easily made in a two-dimensional configuration and its performance is almost as good as the button arrangement. A further increase in performance is obtained in the dual exit nonvented vortex amplifier. Dual exits provide an increase in performance of about 70 percent over a single exit vortex amplifier; that is, the maximum flow capacity of the amplifier is increased 70 percent with identical control flows.

Vented Vortex Amplifier

The vented vortex amplifier uses a receiver tube located and displaced axially away from the vortex

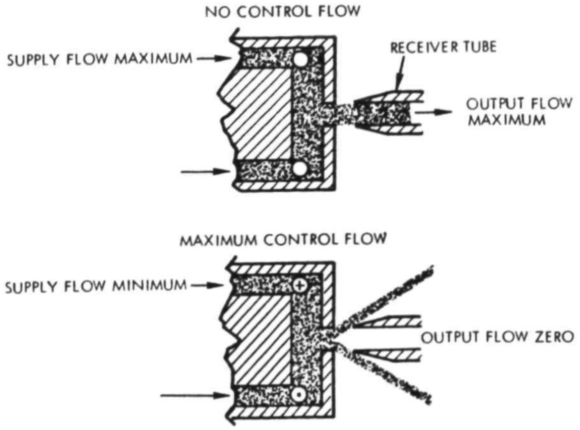


FIGURE 51.–Vented vortex amplifier (ref. 18).

chamber outlet orifice as shown in figure 51. With no control flow to the amplifier, the output flow exists from the vortex chamber in the form of a well-defined axial jet. Maximum flow is thus recovered in the receiver tube and the recovery characteristic is similar to that achieved in the receiver of a jet pipe valve. When control flow is applied, a vortex field is generated within the amplifier and the output flow begins to form into a hollow conical shape such that some of the flow is diverted to the exhaust. With maximum control flow a sufficiently strong vortex is generated so that all the existing flow fans out to miss the receiver tube, and the output flow may be modulated fully down to zero.

The vented vortex amplifier is also used as a pressure amplifier as shown in figure 52.

LOGICAL NOR AMPLIFIERS

The NOR amplifier is often found in relatively low-power digital circuits, particularly in industrial applications. In simple terms, the NOR gate provides an output signal when no control signals are present. Since the NOR function is the most basic and universal logic concept, it can be used or interconnected to provide all other logic functions such as AND, OR, NAND, NOT, exclusive OR, and flip-flop. The use of these logic functions is described in appendix A.

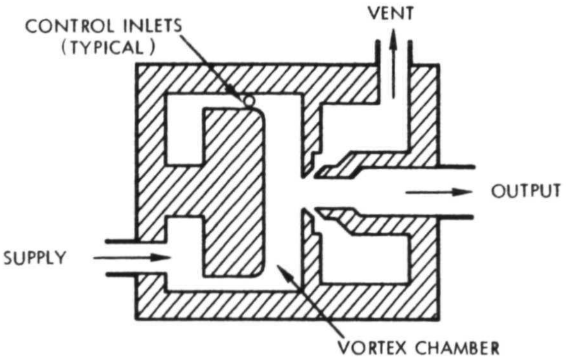


FIGURE 52.–Vortex pressure amplifier configuration (ref. 18).

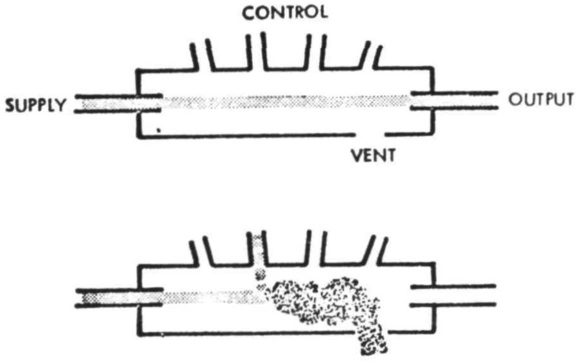


FIGURE 53.–Turbulence (flow mode) amplifier configuration and operation (ref. 18).

Turbulence Amplifier

The turbulence amplifier consists of a supply tube and an output tube precisely aligned in a vented cavity and one or more control input tubes perpendicular to the power jet axis. The supply is introduced into the vented cavity as a laminar stream which is recovered in the output at a relatively high pressure. When one or more control flows are introduced as shown in figure 53, the jet becomes turbulent before reaching the receiver and the output pressure drops sharply. Although turbulence amplifier is the term widely used to describe this type of device, some prefer to call it a flow mode amplifier. This is logical because the operating principle is based on flow change from the laminar to the turbulent mode. The high-gain characteristic exhibited by the turbulence amplifier in the transition region is very useful for digital applications. However, the device is not practical for use as a proportional amplifier because in the transition region the output signal-to-noise ratio is very low and the output pressure is quite sensitive to small changes in the supply pressure.

Flow Interaction NOR Amplifier

The flow interaction NOR amplifier (fig. 54) operates somewhat like the turbulence amplifier. Laminar flow is developed in the long supply nozzle and the power jet remains laminar as it flows through the interaction cavity and reaches the output receiver. The power jet flows adjacent to the top plate as it moves through the interaction cavity and the presence of the top wall reduces the effects of ambient noise. Control flow deflects the power jet to the side and away from the top plate to reduce the output pressure. A portion of the deflected supply jet also tends to recirculate in the interaction cavity and acts as a positive feedback which further disrupts the jet and decreases the output even further.

Two-Dimensional Laminar NOR Amplifier

The operation of the laminar NOR amplifier (fig. 55) depends on the deflection of a laminar supply jet rather than the laminar turbulence transition which is characteristic of the turbulence amplifier. In this device, the adjacent side wall and the top and bottom walls are a strong stabilizing influence on the supply jet as it flows to the output port. When a control signal is applied, the supply flow is deflected into the vent port. The additional vent holes in the straight wall immediately upstream of the output port are required to decrease the static pressure buildup along the wall when the output port is blocked. The vents provide improved blocked-output performance as well as a significant increase in the blocked-output pressure recovery.

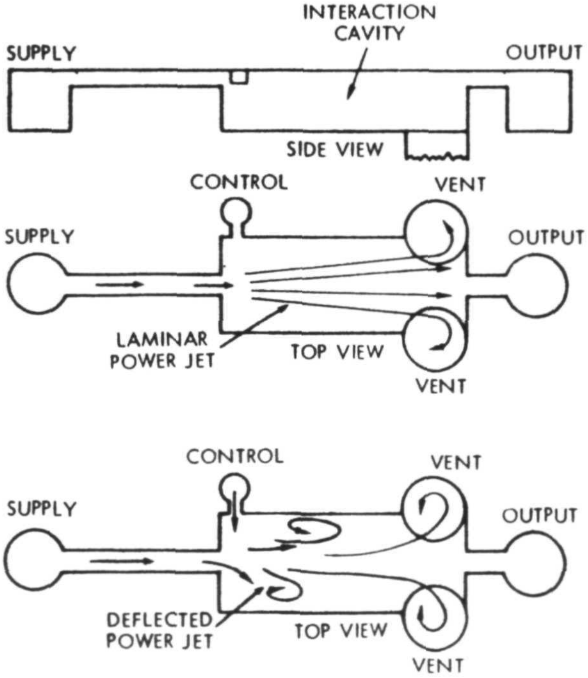


FIGURE 54.–Flow interaction NOR gate (ref. 18).

Impact Modulator NOR Amplifier

In the impact modulator NOR gate (fig. 56), two submerged jets emerge from opposed supply nozzles along the same axis so that they impact and form a radial jet. The axial location of this radial jet depends upon the momentum of each of the two impinging jets. A concentric orifice is placed between the two supply nozzles such that the radial jet is enclosed in an output chamber and separated from a vented chamber. Transverse control jets are applied to the supply jet in the vented chamber; this reduces the axial momentum of this jet so that the radial jet moves into the vented chamber and the output pressure is drastically reduced.

This NOR gate is particularly well suited to logic

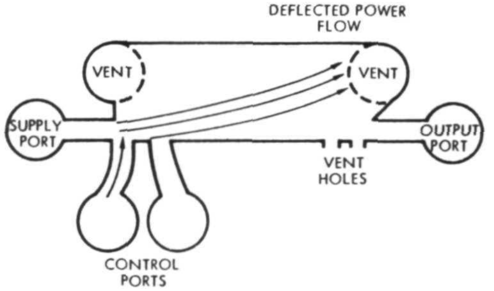


FIGURE 55.–Laminar NOR gate (ref. 18).

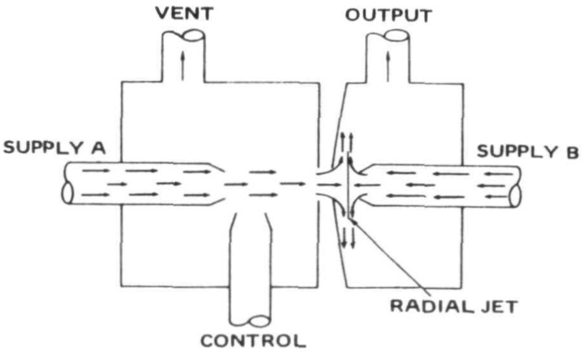


FIGURE 56.–Impact modulator NOR gate (ref. 18).

applications because of its high input and output impedances and a high pressure gain. There is also complete isolation between individual control inputs as the control signals are applied in a completely vented chamber. Changes in output conditions do not affect input pressure and flow because of the concentric orifice separating the output and the vented chambers.

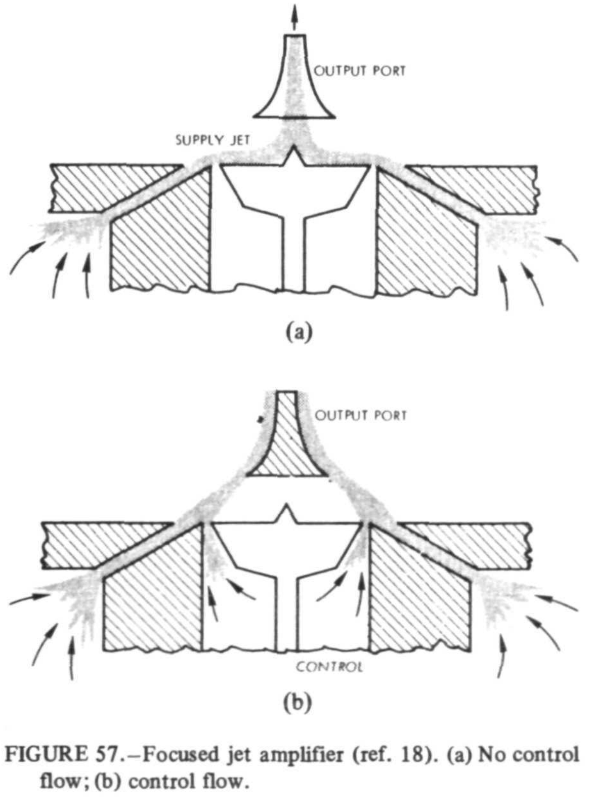
Focused Jet Amplifier

The focused jet amplifier (fig. 57) uses an inwardly directed annular jet that adheres to the upper surface of a flow separator by wall attachment to form a focused jet that is collected at the output tube. The application of an annular control signal prevents attachment of the power jet to the flow separator and the flow is directed away from the output tube so that the output flow is greatly reduced.

SPECIAL DEVICES

Boundary Layer Amplifier

The boundary layer amplifier (fig. 58) relies upon the forced separation of a stream flowing over a curved surface for its operation. With no control flow, the supply flow adheres to the adjacent curved surface until well downstream of the control duct so that the supply flow misses the output and is vented. As control flow is applied into the boundary layer of the curved surface, the point of separation moves upstream so that the supply flow is directed into the output duct.



(a)

(b)

FIGURE 57.–Focused jet amplifier (ref. 18). (a) No control flow; (b) control flow.

A typical boundary layer amplifier in a two-dimensional configuration is shown in figure 59. Bias flow is used in this device to force the power jet to unlock and return to the off position when the control flow is removed. The number and location of the control slots have a significant effect on the characteristics of the amplifier and the island functions to eliminate output hysteresis effects.

Double-Leg Elbow Amplifier

The elbow amplifier (fig. 60) is essentially a more complex version of the boundary layer amplifier. The primary differences are that it has a passive input

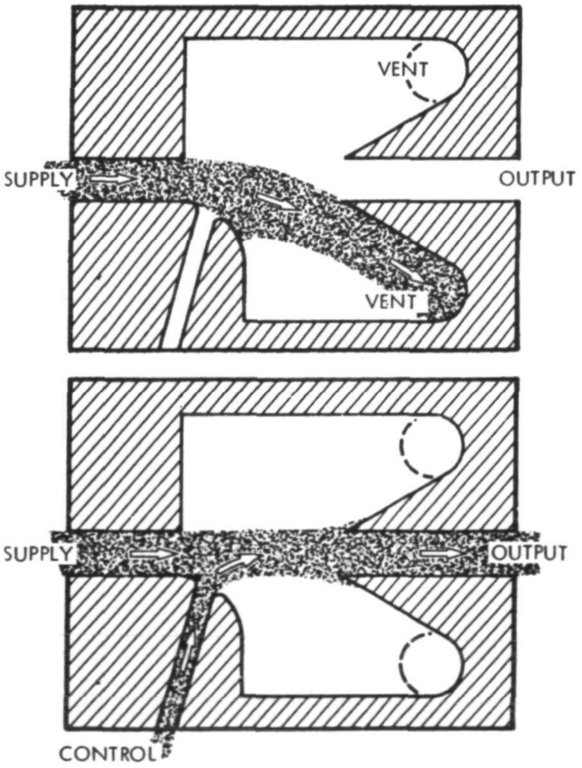


FIGURE 58.–Boundary layer amplifier operation (ref. 18).

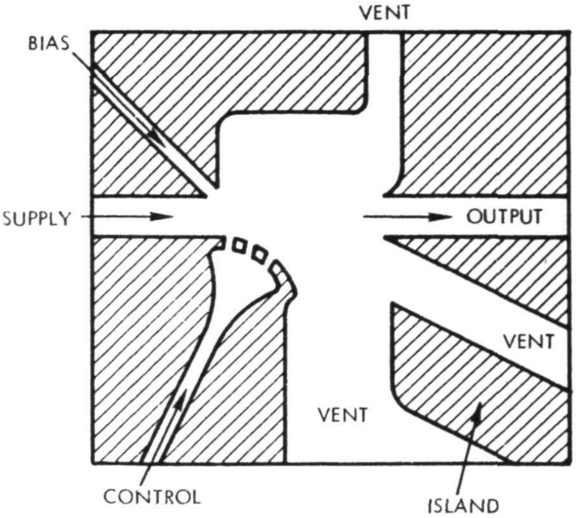


FIGURE 59.–Boundary layer amplifier configuration with bias flow (ref. 18).

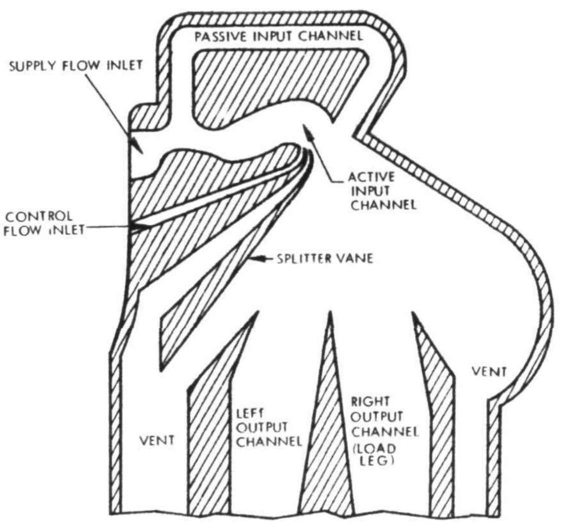


FIGURE 60.–Double-leg elbow amplifier (ref. 18).

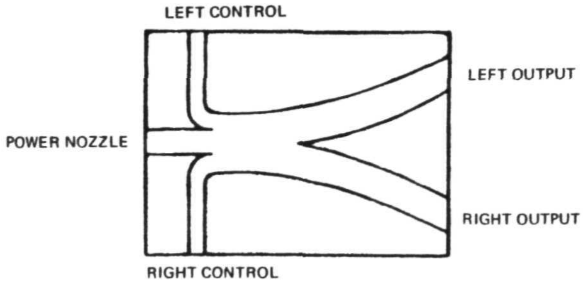


FIGURE 61.–Induction amplifier (ref. 18).

channel and two output ducts. Without control flow the momentum flux in the active input channel is low near the outlet of the passive inlet channel so that the combined flow is directed into the left output channel. As control flow is applied, the point at which flow in the active leg separates from the channel wall moves upstream as in the boundary layer amplifier. As this occurs, the momentum distribution across the flow changes such that the combined flow moves toward the right output channel. The control action is proportional since the portion of the power stream that flows into either of the output ports depends upon the momentum distribution of the combined active and passive flows.

Induction Amplifier

The induction amplifier (fig. 61) is essentially a back-to-back arrangement of two airfoils. As the power jet is turned on, the flow will adhere (by asymmetry or through the use of a bias pressure) to one of the airfoil-shaped boundaries downstream of the power nozzle. Presuming that the flow is originally flowing to the left output duct, a control signal must be applied to the right control duct to switch the flow. The control stream from the right control duct adheres to the outside wall of the right output duct. This flow functions to reverse the transverse pressure gradient across the power jet and thus cause the power jet flow to switch to the right output duct.

Except for the switching principle, the characteristics of this device are similar to those of the wall attachment amplifier.

Edgetone Amplifier

The edgetone amplifier (fig. 62) is a high-speed flip-flop that uses a fluid dynamic phenomenon called the edgetone effect. Consider a fluid jet impinging on the tip of a wedge such as the tip of the splitter shown in figure 62. With the proper amplifier configuration, the supply jet will continuously oscillate back and forth across the wedge tip alternately shedding vortices on each side. An output occurs in the edgetone amplifier when the power jet stably oscillates between the tip of the wedge-shaped splitter and the cusp at the entrance to the output duct in use. The control jets are used to switch the power

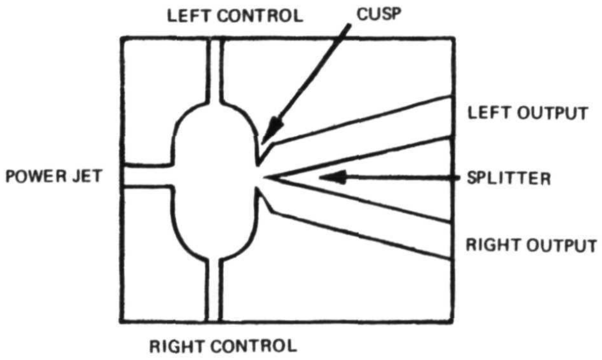


FIGURE 62.–Edgetone amplifier (ref. 18).

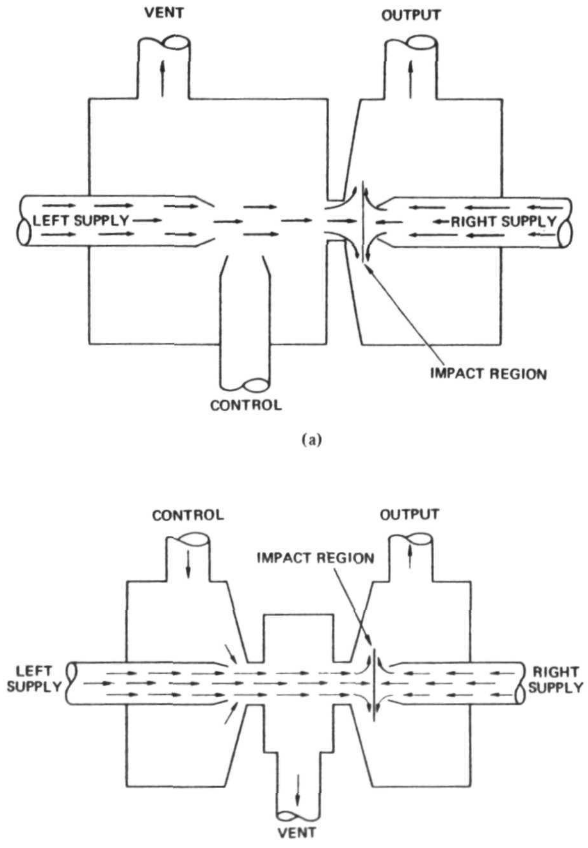


FIGURE 63.–Transverse and direct impact modulators (ref. 18). (a) Transverse impact modulator; (b) direct impact modulator.

stream to the opposite output duct where stable oscillation is again established.

The primary functional differences between the edgetone amplifier and a typical wall attachment amplifier are the faster switching time (0.1 millisecond or less) and the lower control pressures required for the edgetone amplifier.

Impact Modulators

Impact modulation is a jet interaction phenomenon that is achieved by the use of two axially opposed power jets that provide a planar impact region. There are two versions of this device, the transverse impact modulator and the direct impact modulator (fig, 63).

In the transverse impact modulator (fig. 63a), maximum output is obtained when the planar impact region is closest to the output duct. When a transverse control signal is applied, the momentum of the left supply jet is decreased and the impact region moves to the left. The device functions as a proportional amplifier with negative gain since the output flow and pressure decrease as the control pressure and flow are increased.

In the direct impact modulator (fig. 63b), the supply flows and pressures are adjusted so that the planar impact region is closer to the left supply jet. As the concentric control signal is applied, the momentum of the left supply jet is increased and the impact region moves to the right. This results in increased output flow and pressure as the control flow and pressure are increased so that the device is a proportional amplifier with positive gain.

OSCILLATORS

Fluidic oscillators require feedback for operation just like their electronic counterparts. Several types have been employed in timer circuits, temperature sensors, pressure references, and analog-to-digital converters.

Wall Attachment Oscillators

An external feedback oscillator which features a wall attachment flip-flop and two output feedback loops is shown in figure 64. When the supply flow is initially turned on, the power jet will attach to either the left or right wall and flow out the respective output duct as in a normal flip-flop. Presuming the power jet is initially attached to the right wall, part of the power stream is returned to the right control by the external feedback loop so that the power jet is switched to the left wall when the right control pressure reaches the correct switching pressure. This

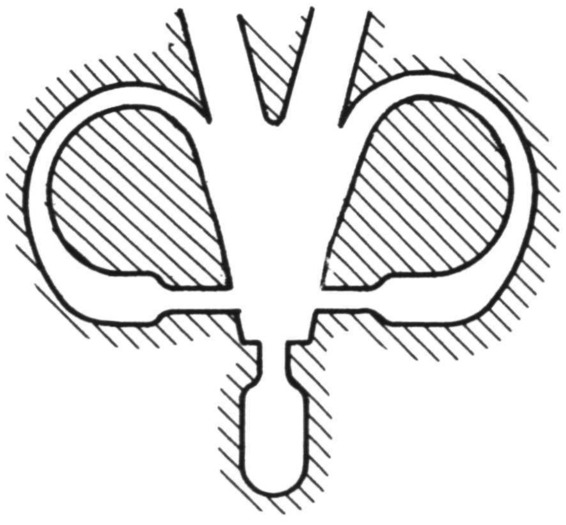


FIGURE 64.–External feedback oscillator (ref. 18).

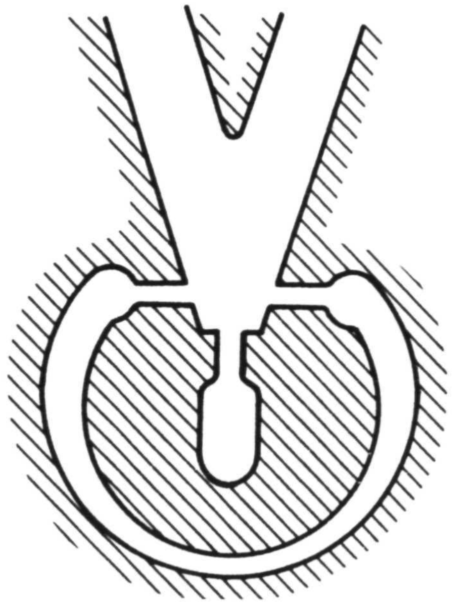


FIGURE 65.–Coupled control oscillator (ref. 18).

process is repeated so that the power jet oscillates at a frequency that depends on the sum of the transit time of the fluidic signal through the feedback path, and the power jet switching time.

The coupled control oscillator also uses a fluidic flip-flop and a feedback loop joining the two control ports (fig. 65). Assuming that the power jet is about to attach to the right wall, a rarefaction wave due to the suddenly increased entrainment at the right control port travels around the control passage and is reflected at the left control port. This reflected wave, a compression, then travels back to the right control port causing the jet to switch to the left wall and the process is repeated.

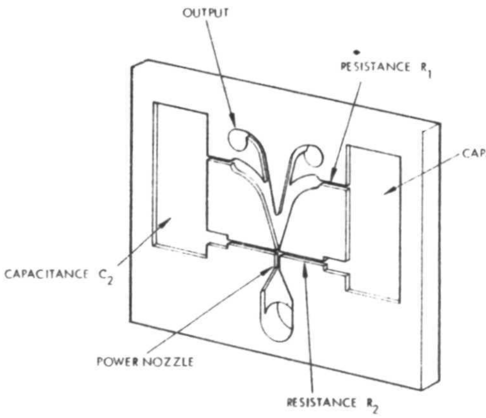


FIGURE 66.–Relaxation oscillator (ref. 18).

Relaxation Oscillator

This oscillator is essentially an external feedback oscillator with a lumped resistance-capacitance-resistance (R-C-R) network in each of the output feedback loops (fig. 66). The R-C-R network makes the relaxation oscillator relatively insensitive to temperature and pressure. However, careful design is necessary if pressure and temperature insensitivity are required together.

Pressure-Controlled Oscillator

This oscillator is another special form of the external feedback oscillator (fig. 64), which varies in output frequency as an approximately linear function of the supply pressure. This is accomplished by varying the resistance-inductance-capacitance (R-I-C) components in the output feedback loops. The pressure-controlled oscillator can use either a wall attachment flip-flop or a jet interaction proportional amplifier to achieve the gain necessary for oscillation.

Turbulence Amplifier Oscillator

This oscillator (fig. 67) utilizes a turbulence amplifier and a single output feedback loop as used in the external feedback oscillator. When the supply is

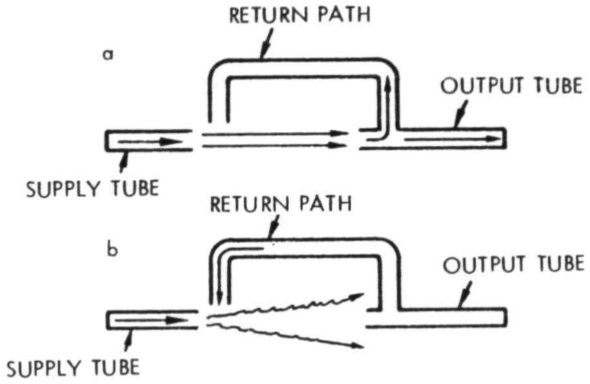


FIGURE 67.–Turbulence amplifier oscillator (ref. 18).

turned on, the laminar power jet is recovered in the output tube as in a typical turbulence amplifier. However, in this case, a portion of the output flow enters the return path as shown in figure 67a so that it impinges on the power jet as shown in 67b. The return flow causes the power jet to become turbulent with the resulting decrease in the output pressure. This causes the flow along the return path to decrease or stop so that the power jet again becomes laminar and the cycle repeats itself.

Tuning Fork Fluidic Oscillator

This precision oscillator (fig. 68) consists of a temperature-compensated tuning fork, a load sensitive fluidic flip-flop, control transmission lines, and a feedback transmission line. The supply stream emerges from an aperture in one tine (control) of a tuning fork and is alternatively switched to the two downstream channels as the control tine oscillates. The two downstream channels provide control inputs to the load sensitive flip-flop which oscillates accordingly. One fluid pulse train from the flip-flop is fed back and impinged on the driven tine of the tuning fork to maintain oscillation of the fork at its natural frequency. The other flip-flop output is used as the output signal of the oscillator. The oscillator uses the air pulse only to apply sufficient energy to the tuning fork to sustain oscillation, or it is insensitive to variations in the speed of sound in the working fluid.

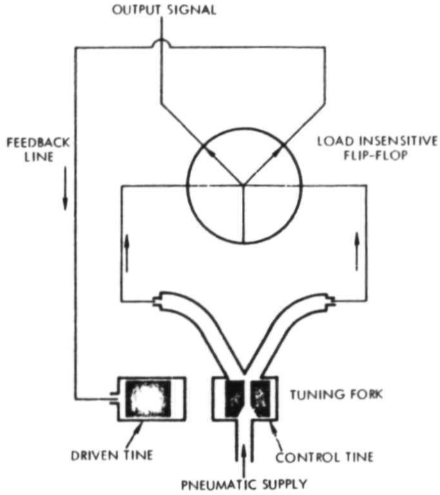


FIGURE 68.–Fluidic tuning fork oscillator (ref. 18).

MOVING-PART DEVICES

Fluidics is generally associated with control and logic systems operating at low-power levels, whereas ordinary moving-part devices are thought of in terms of controlling power functions. The advent of fluidics has increased the number of moving mechanical part devices available to perform control functions. Moving-part devices are useful in hybrid fluidic systems to boost a low-pressure signal to a useful working pressure, i.e., sufficient to operate a valve actuator. These power interfaces can be either gas-to-gas, gas-to-hydraulic fluid, or even gas-to-liquid propellant interfaces.

FLUID INTERFACES

Many early fluidic applications were of the hybrid variety in that transducers were required to interface with other modes of control. Relatively little original work was done to develop new devices in this area initially, and even today many of the available interface components are adaptations of commercially available hardware for hydraulic and pneumatic control.

Electrical-To-Fluid Transducers

In most electrical-to-fluid (E-F) transducers, an electrical signal produces a mechanical movement of an element into the active area of a fluidic device. A wide variety of E-F transducers is in general use. For example, an E-F transducer for on-off or digital operation can be a solenoid valve, and for proportional control it can be a torque motor-driven flapper valve. Several E-F transducers of this type are shown in figure 69.

Practical E-F transducers have been made that use the secondary effects of acoustic power, i.e., acoustic streaming and radiation pressure. For example, a turbulence amplifier can be made to switch to the NOR condition by means of sound waves. The device shown in figure 69 uses an electrically induced magnetic field to position or oscillate a diaphragm that varies the differential pressure across a fluidic proportional amplifier. A piezoelectric ceramic disc can also be used in place of the electromagnetic driver and diaphragm. These E-F transducers are capable of producing a relatively low-pressure pneumatic signal in the range from steady state to about 2000 Hz.

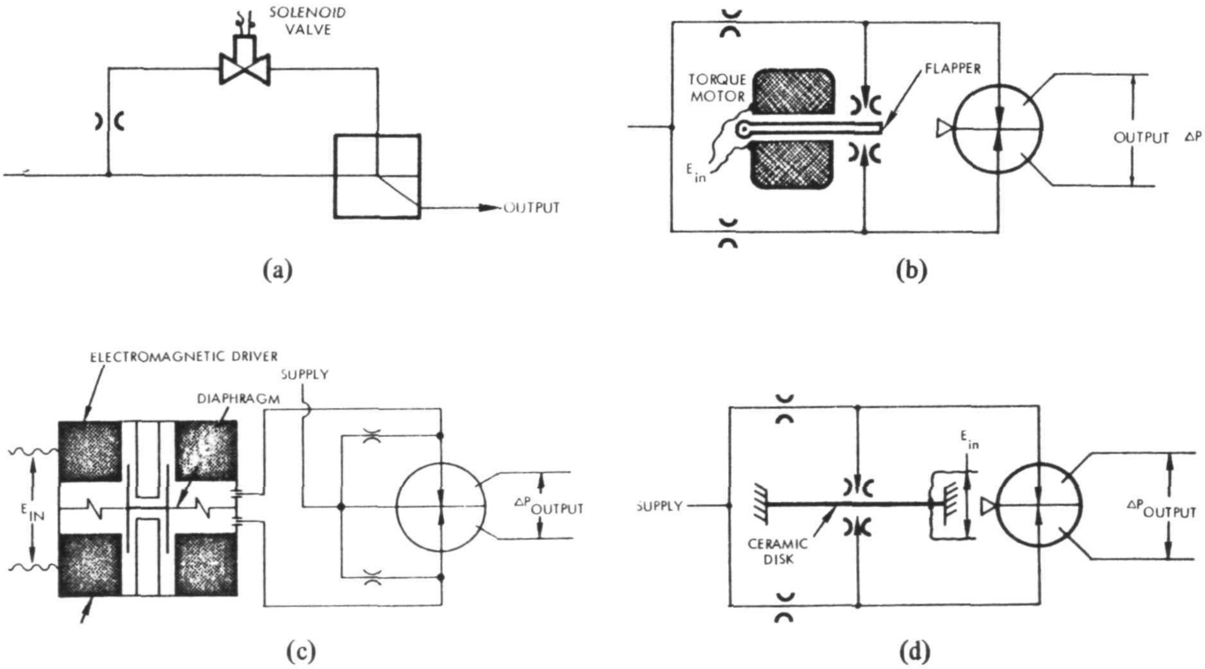
Fluid-To-Electrical Transducers

The most widely used fluid-to-electrical (F-E) transducers are simple pressure switches, pressure transducers, and hot wire probes. Most pressure switches and many pressure transducers are limited to application in systems with a bandwidth of less than 100 Hz because of the additional transducer volume involved. Flush mounted, piezoelectric pressure transducers and the newer semiconductor strain gage elements (0.10 in. sensing diameter) are capable of operating in components with bandwidths in excess of 20 000 Hz. Thermistor or hot wire probes have also been installed in the control and output channels of fluidic devices to indicate the presence or absence of flow.

Heater elements or hot films can be installed in the output ducts of a proportional amplifier and connected in a bridge circuit as shown in figure 70a. The bridge output voltage is then proportional to the differential cooling of the two sensors by the output flows. Another type of differential F-E transducer uses a small semiconductor or wire strain element mounted between the output legs of a proportional amplifier as shown in figure 70b. This transducer will produce a sensitive and accurate output signal directly proportional to the amplifier differential output pressure. Both of these devices are capable of bandwidths greater than 20 000 Hz, depending on how they are installed in relation to the fluid system.

Mechanical-To-Fluid Transducers

One of the simplest mechanical-to-fluid (M-F) transducers is a pressure divider, where the exit is a



(a) (b)

(c) (d)

FIGURE 69.–Electrical-to-fluid (E-F) transducers (ref. 18). (a) Solenoid valve E-F transducer; (b) torque motor-driven E-F transducers (c) piezoelectric ceramic disc E-F transducer; (d) diaphragm oscillator type E-F transducer.

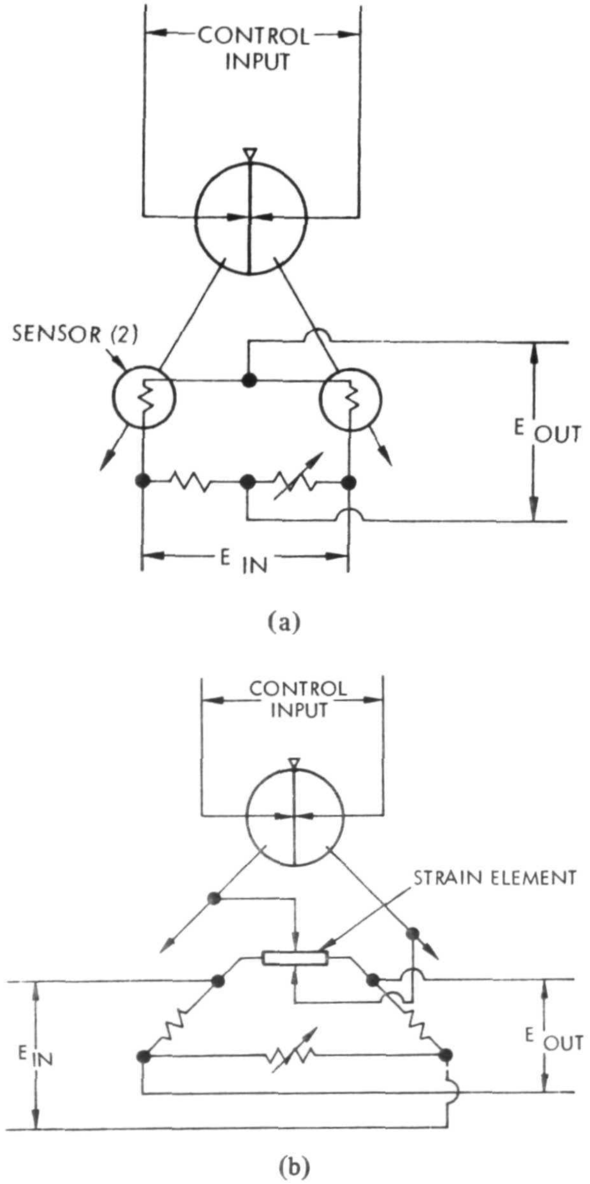


FIGURE 70.–Fluid-to-electrical (F-E) transducers (ref. 18). (a) Hot film type F-E transducer; (b) strain element type F-E transducer.

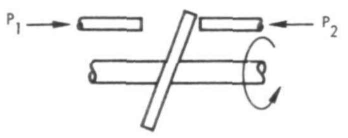
variable orifice controlled by the operation of a flapper. The flapper can be either a translating member or a rotating cam attached to the mechanical device. Another type of M-F transducer is the interruptible jet that is essentially a turbulence amplifier in which the turbulence inducing element is an object that intrudes into the jet stream. For digital circuitry, the concept of the traditional player piano roll would permit the use of complex programmed inputs. Another version of this concept uses standard punch cards as the input signal or programming device.

Analog fluidic systems require a differential pressure signal at the interface between the transducer and the system input. The M-F transducers shown in figure 71 were conceived to perform this function. In devices (a), (b), and (c) the output nozzles (P_1 and P_2) are each supplied from a constant pressure source through a choked orifice. As the displacing member moves closer to one nozzle and farther away from the other, the resulting changes in back pressure are reflected in the differential pressure signal P_1 minus P_2. The transducer in (d) functions in a similar manner, except that the change in orifice area is accomplished within the transducer itself.

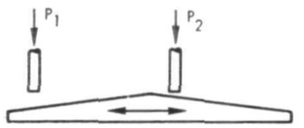
Fluid-to-Mechanical Transducers

Fluidic devices provide a relatively low output pressure that can be amplified fluidically or can be used directly to drive or operate a variety of devices.

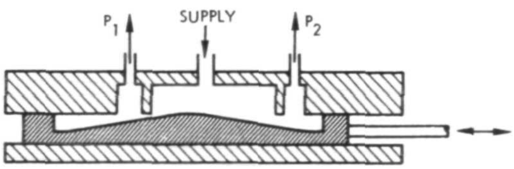
(a) ANGULAR DISPLACEMENT WITH CAM



(b) ANGULAR DISPLACEMENT WITH WOBBLE PLATE



(c) LINEAR DISPLACEMENT WITH UP-DOWN RAMP



(d) LINEAR DISPLACEMENT WITH VARIABLE ORIFICES

FIGURE 71.–Differential type mechanical-to-fluid (M-F) transducers (ref. 18).

These devices are generally adaptations of existing pneumomechanical devices–for example, a fluidic signal may be used to position a spool valve in a power circuit. Other typical applications would be the control of a valve with a diaphragm, piston, or a geared gas turbine actuator.

FLUIDIC SENSORS

The sensing of system variables is fundamental to all control functions. The output of a sensor is a function of a system variable such as temperature, position, angular rate, or acceleration. Whether a device is called a sensor, an interface element, or a transducer is often a matter of opinion or definition. For example, many of the M-F transducers discussed previously could be called sensors because they sense the physical position of an object and provide an output which is a function of the sensed position.

The following devices are representative of the sensors that have been reported in the current literature and those that are novel in terms of fluidic principles.

High Impedance Pressure Sensor

Pressure signals are normally sensed directly by fluidic circuits. However, in some situations the fluid producing the control input data may be toxic, corrosive, dirty, or hot so that it may not be desirable to have the fluid enter the fluidic circuit. This is especially true where continued exposure to external contamination could render a system inoperative or where human exposure to a toxic exhaust gas could be harmful. The high impedance pressure sensor provides a means by which pressure levels can be detected without flowing the sensed media into the sensor.

The high impedance pressure sensor (fig. 72) is essentially a bistable wall attachment amplifier with a bypass channel from the supply to one control port. This control port is designated as the control input and the opposite control port is then designated as the bias input. When the supply fluid is turned on, some fluid is bypassed in the control input channel where it impinges on the far wall causing the stream to split as shown in figure 72a. A relatively small portion of the stream is entrained by the power jet in the interaction region and the remaining portion is discharged through the control channel. A bias input is adjusted to cause the power jet to attach initially to the opposite or right wall. When the control input is restricted by either a physical blockage or a control signal of the proper magnitude, the power jet will switch to the left output port (fig. 72b). A variable bias resistor is used to adjust the sensitivity of the sensor and, consequently, the control pressure level at which the supply stream switches.

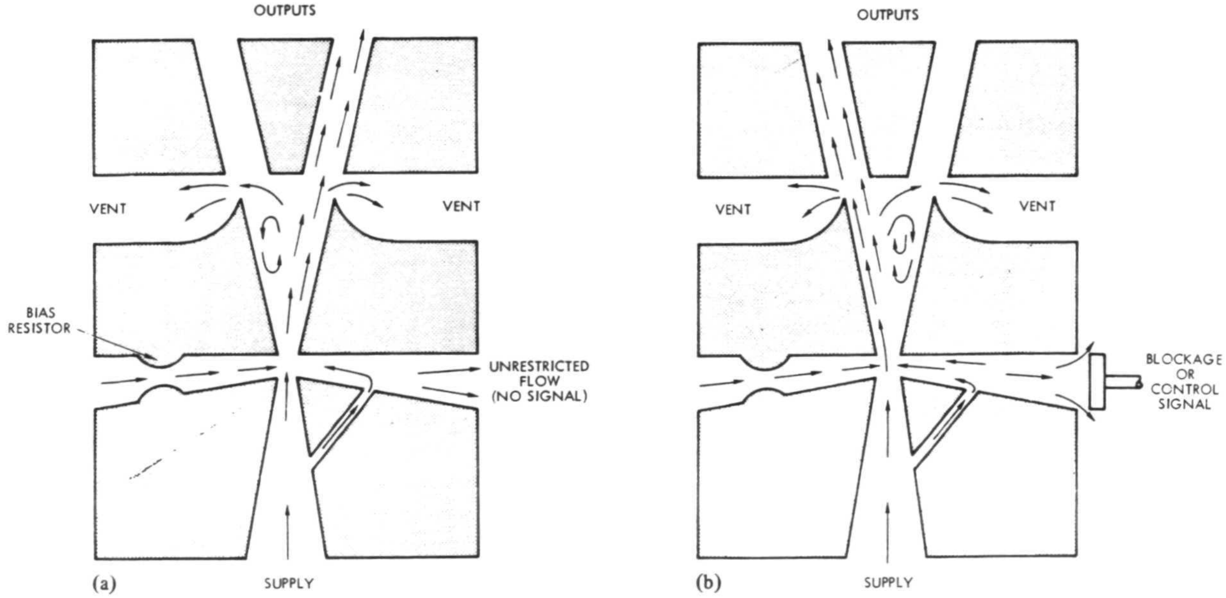


FIGURE 72.–High impedance pressure sensor (ref. 18). (a) No control signal; (b) control signal.

The pressure sensor can be modified for use at high altitudes or in outer space as shown in figure 73. This is accomplished by interconnecting the vents and the bias input and discharging the flow through a common orifice. The sensor will then function independently of atmospheric back pressure provided the vent pressure is high enough to choke the vent orifice.

Temperature Sensors

Several types of external feedback fluidic oscillators have been developed for measuring gas temperature. Although many of these vary in configuration and design, their basic operation depends on the fact that the speed of wave propagation in the external feedback path is primarily a function of gas temperature (fig. 74). Therefore, if the switching time for the active fluidic element (wall attachment flip-flop) in the oscillator is assumed to be zero, the oscillator frequency is

$$F = \frac{u_c}{2\ell}$$

where F = frequency (Hz)

u_c = speed of wave propagation of the gas (m/sec)

ℓ = length of the conduit (m)

Theoretically, the oscillator temperature sensor will operate in virtually any environment as long as the minimum flow velocity necessary for operation is

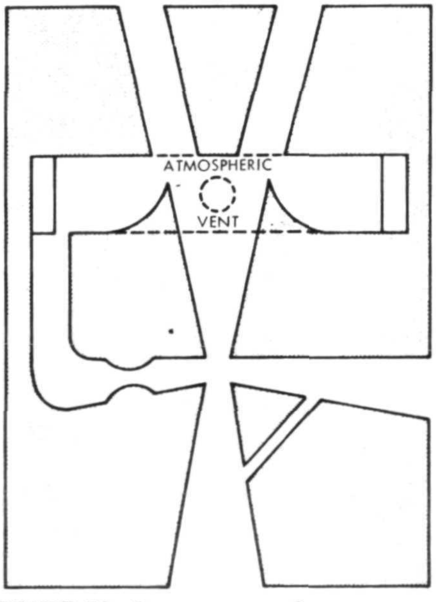


FIGURE 73.–Pressure sensor for space operation (ref. 18).

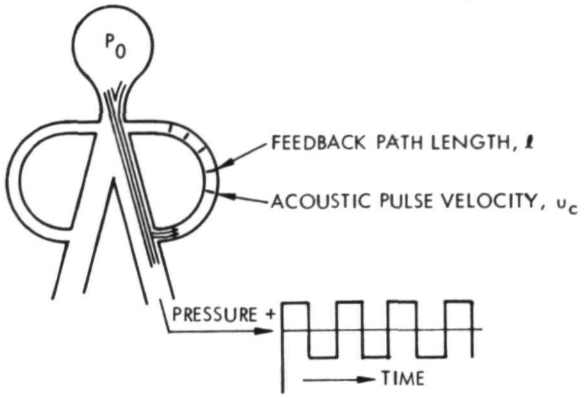


FIGURE 74.–Fluidic oscillator temperature sensor (ref. 18).

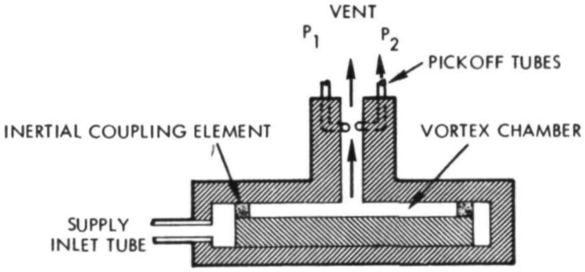


FIGURE 75.–Vortex rate sensor (ref. 18).

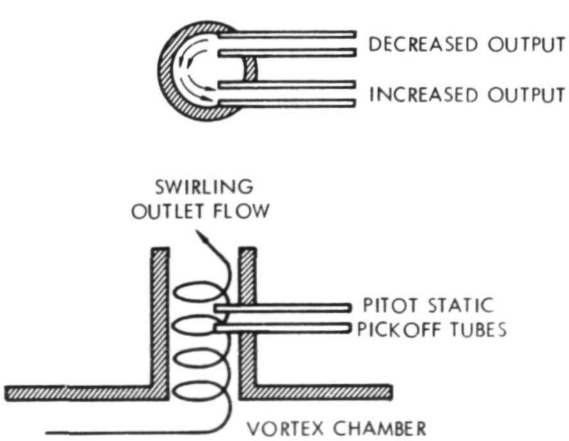


FIGURE 76.–Rate sensor aerodynamic pickoff tubes (ref. 18).

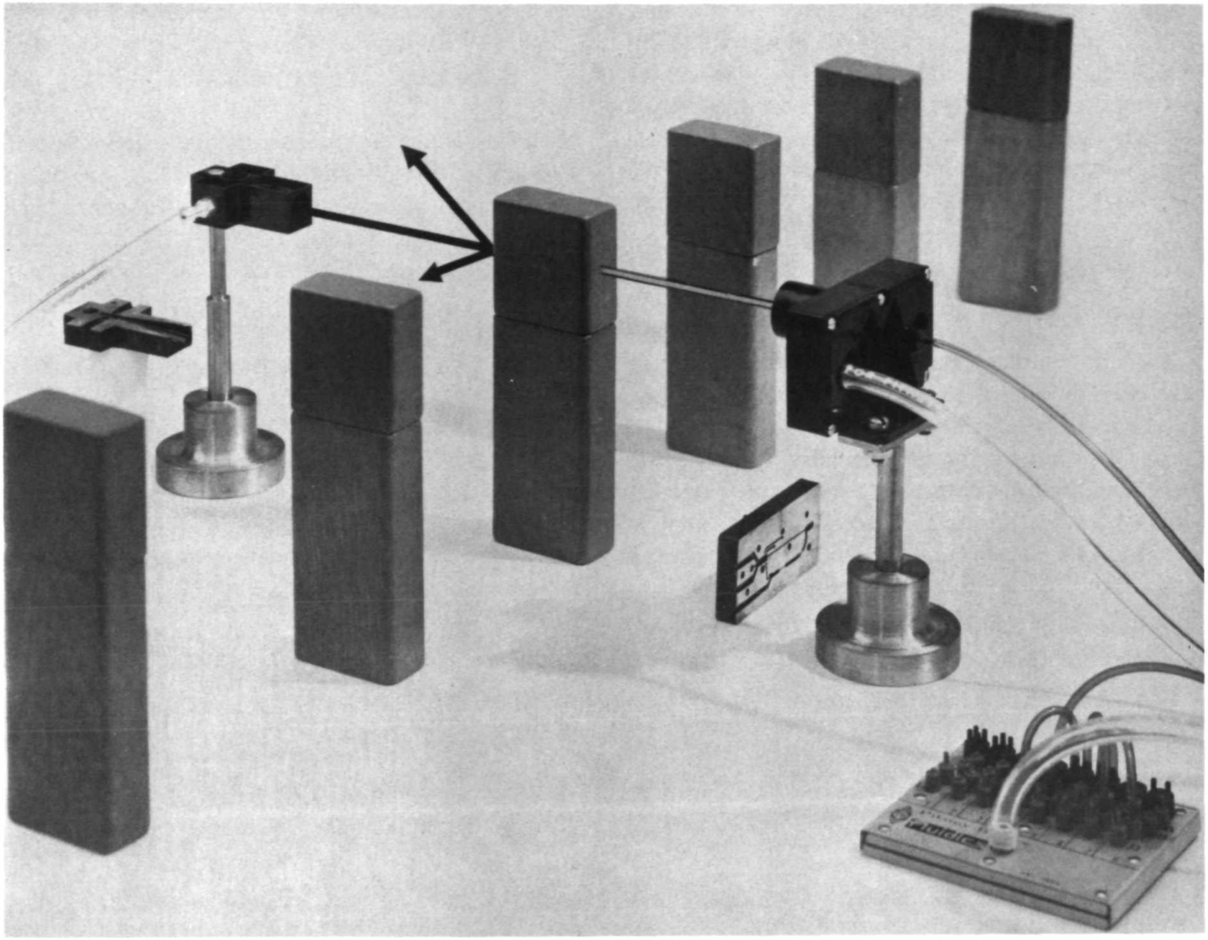


FIGURE 77.–Fluidic ear acoustic sensor.

maintained. The temperature range for a given device is determined by the liquification temperature of the working gas at low temperatures and the melting point of the sensor material at elevated temperatures.

Vortex Rate Sensor

A typical vortex rate sensor is shown in figure 75. Supply fluid flows through the inertial coupling element, through the vortex chamber, and out the vent. The coupling element is usually a porous material, but uniformally spaced vanes have also been used.

When the angular rate is zero, supply fluid passes through the coupling ring and flows radially through the vortex chamber and out the vent. When an angular rate is imparted to the sensor, a tangential velocity is induced in the supply fluid by the coupling element which is amplified in the vortex chamber due to the conservation of angular momentum. This increased velocity is detected with an aerodynamic pickoff located in the vent tube. The pickoff (fig. 76) senses angular rate by measuring the vorticity imparted to the outlet flow, i.e., the pressure differential generated across the pickoff tubes is directly proportional to the applied angular rate.

Acoustic Sensor

The fluidic ear acoustic sensor shown in figure 77 generates and receives an acoustic beam for object sensing. The sound beam is transmitted from an air whistle at 50 kHz to a narrowband sound-sensitive amplifier.

CHAPTER 7

How to Get Started in Fluidics

This chapter is for newcomers to fluidics technology. Hopefully this survey will sow a seed of interest that will result in totally new applications. Such applications may include the use of relatively conventional fluidic systems in new places.

We saw in chapter 5 that engineering costs can be a stumbling block to the use of fluidics in some cases. One way to get a feel for the need for in-house technical capability is to consider two small companies with no prior fluidics experience and with two differing applications in mind which lend themselves to the use of a fluidic system:

Company A has a natural application for the installation of several fluidic counters to monitor a production line operation. Assuming no other needs, there is no reason why Company A cannot simply purchase a complete system such as that shown in figure 34. This unit can be purchased complete with fluidic sensing head and installed according to the manufacturer's instructions, probably even without the necessity of a visit from the vendor's field service representative. There is really no need for anyone in Company A being able to tell the difference between a wall attachment amplifier and a vortex rate sensor.

Company B also has a natural application for fluidics, but as a control system to go on a product the company sells. Here the problem becomes more complex and includes such questions as:

- Is this strictly a one-shot application (in which case subcontracting the control system may be most appropriate), or is this the first of what is hoped to be a whole new line of products?
- Is the particular control system one that lends itself well to the type of systems offered by one or more fluidics manufacturers, or does it have really unique requirements that will take some development effort?
- Is it desired to do the job with the staff on hand? (If it is necessary to hire another controls engineer for this new line, it could pay to try to find one with a fluidics background, or to retain a consultant or controls engineering firm for the job.)
- Would there be genuine advantage in having a unique, proprietary, perhaps patented control system, or would a universal one do as well?
- Will customer service have to be provided? If so, not only the design department, but the service organization will require a certain level of education on the particular type of fluidic system to be employed.

In one set of circumstances Company B may be able to add a fluidic control system to its product line without developing strong in-house technical ability in the field. Another set of answers to the questions posed above will obviously dictate really diving into the technology of fluidics. This latter instance is essentially where Bardons & Oliver was in 1965 in our example of fluidic turret lathe controls.

Machine Design published an excellent article in the January 8, 1970 issue entitled "Will Fluidics Make It?" (ref. 160). This survey-type article indicated that in the opinion of several leading fluidics manufacturers the average customer could at that time successfully design and build his own fluidic system. Even those who demurred felt that this would soon be the case. Comments included:

> "The state-of-the-art is such that the informed user can now sketch out a circuit, buy and assemble components, and expect the system to work."
>
> "Awfully close, but not today."
>
> "They can just buy the parts and put 'em in a box."
>
> "The systems that I have seen and heard of are systems that I believe any well-trained technician can handle, and I don't think there is any necessity for engineering."

This article also pointed to the significant improvement in quantity and quality of systems engineering service which the fluidics manufacturers provide. The indication is that the fluidics manufacturers now realize that most customers want to be able simply to provide a performance specification and be given a system that will meet it.

This and other evidence points to an interesting aspect of the fluidics business now. The average user is acquiring the ability to design and develop his own fluidic systems. At the same time, some fluidics manufacturers have added services. There are also still some systems houses that will engineer a fluidic system for the user. One guideline would seem to be: Don't go to the expense of developing in-house engineering ability unless the need is clear.

BEWARE THE PROPRIETARY PITFALLS

The business concern that chooses to patent, develop, manufacture, and sell a new fluidic device must consider an array of prior patents which compares in number with those on automobile carburetors and mousetraps. An interesting conclusion may be drawn from a review of recent patents on fluid amplifiers and related fluidic components. Many of these have been issued to firms that outwardly evidence no interest in fluidics from either a user's or manufacturer's point of view, which suggests there is more active investigation into fluidics' potential than the literature indicates.

SPECIFYING THE FLUIDIC SYSTEM

There are no hard and fast rules, nor any sample specifications to guide the writer of a fluidic system specification at present. This situation is gradually improving, however, and the specifier would do well to ensure that he is aware of the latest standardization publications of such organizations as the National Fluid Power Association (NFPA), Society of Automotive Engineers (SAE), and American Society of Mechanical Engineers (ASME). Some NFPA Recommended Standards which the author of an industrial fluidics specification would do well to know are:

1. T3. 7. 70. 3, *Method of Rating Performance of Fluidic Devices,* January 15, 1970 (ref. 248).
2. T3. 7. 68. 2, *Graphic Symbols for Fluidic Devices and Circuits,* February 1, 1968 (ref. 4).
3. T2. 70. 1, *Glossary of Terms for Fluid Power,* 1970 (ref. 249).

These are available from the National Fluid Power Association, Thiensville, Wisconsin 53092.

For military procurements, Military Standard (MIL-STD-1306), *Fluerics, Terminology and Symbols,* July 17, 1968 (ref. 5), is applicable at present. Military Standards are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20005. Aerospace applications not falling under the other categories would properly use SAE Aerospace Recommended Practice (ARP 993A), *Fluidic Technology,* Revised February 15, 1969 (ref. 3), available from Society of Automotive Engineers, Inc., 2 Pennsylvania Plaza, New York, N.Y. 10001.

Specifications on fluidic components are prepared by the component manufacturers. Reference 250 describes a method developed for understanding and using these specification sheets.

DIGITAL, PROPORTIONAL, OR HYBRID?

Digital Fluidics

Most common industrial fluidic systems are primarily digital. These systems use pneumatic or hydraulic signals to perform binary logic or control functions. Only the simplest process controls, however, lend themselves to the use of digital fluidics.

Proportional (Analog) Fluidics

Proportional fluidics, commonly called analog fluidics, employ fluid flow to provide continuously adjustable, proportional control. Because the control of fluid flow is similar in many respects to the control of unidirectional electric current, the design of most early proportional fluidic systems has been similar to that of d-c electronic systems (ref. 251). Minor annoyances such as leaks and turbulent flow noise can create serious problems with proportional fluidics. Just as a-c electronic circuitry was used to overcome problems such as the basic thermionic noise in electronic systems, a form of proportional fluidics called a-c fluidics has been developed to overcome these leakage and noise problems.

This new form of proportional fluidic control is based upon controlling and monitoring the frequency of pressure pulses rather than the intensity of a steady pressure signal. The term a-c is somewhat misleading in that the direction of flow does not change. Instead, signals are superimposed as fluctuations on constant d-c component of flow. The a-c term is appropriate because the terminology used is similar to that of a-c electronics with words such as inductance, frequency modulation, phase shift, and pulse width. All the frequency-dependent fluidic systems described earlier in this book, such as the temperature sensor on the X-15 in chapter 2, are essentially a-c proportional fluidic systems.

Proportional fluidic systems require special care in execution, and a-c fluidics require an even more sophisticated approach, preferably by one familiar with electronic controls. Those who are interested in further details are referred to the documents cited in chapter 8, as well as the bibliography.

SELLING YOUR FLUIDIC SYSTEMS (OR SELLING YOURSELF ONE)

A number of instances came to light in the course of this survey which emphasized what a poor selling job most technical people do. Incomplete analyses of "what the customer really wants to buy" haven't done fluidics any favors.

An example concerns an artillery fuse design. Starting with an essentially clean sheet of paper, a thorough technical analysis and tradeoff study showed a fluidic design to be better than any other candidate fuse. An excellent design was prepared, along with a complete analysis showing how good it was and how superior it was to the other candidate systems. This was finally presented to the customer (or decision-maker, in this case). His response was in essence, "It looks great, but how are you going to make X00 000 of them in 6 months?" No thought had been given to this problem. There was no way, so a nonfluidic alternative had to be chosen. Even a mousetrap manufacturer won't run a full-page advertisement in a national magazine until he has estimated how he can meet the demand he expects to stimulate.

Another general example may be found in the commercial airplane business. All too familiar is the story of the fluidics researcher, who after several years of study and experiment, has finally found the ideal application for fluidics on the company's latest product. The new plane is only now having its various systems selections made, so our struggling fluidics engineer makes up a model of the proposed system—breadboard, of course. The customer (program manager or senior airplane designer) has been fed all the performance curves, weight advantages, etc., and finally comes to the laboratory to see it work. He takes one look at yards of spaghetti comprising the breadboard model, and says, "No one is putting plastic tubing on my airplane," and strides out, mind closed. Even a black aluminum cover over the logic might have helped. Perhaps some photographs of an all-metal similar system shown in advance could have averted disaster.

Fluidics systems offer great potential in many applications. This potential will be realized only where thorough analysis of the customers' requirements is used in selling the particular fluidics approach proposed. This applies even if the salesman is his own customer.

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CHAPTER 8

Sources of Additional Information

FLUIDICS TECHNOLOGY

If ever a new field has been documented from its inception, it is fluidics. A browse through any of the numerous bibliographies on fluidics can give the impression that every researcher who ever made a flip-flop work in the laboratory promptly sat down and wrote a paper or article on it. (The bibliography for this book consists primarily of applications-oriented references. For every one of these there must be several specialized phenomenological or design-oriented references in the literature.)

Ironically, in view of this apparent plethora of documentation, one of the biggest gripes about fluidics until recently has been the lack of appropriate texts for someone trying to design or specify a fluidic system for the first time. This gap is rapidly being filled. In this survey we have steered away from direct reference to these generally available texts in favor of other reference matter. It is strongly recommended that the engineer or manager starting to learn about fluidics review several of the most recent texts. An excellent way to expedite an education in fluidics is to avail oneself of one of the introductory courses offered from time to time by fluidics manufacturers or one of the university short courses on the subject.

Texts on Fluidics

Some representative texts on fluidics are listed below. The reader is advised to ask about the availability of even more recent books on fluidics. For example, the American Society of Mechanical Engineers (ASME) is currently sponsoring the preparation of a handbook for user-engineers under the direction of Dr. Ray Bowles of Bowles Fluidics Corporation.

Fluidics: Components and Circuits, B. K. Foster and G. Parker, Wiley-Interscience, New York, 1971 (ref. 254).

Fluidic Systems Design, C. Belsterling, Wiley-Interscience, New York, 1971 (ref. 255).

Fluid Amplifiers, J. M. Kirshner (ed.), McGraw-Hill, New York, 1966 (ref. 256). (This book is an edited collection of lectures given at HDL.)

Fluidics, E. F. Humphry and D. H. Tarumoto (ed.), Fluid Amplifier Associates, Inc., Boston, 1965 (ref. 257).

Fluidic System Design, Daryl L. Letham, published as a series in *Machine Design* between February 16, 1966 and March 16, 1967 (ref. 258). (This series is available in a 4-volume reprint from The Penton Publishing Co., Cleveland, Ohio 44113.)

Speciality Periodicals

Two publications devoted exclusively to fluidics are:

Fluidics Quarterly, Fluid Amplifier Associates, Ann Arbor, Michigan

Fluidics Forum, 419 Plaza Building, Pittsburgh, Pennsylvania 15219

Government Publications and Information Retrieval Sources

Technical reports can be found by searching NASA Scientific and Technical Aerospace Reports (STAR) and International Aerospace Abstracts (IAA). A data bank of NASA documentation is maintained at the NASA Scientific and Technical Information Facility, P. O. Box 33, College Park, Maryland 20740. The six Regional Dissemination Centers named below maintain a data base of unclassified NASA documents.

Aerospace Research Applications Center
Indiana University Foundation
Bloomington, Indiana 47405
Phone (812) 337-7970

Knowledge Availability Systems Center
University of Pittsburgh
Pittsburgh, Pennsylvania 15213
Phone (412) 612-3500, Ext. 6352

Technology Application Center
University of New Mexico
Box 185
Albuquerque, New Mexico 87106
Phone (505) 277-3118

New England Research Application Center
University of Connecticut
Storrs, Connecticut 06268
Phone (203) 429-6616

North Carolina Science and Technology Research Center
Post Office Box 12235
Research Triangle Park, North Carolina 27709
Phone (919) 834-7357 or 549-8291

Western Research Applications Center
University of Southern California
Los Angeles, California 90007
Phone (213) 746-6133

Copies of NASA reports in microfiche or hard copy can be obtained from these centers, or the National Technical Information Service (NTIS), Springfield, Virginia 22151. Copies of reports announced in IAA can be obtained from the American Institute of Aeronautics and Astronautics, Inc., 750 Third Avenue, New York, New York 10017.

Anyone wishing to consult NASA publications and sponsored documents may do so at a large number of public, university, and other libraries. The most nearly complete collections are available at the public libraries (usually the central ones) in the following cities:

California:	Los Angeles, San Diego
Colorado:	Denver
Connecticut:	Hartford
Delaware:	Wilmington Institute Free Library
Maryland:	Enoch Pratt Free Library, Baltimore
Massachusetts:	Boston
Michigan:	Detroit
Minnesota:	St. Paul
Missouri:	Kansas City
New Jersey:	Trenton
New York:	New York, Brooklyn, Buffalo, Rochester
Ohio:	Cleveland, Cincinnati, Dayton, Toledo, Akron
Oklahoma:	Oklahoma City
Tennessee:	Memphis
Texas:	Fort Worth, Dallas
Washington:	Seattle
Wisconsin:	Milwaukee

In addition, NASA's technical documents and bibliographic tools are deposited in 11 special libraries. Each library listed below is prepared to furnish reference service, interlibrary loans, photocopies, and help in obtaining personal copies of NASA documents by microfiche if requested. These special libraries are located as follows:

California:	Univ. of California Library, Berkeley
Colorado:	Univ. of Colorado Libraries, Boulder
District of Columbia:	Library of Congress
Georgia:	Georgia Institute of Technology, Atlanta
Illinois:	The John Crerar Library, Chicago
Massachusetts:	Mass. Institute of Technology, Cambridge
Missouri:	Linda Hall Library, Kansas City
New York:	Columbia University, New York
Pennsylvania:	Carnegie Library of Pittsburgh
Texas:	Southern Methodist University, Dallas
Washington:	Univ. of Washington Library, Seattle

NASA has a data bank of more than half a million aerospace documents that can be searched by a computer. The computerized retrospective search is faster than a manual search. A retrospective search of aerospace literature can be obtained through the NASA Scientific and Technical Information Facility or the Regional Dissemination Centers listed above.

A retrospective search may be exhaustive, selective, or negative. An exhaustive search on a subject may produce a large volume of material that requires an excessively long time to review. The researcher should give some thought to making his search as selective as possible. Use of the NASA Thesaurus (SP-7030) will assist the researcher in finding relevant search terms. The NASA Thesaurus can be obtained from the NASA Scientific and Technical Information Facility, the National Technical Information Service, or the Superintendent of Documents, Government Printing Office, for $8.50.

The Regional Dissemination Centers and the NASA Scientific and Technical Information Facility have analysts who will assist a researcher in formulating the search strategy. The Regional Dissemination Centers charge a fee for such a search. However, their service may be desirable because they supply an abstract of the document in addition to bibliographic information. The Scientific and Technical Information Facility supplies only bibliographic information and a notation of content.

Perhaps the experience of the author in researching material for this survey would be of interest. (It also gives an indication of the rate at which fluidics documentation is being published.) The Western Research Applications Center (WESRAC) at the University of Southern California performed the search. Within 48 hours a computer printout listing 895 references was available. (This can reasonably be called an exhaustive search.) In less than a week after the author decided which titles were of interest, two copies of a neatly bound bibliography were delivered. The bibliography included abstracts of the 385 references selected, plus copies of 25 NASA Tech Briefs. Three months later, a "current awareness" update identified 74 new references that had been added to the data bank during the interim.

An important feature of searches performed by Regional Dissemination Centers such as WESRAC is that the field of retrieval may be narrowed as much as desired. For example, search terms such as fluidic, medical, heart, breathing, etc., may be used to ensure that only those references in the particular field of interest will appear on the computer printout. An additional item of interest is the availability of copies of the acutal document. All the selected fluidics references were available on microfiche at WESRAC, and some were available in hard copy. Hard copy items not on hand could be ordered. These references could be reviewed at WESRAC for no charge or purchased for retention. Whether the desire is to update or to ensure the completeness of an existing bibliography or library (as in this case), this certainly is an excellent way to start.

Technical Papers From Symposia

Most technical papers given at symposia and conferences are available from the sources indicated above. Additional sources for the ASME Symposia, Cranfield Conferences, and HDL Symposia are:

The American Society of Mechanical Engineers
345 East 47th Street
New York, New York 10017

The British Hydromechanics Research Association
Cranfield, Bedford, England

All U.S. Government authored or sponsored publications including proceedings of the HDL Symposia and reports in the HDL Fluerics or Fluid Amplification series may be obtained from:

National Technical Information Service (NTIS)
Sills Building
5285 Port Royal Road
Springfield, Virginia 22151

Periodicals

Several magazines or trade journals have carried articles on fluidics developments in recent years. Among these are:

Control Engineering
Dun-Donnelley Publishing Corporation
466 Lexington Avenue
New York, New York 10017
Design News
Cahners Publishing Company
221 Columbus Avenue
Boston, Massachusetts 02116
Hydraulics & Pneumatics
Industrial Publishing Company
414 Superior Avenue West
Cleveland, Ohio 44113
Machine Design
Penton Publishing Company

1111 Chester
Cleveland, Ohio 44114

Product Engineering
Morgan-Grampian, Inc.
16 West 61st Street
New York, New York 10023

Bibliographies

An attempt to list all the currently available bibliographies on fluidics would be as audacious as trying to list all the firms involved in the fluidics business. Two that have proven especially helpful for one reason or another are:

Fluerics 23: A Bibliography, HDL Staff, HDL-TR-1495, Harry Diamond Laboratories, Washington, D.C. 20438, April 1970 (ref. 259). (This document is updated periodically. In its present form it represents a particularly handy reference because of its key-word-in-context (KWIC) indexing and author listing.)

Fluid Amplifier State-of-the-Art Report, Volume II-A, Bibliography, M. J. Osborn, prepared by General Electric Co., Schenectady, N.Y. under Contract NAS8-5408 for NASA Marshall Flight Center, March 1966 (ref. 260). (Somewhat dated now, this bibliography and its 1963 predecessor (ref. 8) are comprehensive and include abstracts of most listings.)

For less than an engineer's salary for one week, a firm or individual may have a retrospective search made of NASA's data bank by computer as described above.

A Special Fluidics Information Center

The Fluidics Reference Center (FRC) was established in 1969 at The Pennsylvania State University under the direction of Dr. J. Lowen Shearer, Rockwell Professor of Engineering, to provide a readily accessible bank of literature and information pertinent to fluidics. The FRC is equipped to offer computerized bibliography preparation with abstracts of key references. A key feature of the FRC is the cataloging of references by main areas and subareas. This project has been funded by the College of Engineering, the Conference Center of The Pennsylvania State University, and NASA grants. It is recommended that inquiries be directed to:

Dr. J. L. Shearer
Fluidics Research Center
Systems and Controls Laboratory
The Pennsylvania State University
University Park, Pennsylvania 16802

THE FLUIDICS INDUSTRY

Where can one find a current list of fluidics manufacturers? Is there a fluidics "systems house" in my locale? First, contact the National Fluid Power Association (NFPA), Thiensville, Wisconsin 52092. Secondly, the following published lists are referenced:

Companies in Fluidics, *Fluidics Quarterly*, vol. 3, no. 2, April 1971, pp. 59-67 (ref. 260).

Manufacturers of Fluid-Logic Devices, *Machine Design*, vol. 42, no. 22, September 10, 1970, pp. 280-286 (ref. 261).

Designers Guide, published annually in the January issue of *Hydraulics and Pneumatics* (see periodicals above).

Developments and problems in the fluidics industry related to aerospace applications are aired semiannually in meetings of the Society of Automotive Engineers (SAE), Committee A-6, Aerospace Fluid Power and Control Technologies. For information, contact SAE, Inc., 2 Pennsylvania Plaza, New York, New York, 10001.

APPENDIX A

Digital Circuit Design

The following discussion of digital circuit design is adapted with permission from reference 1. The principles outlined below have been evolved for use with pneumatic, hydraulic, electrical, electronic, mechanical, and optical controls and should apply equally well to fluidic digital circuit design.

Binary arithmetic is the operating arithmetic for all modern computing and logic devices with binary-to-decimal conversion used only where the number is desired in familiar decimal form. The reasons for the universal use of binary techniques are the simplicity of the system for all arithmetic manipulations, such as addition and multiplication, and the ease with which the desired function can be implemented with any two-state device, such as a simple switch of any type.

Symbolic logic notation is the language used to express binary arithmetic functions and the logical decision-making functions. The equations used to express the problem (and its solution) are in the form of symbolic logic. Thus, logic is the language of binary arithmetic. To understand binary systems (and their implementation with logic devices), it is necessary to know binary arithmetic and symbolic logic.

BINARY ARITHMETIC

Binary arithmetic uses only two digits. For convenience, the digits chosen are 0 and 1. No other digits are used in binary arithmetic, and all numbers are expressed with these two symbols, as shown in table 10.

The progression of numbers is by powers of 2, as follows:

$$\begin{aligned} 1 &= 1 = 2^0 \\ 10 &= 2 = 2^1 \\ 100 &= 4 = 2^2 \\ 1000 &= 8 = 2^3 \\ 10000 &= 16 = 2^4 \\ 100000 &= 32 = 2^5 \end{aligned}$$

Thus, the binary number

$$10101 = 16 + 4 + 1 = 21$$

Similarly, numbers to the right of a decimal point can be found from negative powers of 2:

$$\begin{aligned} 0.1 &= 2^{-1} = 1/2 \\ 0.01 &= 2^{-2} = 1/4 \\ 0.001 &= 2^{-3} = 1/8 \end{aligned}$$

Therefore, any decimal number can be expressed in binary form, and vice versa. Note that in binary all numbers can have only the two chosen marks. Numbers appear like this: 11101, 111011, 1101111, 1111111.

ADDITION WITH BINARY NUMBERS

Binary is the easiest set of numbers in which to perform arithmetic; in binary, we need remember only the following two simple rules:

Rule 1: 0 plus 1 is 1

Rule 2: 1 plus 1 is 0 and carry a 1 to the next column left.

With these two rules we can perform addition. Thus, if we are to add 2 and 3 (binary 10 and 11)

$$\begin{array}{rl} 10 & = 2 \\ \underline{11} & = 3 \\ 1 & \\ 0 & \text{carry 1 left} \\ \underline{1} & \text{the carry} \\ 101 & = 5 \end{array}$$

Let us add two bits (binary digits) which we shall call A and B. As each bit can be a 0 or a 1, there are four possible combinations of A and B, as shown in the input column of the truth table in table 11.

TABLE 10.–*Binary Equivalents of Decimal Numbers (ref. 1)*

Decimal Number	Binary Number
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	1010

TABLE 11.–*Simple Two-Input, Two-Output Truth Table (ref. 1)*

Input		Output			
				S exists when	C exists when
A	B	S	C		
0	0	0	0		
0	1	1	0	$\bar{A}\ B$	
1	0	1	0	$A\ \bar{B}$	
1	1	0	1		$A\ B$

Note that a sum (S) exists when either A or B is 1; a carry (C) exists only when both A and B are 1. These situations are expressed in the language of logic in the last two columns.

SYMBOLIC LOGIC NOTATION

In the language of logic, each bit is called A, B, etc., if it is a 1; it is called $\bar{A}$, $\bar{B}$, etc., if it is a zero, with the bar representing the word not. That is,

$$\bar{A} = \text{not } A$$
$$\bar{B} = \text{not } B$$

From table 11, if the inputs are $A = 0$ and $B = 1$, then a sum exists. This (not A and B) is written

$$S = \bar{A}B$$

Similarly, if $A = 1$ and $B = 0$, a sum exists. This (A and not B) is written

$$S = A\bar{B}$$

We can now say that an adder is a device that develops an output signal when

$$\begin{aligned} S &= (A \text{ and not } B) \text{ or } (B \text{ and not } A) \\ &= A\bar{B} \text{ or } B\bar{A} \end{aligned}$$

THE AND, OR CONCEPT

In 1854, the book *Laws of Thought* by George Boole was published. Boole proposed the theory that the logical relationship between objects can be expressed in terms of the concepts AND and OR; that is, given objects A and B, then the only relations involving A and B can be expressed as (1) A AND B, meaning that both must exist at one time, or (2) A OR B, meaning that one can exist without the other. The expression A AND B is usually written $A \cdot B$ or AB; A OR B is written $A + B$, with the + sign meaning OR. Note that it does not mean addition.

The simplicity of binary techniques has caused the arithmetic based on Boole's postulates to become a powerful tool for designing circuits involving switching and interlocking relations. Today, Boolean algebra (symbolic logic arithmetic) is used in the design of most digital circuitry. The extent of the field can be inferred from the fact that more than 60 manufacturers now offer electronic modules (called gates), that perform the simple AND and OR functions, described by the following:

Consider two binary variables (A, B). As there are two conditions for each variable and two possible relations (AND, OR), there are only eight possible relationships (called logic expressions):

$$A + B \text{ (}A \text{ OR } B\text{)} \tag{1}$$
$$AB \text{ (}A \text{ AND } B\text{)} \tag{2}$$
$$A\bar{B} \text{ (}A \text{ AND not } B\text{)} \tag{3}$$
$$B\bar{A} \text{ (}B \text{ AND not } A\text{)} \tag{4}$$
$$\bar{A}\bar{B} \text{ (not } A \text{ AND not } B\text{)} \tag{5}$$
$$\bar{A} + \bar{B} \text{ (Not } A \text{ OR not } B\text{)} \tag{6}$$
$$A + \bar{B} \text{ (}A \text{ OR not } B\text{)} \tag{7}$$
$$B + \bar{A} \text{ (}B \text{ OR not } A\text{)} \tag{8}$$

Logic expressions can be factored, multiplied together, etc., by following a few obvious (logical) rules:

$$AA = A \tag{9}$$
$$A + B = B + A \tag{10}$$
$$A = A \tag{11}$$
$$A\ (B + C) = AB + AC \tag{12}$$
$$A + BC = (A + B)\ (A + C) \tag{13}$$
$$A + AB = A \tag{14}$$

$$A + AB + AC + AD = A \qquad (15)$$
$$\overline{AB} = \bar{A} + \bar{B} \qquad (16)$$
$$\bar{A} + \bar{B} = \bar{A}\,\bar{B} \qquad (17)$$

Most of the above rules are obvious. A AND A must be A; if A must exist in the expression $A + AB$, then A alone is all that is needed. Expressions (16) and (17) follow from the single most powerful manipulative technique, one that permits any logic expression using AND relations to be converted into another expression using OR relations–the DeMorgan inversion.

The two basic logic operations are AND and OR. Expressions involving AND logic can be changed into OR logic, and vice versa, by use of DeMorgan's theorem, also known as the involution law, inversion postulate, or dualization law. DeMorgan's theorem states that a logic expression can be inverted simply by (1) inverting each term of the expression, (2) changing each AND element into an OR element, and (3) changing each OR element into an AND element. For example, to invert the expression $A + B$:

$$A + B \text{ inverted} = \overline{\mathrm{A} + B} = \bar{A}\,\bar{B}$$

To invert AB

$$\overline{\mathrm{AB}} = \bar{A} + \bar{B}$$

To invert the expression $(\overline{A + B}) + (AB)$

$$\overline{(\overline{A + B}) + (AB)} = (A + B)\,(\overline{AB}) = (A + B)\,(\bar{A} + \bar{B})$$
$$= A\bar{B} + B\bar{A}$$

Note in the above, that each term in parentheses is considered an entity. To invert $C = AB$, we get

$$\bar{C} = \overline{AB} = \bar{A} + \bar{B}$$

To invert $C = A + B$

$$\bar{C} = \overline{A + B} = \bar{A}\,\bar{B}$$

If we invert the last expression

$$\bar{\bar{C}} = C = \overline{\overline{\bar{A}\,\bar{B}}} = A + B$$

Note here that $\overline{AB} = \bar{A} + \bar{B}$.

Even the most complicated digital computer in existence is based on only the simple logical functions of addition and comparison. All multiplication is but a series of additions; all decisions are made by comparing some number (the result) with some predetermined number. Thus, addition and comparison are the two basic functions of all digital circuits, and the two simple symbolic expressions for the half-adder and comparator appear time and time again in all digital and logical circuits.

Half-Adder: $S = A\bar{B} + B\bar{A}$
Comparator: $S = AB + \overline{AB}$

AND and OR are the two basic logical relations. All other expressions are but variations of the AND and OR relations and can be expressed in AND, OR terms by the DeMorgan technique, including the common NOR logic.

DIGITAL LOGIC OPERATORS

The basic building block used in the design of logic-type circuitry is the operator OR gate. A gate is defined as a device having several inputs and designed so that there is an output when and only when a certain definite set of input conditions is met. Digital logic uses the three basic operators used in Boolean algebra: AND, OR, and NOT. In addition, there are three more operators which are useful combinations of the basic operators: NOR, NAND, and exclusive OR. A final operator is the flip-flop which is actually a memory function.

Control systems make decisions based on information, but automatic systems are generally lacking in value judgment. This means we must define our operators precisely so there can never be a doubt about their exact meaning. The accepted logic definitions are very similar to the common language definitions and are not difficult to remember.

In system design, the easiest way to think of operators is as black boxes. A black box takes information in and gives a decision out. The exact means used to convert information into a decision is not important, but it is necessary to know what decision the black box makes. This is accomplished by naming the black box after the operator that describes its decision, so that several black boxes are available, which are named AND, OR, NOT, NOR, NAND, exclusive OR, and flip-flop.

The information inputs must be in Yes or No form. For example, the part is in position or it is not; in position is Yes, not in position is No. Then the black box operators may be defined in terms of the inputs and outputs as shown in table 12.

Several sets of standard symbols have been adopted

TABLE 12.–*Black Box Definitions (ref. 1)*

Black Box Name (Operators)	Information (Inputs)	Decision (Output)
AND	All yes	Yes
	One or more no	No
OR	One or more yes	Yes
	All no	No
NOT	No	Yes
	Yes	No
NOR	All no	Yes
	One or more yes	No
NAND	One or more no	Yes
	All yes	No
Exclusive OR	One yes, one no	Yes
	Both yes	No
	Both no	No
Flip-Flop	Last input yes	Yes
	Last input no	No

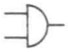
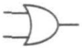
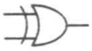
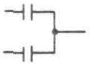
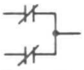
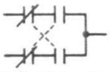
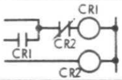
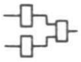
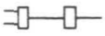
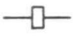
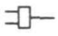
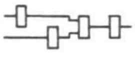
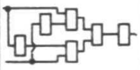
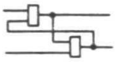
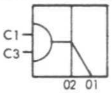
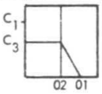
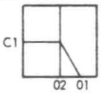
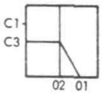
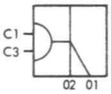
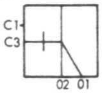
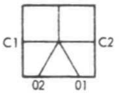
to facilitate the ready identification of the digital logic operators. The symbols defined in MIL-STD-806 (ref. 252) are shown in the digital logic cross-reference chart (table 13) along with abbreviated function descriptions.

DESIGN PROCESS

Fluidic circuit design can proceed at any level, depending on the complexity of the circuit involved. Complex circuits can be converted into Boolean functions and simplification techniques used to minimize the amount of circuitry involved. Minimization can be accomplished by computer techniques or, in the simpler cases, by the Veitch diagram or Harvard chart methods (ref. 253). The elementary form of the Boolean functions or operators may then be converted into standard digital logic operators and a circuit drawn using standard logic or fluidic device symbols (table 13).

Digital circuit theory is well established and can easily be applied to fluidic circuit design. However, where power drain is not particularly significant the design of simple digital circuits can be accomplished directly with fluidic device symbols. NOR logic can also be used to design simple circuits for many applications which can have economic advantages in that all of the connective logic can be accomplished with a single logic element (table 13).

TABLE 13.–*Digital Logic Cross-Reference Chart (ref. 1).*

LOGIC OPERATORS	AND	OR	NOT (INVERTER)	NOR	NAND	EXCLUSIVE OR	FLIP-FLOP
FUNCTION DESCRIPTION	OUTPUT IF ALL CONTROL INPUTS ARE ON	OUTPUT IF ANY CONTROL INPUT IS ON	OUTPUT ONLY IF INPUT IS OFF	OUTPUT IF ALL CONTROL INPUTS ARE OFF	NO OUTPUT IF ALL CONTROL INPUTS ARE ON	OUTPUT IF ONE OF TWO INPUTS IS ON	RETAINS OUTPUT CONDITION CORRESPONDING TO LAST INPUT
MIL-STD-806 SYMBOL			 (NEVER USED ALONE				
RELAY LOGIC							
BOOLEAN ALGEBRA OPERATOR	$(A)\cdot(B)$	$(A)+(B)$	$\overline{(A)}$	$\overline{(A)+(B)}$	$\overline{(A)\cdot(B)}$	$(A\cdot\bar{B})+(\bar{A}\cdot B)$	
NOR LOGIC							
FLUIDIC DEVICE SYMBOL							
TRUTH TABLE	C1 C3 01 0 0 0 1 0 0 0 1 0 1 1 1	C_1 C_3 01 0 0 0 1 0 1 0 1 1 1 1 1	C1 02 0 1 1 0	C1 C3 02 0 0 1 1 0 0 0 1 0 1 1 C	C1 C3 02 0 0 1 1 0 1 0 1 1 1 1 0	C1 C3 01 0 0 0 1 0 1 0 1 1 1 1 0	C1 C2 01 02 1 0 1 0 0 0 1 0 * 0 1 0 1 0 0 0 1 * 1 1 NOT VALID

*DEPEND ON PREVIOUS STATE

Glossary of Fluidics Terminology

Chapter 2 describes the contribution NASA has made in standardizing the terminology and symbology of fluidics. The definitions provided below are compiled from references 1, 3, 5, and 249.

Active–Adjective to describe an amplifying or switching device that depends upon a separate supply source of power in addition to the signal power.

Actuator–A component device or system that provides a mechanical actuation in response to some input signal.

Amplifier–An active device or component that provides a variation in output signal having a potential power level variation which is usually greater than that of the impressed input control signal variation. The variation in output signal bears a specified functional relationship to the input control signal variation.

Analog–Adjective to describe a general class of components or circuits in which all signals may vary continuously (as opposed to signals that may only vary in discrete increments).

Aspect ratio, nozzle (σ)–Ratio of nozzle depth to nozzle width.

Bandwidth–The operating frequency range of a device as defined by the minimum (usually zero or steady state) and maximum operating frequencies. An indication of maximum operating frequency is the frequency at which the output signal lags the control signal by 45° for a specified load and control amplitude.

Beam deflection amplifier–See jet deflection amplifier.

Bias–Magnitude of input signal to null or provide zero output signal for differential amplifiers; signal magnitude required to establish operating point for single-ended amplifiers.

Bistable–Of or pertaining to the general class of fluidic devices that maintain either of two position operating states in the presence or absence of the setting input.

Boundary layer amplifier–An amplifier that uses the separation-point control of a power stream from a curved or plane surface to modulate the output.

Capacitor–A passive fluid element that produces a pressure within itself that lags the inflow rate by 90° phase.

Circuit–An array of interconnected components and elements that performs a desired function; for example, an integrator, counter, or operational amplifier.

Closed amplifier–A fluidic amplifier that has no communication with an independent reference, i.e., the interaction region is not vented.

Coanda effect–The wall attachment phenomenon (see fig. 2).

Digital–The general class of devices or circuits whose output is a discontinuous function of its input.

Direct impact modulator–An impact modulator is a proportional fluid amplifier that uses two axially opposed power jets to provide a planar impact region. In the direct impact modulator, the control signal is applied concentrically around one of the power jets, moving the impact region away from that jet and towards the unsupplemented jet. This results in increased output flow and pressure with increased control pressure, so the direct impact modulator is a positive-gain device (see fig. 78).

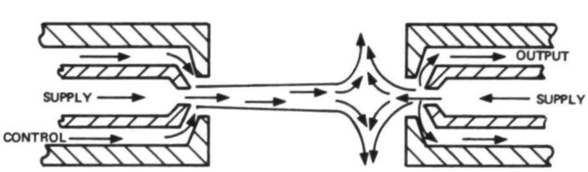


FIGURE 78.–Direct impact modulator (ref. 1).

Double-leg elbow amplifier–A proportional boundary layer amplifier with two output ducts.

Edgetone amplifier–A high-speed planar flip-flop in which the power jet impinges upon a wedge and oscillates stably along one side of the wedge until a control signal causes it to switch the flow. In operation it is very similar to a wall attachment amplifier except that it requires much less control power to switch and it switches much faster.

Element–The general class of devices in their simplest form, used to make up fluidic components and circuits; for example, resistors, capacitors, flip-flops, and jet deflection amplifiers.

Fan-in–The number of control signals (push-pull or single-ended) accepted by a logic gate, which can effect the desired change in state of the logic gate.

Fan-out–The number of components that can be driven by a single component; all components are to be operated at the same supply pressure. Also, components are to be of similar size and have similar switch points. Fan-out value relates to steady state operation unless the corresponding frequency is given.

Flip-flop–A bistable flueric component (reset-set) that changes state with the proper reset-set input of sufficient amplitude and width. It exhibits "memory" (remains in a particular state) once it has switched, without requiring a continual input signal.

Flow amplifier–An amplifier designed primarily for amplifying flow signals.

Flow diverter–A digital flueric amplifier with no memory; designed primarily for high-pressure recovery. It operates on the jet interaction principle.

Flow recovery, output–The maximum output mass-flow rate divided by the supply mass-flow rate. Generally given as the percentage.

Flueric–An adjective sometimes applied to those fluidic components and systems that perform sensing, logic, amplification, and control functions, but which use no moving mechanical elements whatsoever to perform the desired function.

Fluerics–The area within the field of fluidics in which fluid components and systems perform sensing, logic, amplification, and control functions without the use of moving mechanical parts.

Fluidic–An adjective denoting a device or system in which some sensing, control, signal processing (logic), and/or amplification functions are performed through the use of fluid dynamic phenomena (no moving mechanical parts).

Fluidic component–A fluidic device, distinguished from an element by virtue of the fact that it is composed of more than one element.

Fluidic element–See element.

Fluidics–The general field of fluid devices and systems and the associated peripheral equipment used to perform sensing, logic, amplification, and control functions.

Focused jet amplifier–A negative-gain device that uses a combination of wall attachment and jet interaction phenomena.

Frequency response–Usually given in the form of frequency response curves of the variation of output/input amplitude ratio and phase as a function of frequency.

Gain, flow (analog)–Average gain; the slope of a straight line drawn through an input flow versus output flow curve, so that deviations from the measured curve up to the maximum output level are minimized. Deviations should be based on net area. If other than maximum output level is used for the average gain definition, the range should be noted. Measured curve is to be for either low output pressure recovery (resulting from instrumentation) or a value that provides maximum flow gain.

Gain, flow (digital)–Ratio of output flow change to input flow change (from quiescent) required for switching to occur.

Gain, flow (incremental, analog)–The slope of the output flow versus the input flow curve at the operating point of interest.

Gain, power (analog)–Average power gain; ratio of the change in output power to the change in input power; the average value over operating range up to maximum output level unless the range is stated.

Gain, power (digital)–Ratio of the change in output power to the change in input power (from quiescent) for switching to occur.

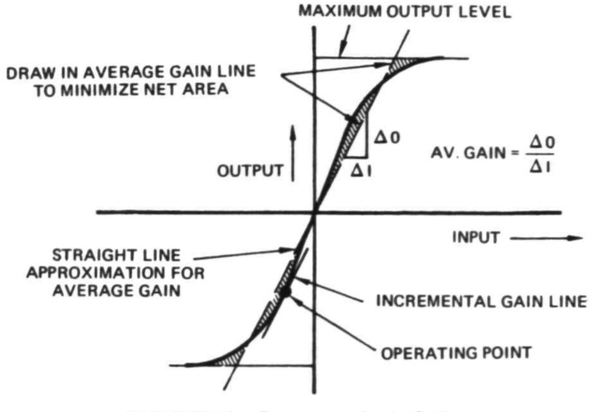


FIGURE 79.–Pressure gain (ref. 5).

Gain, power (incremental, analog)–The slope at the operating point of an input/output power curve.

Gain, pressure (analog)–Average gain; the slope of a straight line drawn through a measured input pressure versus output pressure curve so that deviations from the measured curve up to the maximum output level are minimized. Deviations should be based on net area. If other than the maximum output level is used for the average gain definition, the range used should be noted. Gage pressure values should be used. The measured curve is to be for either zero output flow or a value that provides maximum pressure gain (see fig. 79).

Gain, pressure (incremental, analog)–Incremental gain; the slope of the measured input pressure versus output pressure curve at the operating point of interest (see fig. 79).

Gain, pressure (digital)–Ratio of measured output pressure change to input pressure change (from quiescent) required for switching to occur. All control ports except the one under consideration should be maintained at the quiescent pressure level. Output flow should be zero or a value that results in maximum pressure gain. If gain value is for other than steady state conditions, the test frequency should be stated.

Gate–A single fluidic element.

Hydraulic diameter–The ratio of the cross-sectional area of a flow passage to one-fourth the wetted perimeter of the passage.

Hysteresis, analog amplifier–Total width of hysteresis loop expressed as a percent of peak-to-peak saturation input signal. Measurements must be at frequencies below those where dynamic effects become significant (see fig. 80). Measurements to be made at the widest point on the curve.

Hysteresis, digital amplifier–Width of the hysteresis loop as measured on an input/output curve and expressed as a percentage of the supply conditions; for example, flow hysteresis is the hysteresis loop width (measured on an input/output flow curve), divided by the supply flow (see fig. 81).

Impact modulator–A fluidic amplifier in which the impact

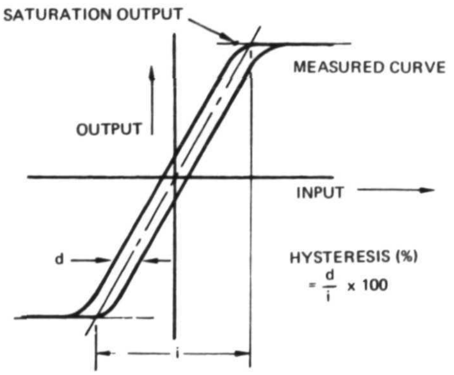


FIGURE 80.–Analog amplifier hysteresis (ref. 5).

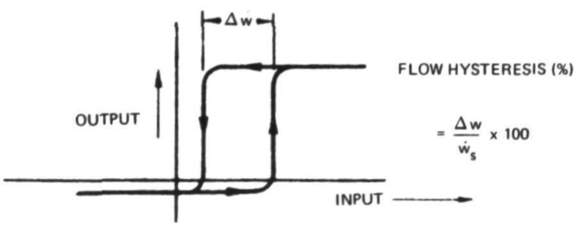


FIGURE 81.–Digital amplifier hysteresis (ref. 5).

plane position of two opposed streams is controlled to alter the output.

Impedance, input–The ratio of pressure change to flow change measured at an input port. Numerical value may depend on operating point, since input pressure-flow curve may not be linear. For active elements, the power source should be connected for measurements.

Impedance, output–The ratio of pressure change to flow change, measured at an output port. Numerical value may depend on operating point, since output pressure-flow curve may not be linear.

Induction amplifier–A bistable device similar to a wall attachment amplifier but with control jets entering tangential to the supply flow in the interaction region, therefore requiring that control flow be applied to the side opposite that to which the jet happens to be attached to induce switching.

Inductor–A passive flueric element which, because of fluid inertance, has a pressure drop across it which leads the through flow by 90° phase.

Interface–A point or component where a transition is made between medium, power levels, modes of operation, etc.

Interface device–A device that provides the interface between one medium (i.e., fluid) and another (i.e., electrical), such as a pressure switch, solenoid valve, pushbutton, transducer, etc.

Jet-deflection amplifier–An analog amplifier that uses a control jet to deflect a fluid power jet for the functional operating principle (see fig. 78).

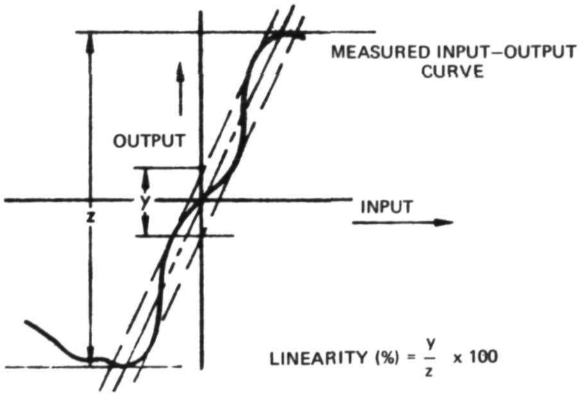


FIGURE 82.–Output linearity (ref. 5).

Linearity deviation, output–Deviation of the measured curve from the straight-line average gain approximation; the ratio of the deviation to the peak-to-peak output range (range should be stated if other than maximum output level) expressed as a percentage (see fig. 82).

Logic elements (also logic gates)–The general category of digital components that provide logic functions; for example, AND, OR, NOR, and NAND. They can gate or inhibit signal transmission with the application, removal, or other combinations of input signals.

Memory–The capability of a logic gate to retain the state of its output signal corresponding to the most recently applied control signal after the control signal is removed.

Passive–The general class of devices that operate on the signal power alone.

Power amplifier–An amplifier designed primarily to provide maximum power gain.

Pressure amplifier–An amplifier designed primarily to amplify pressure signals.

Pressure recovery, output–The difference between the maximum output pressure and the local vent pressure divided by the difference between the supply pressure and the pressure in the interaction region. For closed amplifier, the control port pressure should be used as the reference pressure.

Rankine–An absolute temperature scale on which the unit of measurement equals a Fahrenheit degree; freezing point of water is 491.69° and the boiling point is 671.69°.

Relaxation oscillator–A basic wall attachment oscillator incorporating a lumped resistance-capacitance-resistance network in the feedback loop to reduce sensitivity to temperature and pressure changes.

Resistor–A passive fluidic element which, because of viscous losses, produces a pressure drop as a continuous function of the flow through it.

Response time–The time interval between the application of an input step signal and the resulting output signal. The time measurement for the response to the input step signal is to be made when the output signal reaches a level that is 63 percent of the final output value (see fig. 83).

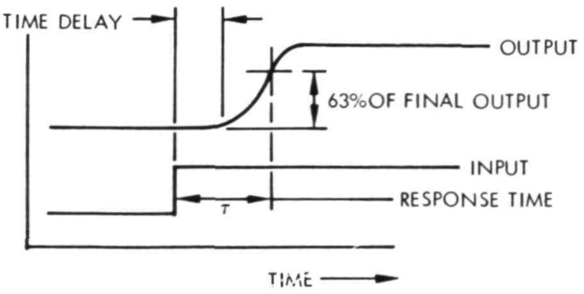


FIGURE 83.–Response time and time delay (ref. 5).

Reynolds number–A dimensionless parameter of fluid flow that often indicates the ratio of inertial-to-viscous forces:

$$N_R = \frac{\bar{u} d_h}{\nu}$$

where d_h = hydraulic diameter, $\bar{u}$ = mean velocity of the fluid, and ν = kinematic viscosity.

SI–An abbreviation indicating the international system of units.

Saturation–The maximum output value regardless of input magnitude (see fig. 84).

Sensor, fluidic–A fluidic device that senses a basic quantity such as rate, position, acceleration, pressure, or temperature, in terms of a fluid quantity such as pressure or flow rate.

Signal-to-noise ratio (SNR) (analog amplifier)–Ratio of maximum (saturation value) output signal amplitude to maximum noise amplitude (at output). Signal and noise data should be r.m.s. values.

Signal-to-noise ratio (digital amplifier)–Ratio of the amplitude of the output signal to the peak-to-peak maximum noise signal. Maximum noise signal is to be measured when the port is active and inactive. The greater value of the two is used in calculating the SNR.

Stream deflection amplifier–See jet deflection amplifier.

Transducer–A device that converts signals from one medium to an equivalent signal in a second medium.

Time delay–The time from the initiation of an input signal until the first discernible change in the output caused by this input signal (see fig. 83).

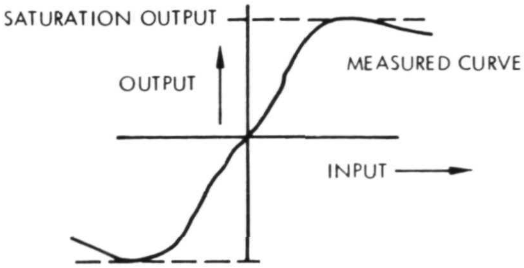


FIGURE 84.–Saturation (ref. 5).

Transport delay–Time required for a fluid particle to travel from the input control port region to the output receiver region.

Transverse impact modulator–An impact modulator is a proportional fluid amplifier that uses two axially opposed power jets to provide a planar impact region. In the transverse impact modulator, the control signal is applied perpendicular to one of the power jets, moving the impact region towards that jet and away from the unimpaired jet. This results in reduced output flow and pressure with increased control pressure, so the transverse impact modulator is a negative-gain device.

Truth table–A table depicting the function of a logic element; all possible combinations of input signals are tabulated along with the corresponding state of the output signal.

Turbulence amplifier–A fluidic component in which the power jet is at a pressure in the transition region of laminar stability. The power jet can become turbulent by a secondary jet, an acoustic signal, or a physical interruption of the power jet, thus changing the state of the output (see fig. 53).

Vented amplifier–A fluidic amplifier that uses vents to establish a reference pressure in the interaction region.

Vortex amplifier–A fluidic amplifier that utilizes the pressure drop across a controlled vortex for the modulating principle (see figs. 1, 46, 51).

Wall attachment amplifier–A digital amplifier that uses jet attachment to a wall (the Coanda effect) for the basic operating principle (see figs. 2, 41, 42).

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