FLUIDICS

A NEW TECHNOLOGY

BY

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Introduction

A new technology has recently been developed in the field of control systems and is expanding, particularly in the U.S.A., at an astounding rate. It will undoubtedly in many existing applications replace pneumatic, electric, and electronic control systems. It also makes possible control systems which would not have been contemplated by conventional means. The object of this article is to acquaint the reader with a general picture of the field of fluidics and some of the possible applications.

Historical

The modern development of this technology began only as recently as 1959 in the then Diamond Ordnance Fuze Laboratory (now Harry Diamond Laboratory) in Washington D.C., U.S.A. This is a U.S. Government Laboratory directed by the U.S. Army Matériel Command. As a result of a casual discussion between Dr. R. E. Bowles and B. M. Horton on some work by Bowles in the realm of fluids in motion—it was associated with vacuum cleaners and fire-fighting equipment—came a suggestion by Horton to use control jets. From this idea was born the concept of fluid amplification, and the potential applications of such devices and systems was envisaged.

Working in their homes, these two engineers, together with R. W. Warren another engineer from the Laboratory, soon developed designs for some of the basic devices. With these designs the inventors were able to obtain U.S. Army support for research and development effort in the Laboratory. During the period 1959 to 1964, Horton secured two patents for these basic devices and Bowles and Warren a single patent. These three patents cover the whole field of fluidics and although the patents have been challenged in a series of proceedings in the U.S.A. the patents have been upheld.

In 1961 Bowles left the Laboratory and set up his own firm (Bowles Engineering Corp.) to specialize in Research and Development in fluidics. The firm purchased the rights from the three inventors and now issues licences to reputable manufacturers for the use of the devices. The U.S. Government enjoys a royalty-free benefit in each of these patents.

One of the basic patents concerns the effect of adjacent walls on a jet stream. The fundamental work on this phenomenon was carried out in 1932 by Professor Henri Coanda. Called the Coanda Effect this phenomenon involves the tendency for a fluid stream emerging from a throat area and moving past a wall to bend and to attach to the wall. Coanda found that applying a small pressure at right angles to the jet stream close to the point of attachment, the jet would detach from the wall. This work by Coanda is one of the keys to modern fluidic technology and his contribution as such was recognized when he was invited to be a Guest of Honour at a Fluidic Amplification Symposium held at the Harry Diamond Laboratories in Washington in October 1965.

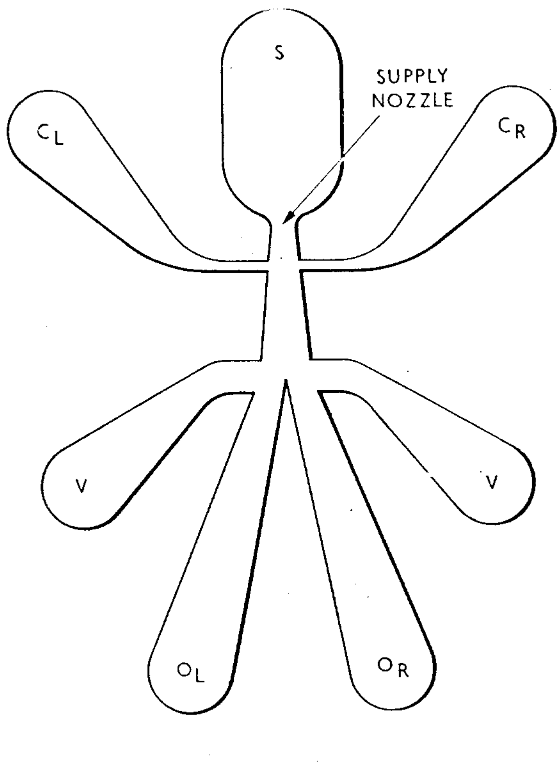

FIG. 1—BI-STABLE JET AMPLIFIER

The Name 'Fluidics'

The name Fluidics is now the generally-accepted name for this technology, although Flueonics (c.f. Electronics) and Solid State Pneumatics have been contenders. A possible definition would be: 'The use of fluids in motion, either gaseous or liquid, to perform functions such as sensing changes in physical environments, logic, computation, and amplification and control of power. The control system resulting from a combination of these functions to be one in which there are in general no moving parts'.

In some applications a more practical system and a simpler solution to a problem can be obtained if occasional use is made of a conventional sensor or actuator. This has led to the use (by purists) of the term Fluerics to mean systems with absolutely no moving parts at all, and the name Fluidics to cover the general technology.

Basic Devices

Bi-Stable Jet Amplifier

A Bi-Stable Jet Amplifier is shown in FIG. 1 as a simplified profile. In this device a jet of fluid emerging from the supply nozzle attaches itself to either the left or right wall and the fluid output from the device is from the left (O_L) or right output ports (O_R). The attachment of the fluid to the boundary wall is by a pressure differential. This attachment is broken if pressure is supplied to the control port adjacent to the jet (C_L or C_R). The fluid stream is then diverted into the opposite output leg and the jet attaches to the opposite wall. The jet will stay attached to a wall even though no control signals are present. This device is thus a 'flip-flop', or relay, which will operate in either of two stable states. It should be noted therefore that this device has a memory in that it will remain 'as set' in response to the last signal. The device is also an amplifier in that the control pressure required to switch the jet is only about 5 to 10 per cent of the supply pressure, while the recovery pressure is about 50 per cent of the supply pressure. These figures are very broad averages using air as the fluid, and do to some extent depend upon size.

Normally these devices can be regarded almost entirely as two-dimensional, the aspect ratio, i.e., depth of supply nozzle to width of supply nozzle, always being less than unity, and as the usual construction is either to engrave or chemically etch the pattern in the material used, the depth of flow passages remains constant. The material used for constructing these devices depends upon the use they are to receive. For ordinary laboratory experiments they may be made in perspex or some similar material. For dimensional stability, particularly when dealing with very small sizes, it is more convenient to chemically

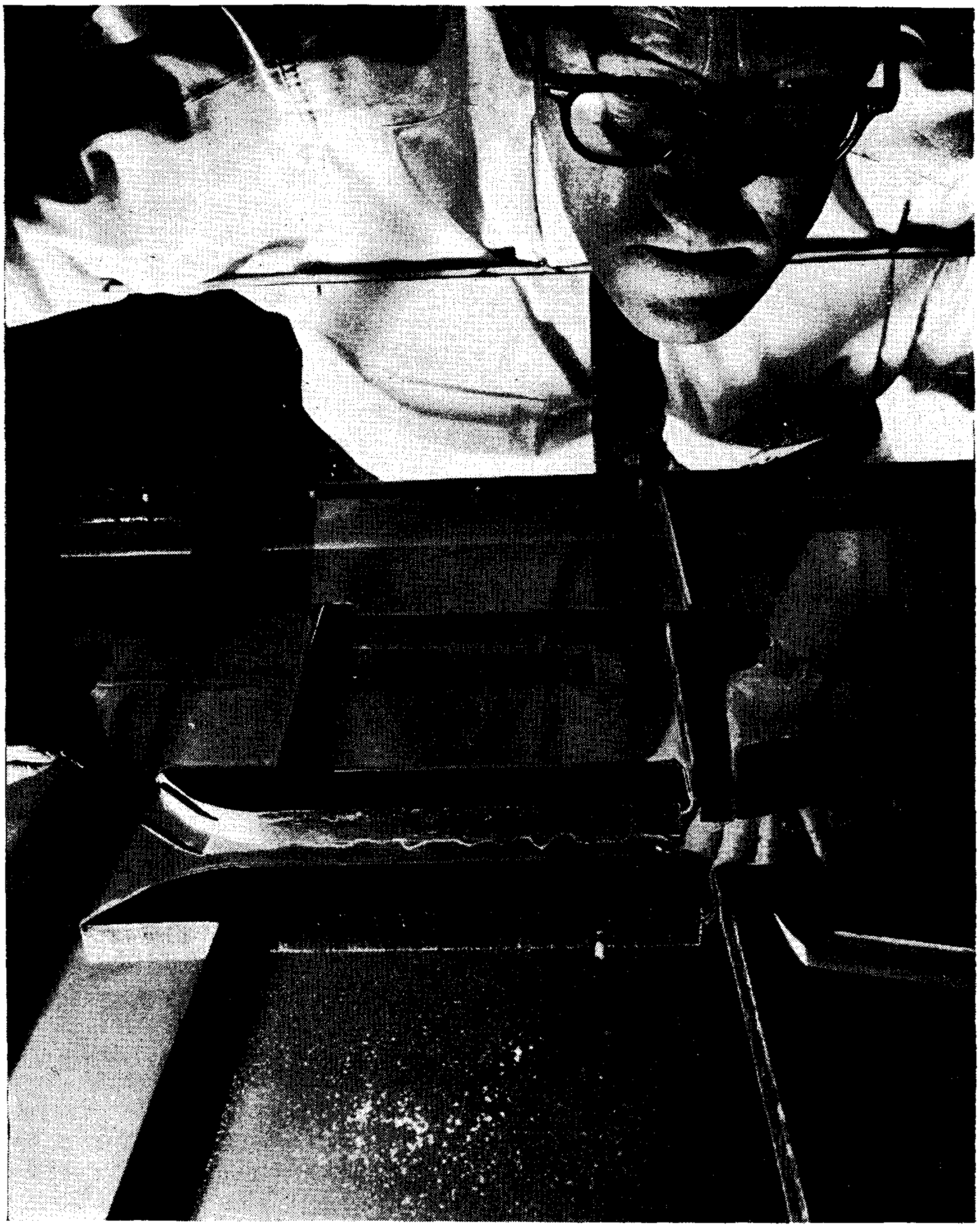

FIG. 2—WATER TABLE

etch on glass or metal, while if the fluid being used is to be a hot exhaust gas it is necessary to make them in a heat resistant steel.

The size of these units varies enormously. For research in a laboratory on the basic devices, it is usual to use a water table. FIG. 2 shows flow through a bi-stable amplifier being examined on a water table, in this case by the introduction of bubbles. Alternatively, spots of dye injected by a hypodermic syringe may be used to aid visualization of the flow pattern. This permits developments of components. It is also possible with these laboratory results to scale them down and calculate the results obtained with air as the fluid. With air, a device as large as 54 in. × 38 in. × 11 in. has been produced, while at the other end of the scale it is possible to have units where the overall size is $\frac{1}{4}$ in. × $\frac{1}{4}$ in. × $\frac{1}{8}$ in. and the air passages only 0·005 in. in depth.

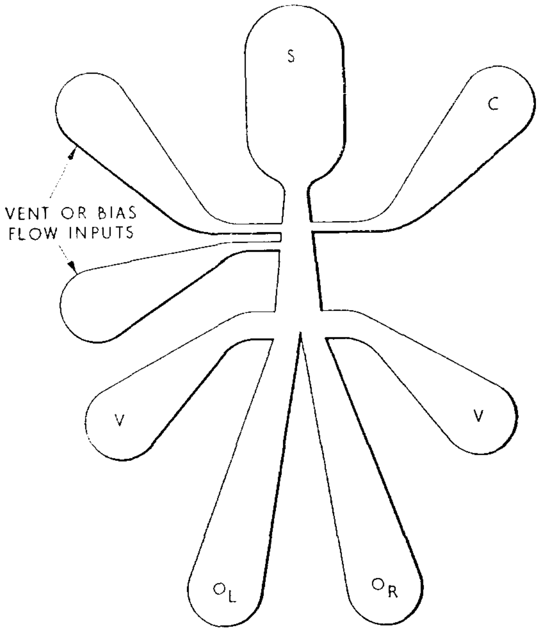

FIG. 3—MONO-STABLE JET AMPLIFIER

Mono-Stable Jet Amplifier

A mono-stable jet amplifier is shown in FIG. 3. This is almost exactly the same as the bi-stable amplifier, except that it is stable only when attached to one wall. This is achieved by providing either a bias flow or a vent which prevents the jet attaching to one wall. This again is a fluid switch, or 'flip-flop'. If a control signal is applied, the fluid jet will be diverted from one output port to the other. Removal of the control signal will cause the jet to return to the mono-stable position. Being a NOR element, or interlock, this device is the heart of many digital logic combinations, including the NOT, OR, EXCEPT and AND elements, which it is well known can be built up from NOR elements.

The switching time of both the bi-stable and mono-stable amplifiers is remarkably high. It does depend upon size and fluid used, but with air and a unit $1\frac{1}{2}$ in. × 1 in. approximately in overall size, the switching time is of the order of 0·5 milliseconds.

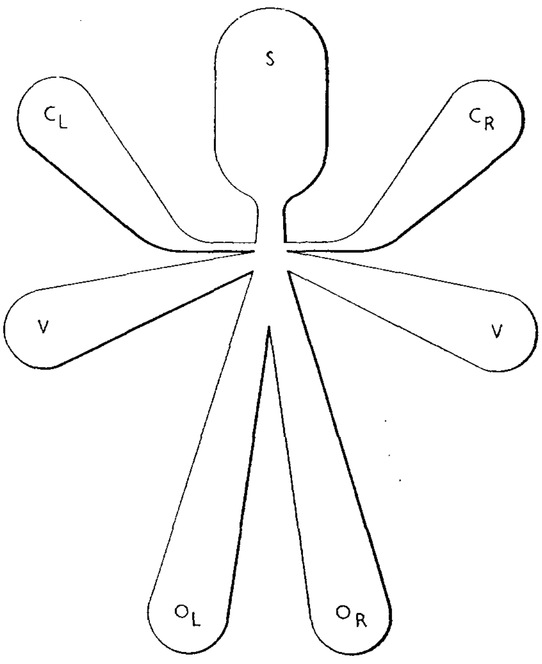

FIG. 4—JET DEFLECTION OR PROPORTIONAL AMPLIFIER

Jet Deflection or Proportional Amplifier

A jet deflection or proportional amplifier is shown in FIG. 4. In appearance it looks the same as in FIG. 1. This device is so designed, however, that, in the mixing area of the supply and control jets, wall attachment has no effect. Close inspection of FIG. 4 will show that this mixing area is in the area of venting of the device, and in the absence of side walls. The object of the design is to obtain outputs that are proportional to the control pressures. The characteristics of a proportional amplifier using air are shown in FIG. 5. From this it will be seen that the supply port was 0·010 in. × 0·030 in. in size, the supply pressure could be between 10 and 50 lb/sq in., the control pressure was between 0 and 5 lb/sq in. and the gain of the amplifier was 8·55.

Fluid Oscillators

A typical profile of a basic oscillator is shown in FIG. 6 together with schematic arrangements of the two basic configurations of oscillators. In configuration

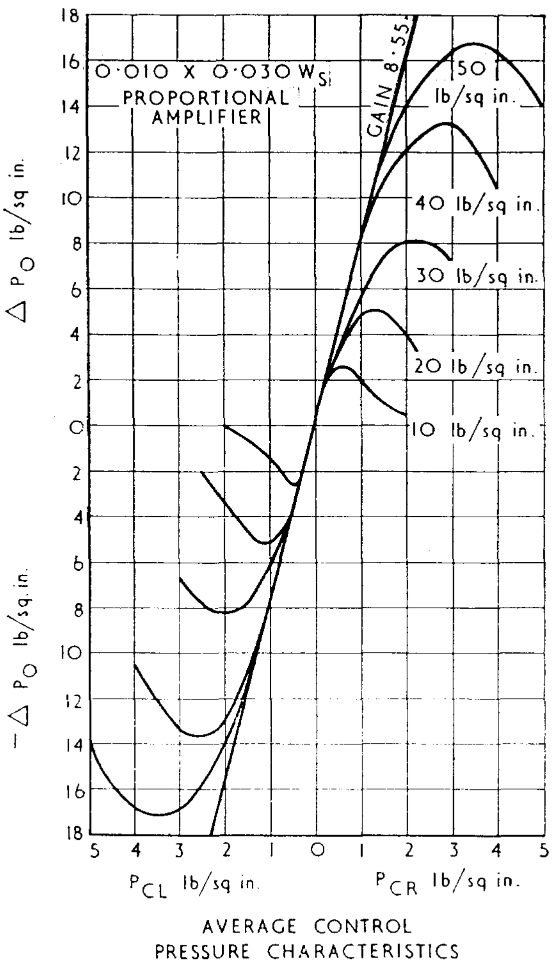

FIG. 5—CHARACTERISTICS OF A PROPORTIONAL AMPLIFIER

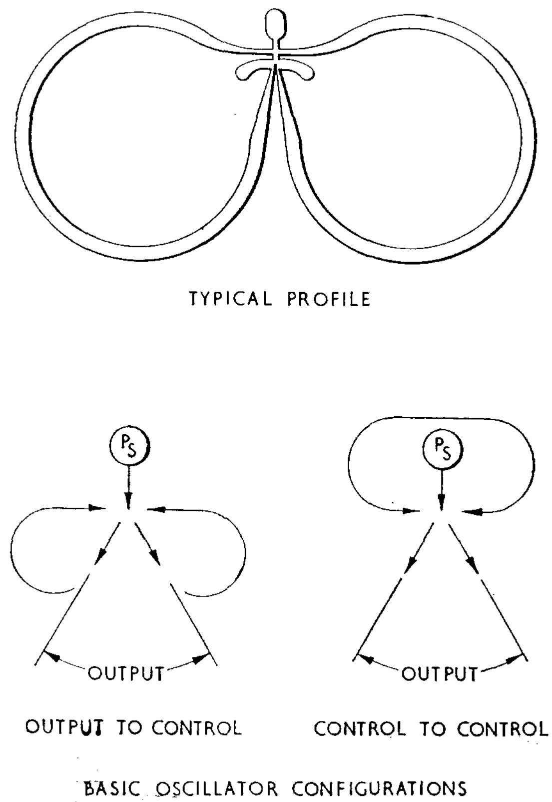

FIG. 6—A FLUIDIC OSCILLATOR AND BASIC CONFIGURATIONS

output to control, it will be seen that tappings have been brought back from the outputs to the control ports. As a result any flow in one output leg produces a control signal which will change the output to the opposite output leg. The device will thus oscillate and although these are 'flows', it only requires a pressure pulse through the connecting channels to effect a change. In configuration control to control, the attachment of the jet to one wall causes a reduced pressure in the vicinity of the control port. This is sufficient to result in a pressure difference between the control ports which will result in a reversal of the jet stream.

The frequency of such an oscillator will depend upon:

(*a*) The characteristics of the device and the delay line

(*b*) The properties of the fluid.

If the path connecting the output to control (delay line) was doubled in length the frequency would be approximately halved. The propagation of a pulse through a fluid occurs at the speed of sound in that fluid. Thus if the density of the fluid changes, the speed of sound and the rate of propagation of a pulse also changes. Thus in the case of the oscillator the frequency will change as the density changes. FIG. 7 shows the characteristics of a fluid oscillator when used in an application for measuring temperature. In this application the gas (the temperature of which it is desired to measure) is passed through the oscillator as the working fluid. The frequency of oscillation will thus vary with the temperature of the gas.

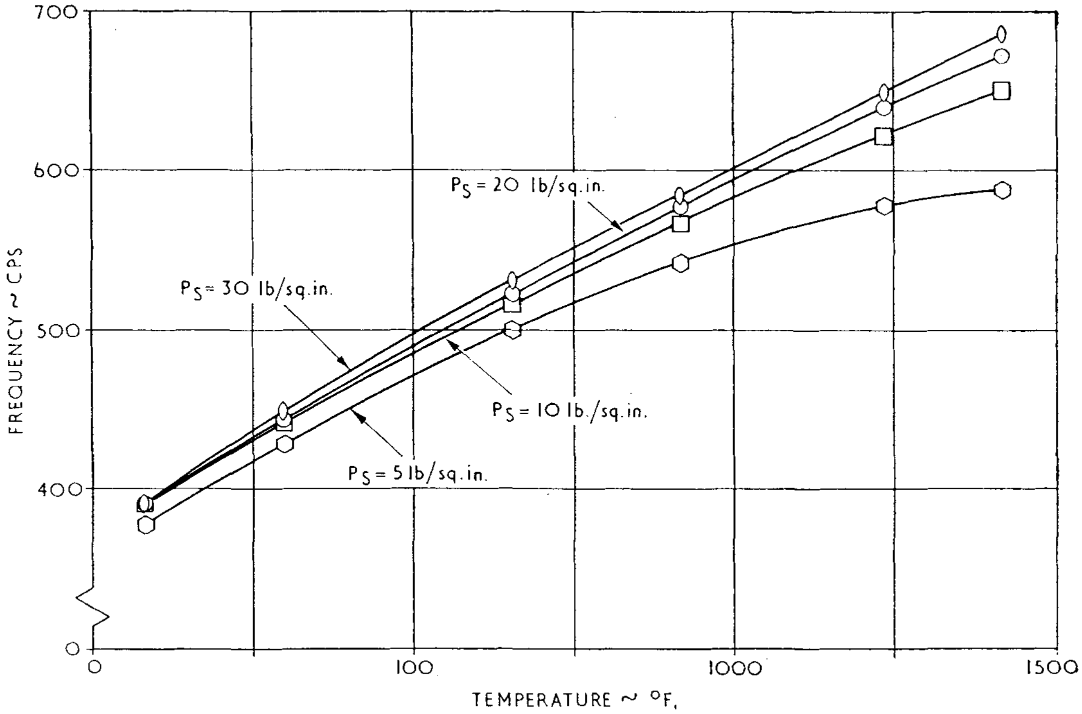

FIG. 7—CHARACTERISTICS OF A FLUIDIC OSCILLATOR IN A TEMPERATURE SENSOR APPLICATION

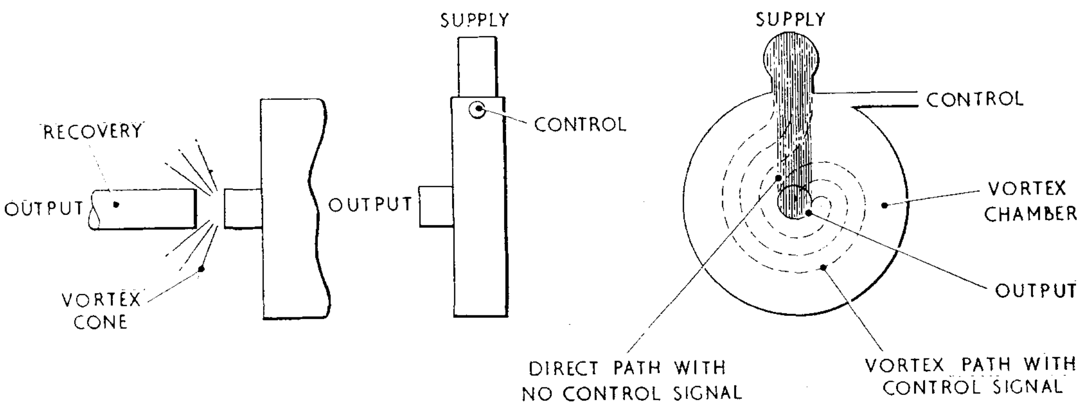

FIG. 8—VORTEX AMPLIFIER

Vortex Amplifiers

Vortex amplifiers work on entirely different principles from those previously mentioned, a diagrammatic arrangement being shown in FIG. 8. In this device the supply fluid passes through a vortex chamber and emerges from a central output duct. In the absence of any control signal the fluid has no rotational velocity and the fluid leaves the centre duct as a solid jet. The characteristic of the device is then simply that of an orifice in a pipe line. If, however, a control jet is introduced tangentially to the supply jet, then the flow follows a spiral path inwards to the output duct. The tangential velocity of the fluid increases considerably as the radius decreases due to the conservation of angular momentum. The impedance of the vortex so formed is greater than that of the direct path so that the total flow from the exit duct decreases as the control flow increases. With this arrangement it is not possible to decrease the output flow to zero as it must include the control flow. This is, however, a small proportion of the supply flow. The supply flow can be reduced to zero as can be seen in the characteristic of such a device shown in FIG. 9.

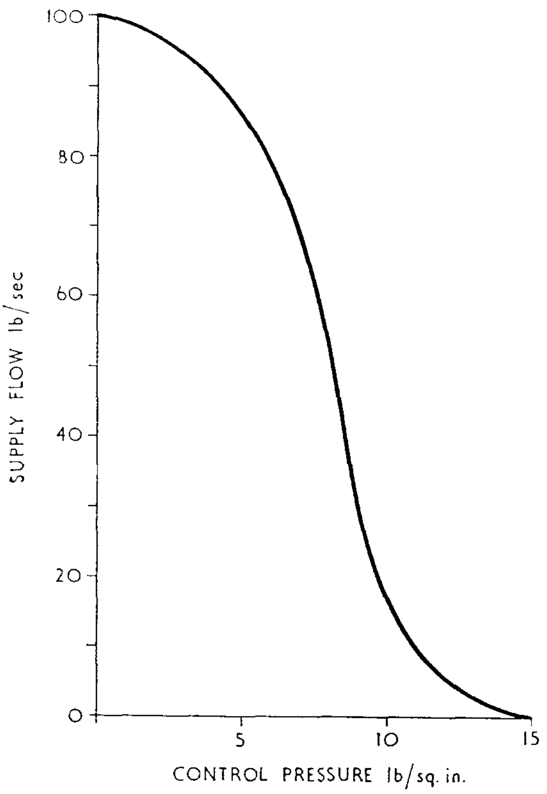

FIG. 9—CHARACTERISTICS OF A VORTEX AMPLIFIER

Zero output flow can be achieved if a break in the output duct is arranged close to the vortex chamber. With this arrangement, at low throughput the fluid emerges in a vortex cone, similar to an oil fuel sprayer, and there is thus no recovery in the output duct. This is also shown diagrammatically in FIG. 8. Vortex amplifiers are particularly suitable for controlling large powers and are analogous to a mechanical valve controlling the flow of fluid in a system.

Turbulence Amplifiers

Turbulence amplifiers are much simpler to understand than the previously described devices. A diagrammatic arrangement of one is shown in FIG. 10. These devices are principally used as logic units and, as can be seen from FIG. 10, a signal at any one of the control jets will cause turbulence inside the amplifier and result in no output. It is therefore a multi-input NOR element from which the other logic combinations can be made up and in this respect it is similar to the mono-stable jet amplifier. It is usual for these devices to be tubular in construction and about $\frac{3}{8}$ in. diameter and about $1\frac{1}{2}$ inches in length.

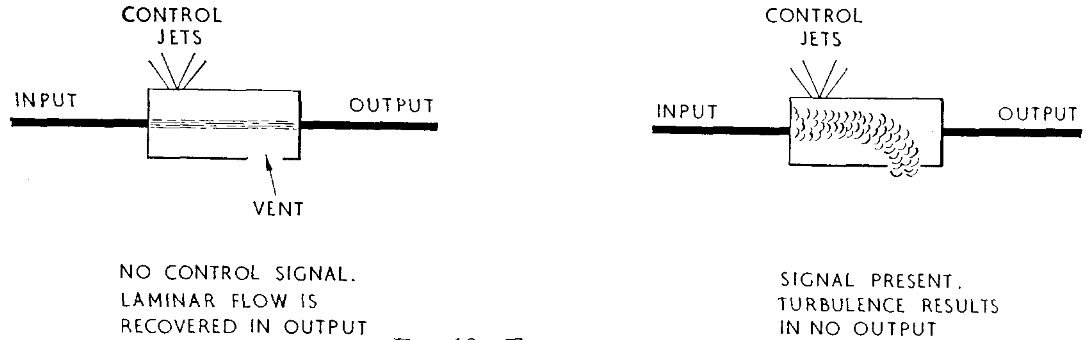

FIG. 10—TURBULENT AMPLIFIER

Amplification is obtained from this device by the fact that the power needed to turn off the device is much less than the power output, and that in a logic system the output from one can be used to control up to six others. The supply pressure is normally about 8 to 12 inches of water and the recovered output about 4 inches of water. The input pressure required at the control jet to 'turn off' the device is less than $\frac{1}{2}$ in. of water. The time required to 'turn off' the device is about 2 milliseconds and the time to 'turn on' about 5 milliseconds. Thus cycles can be anything down to 7 milliseconds' duration.

Developments of Basic Devices

It is possible with the basic devices described above to cascade them, and use the output from one device to be the control input to the next device. By such

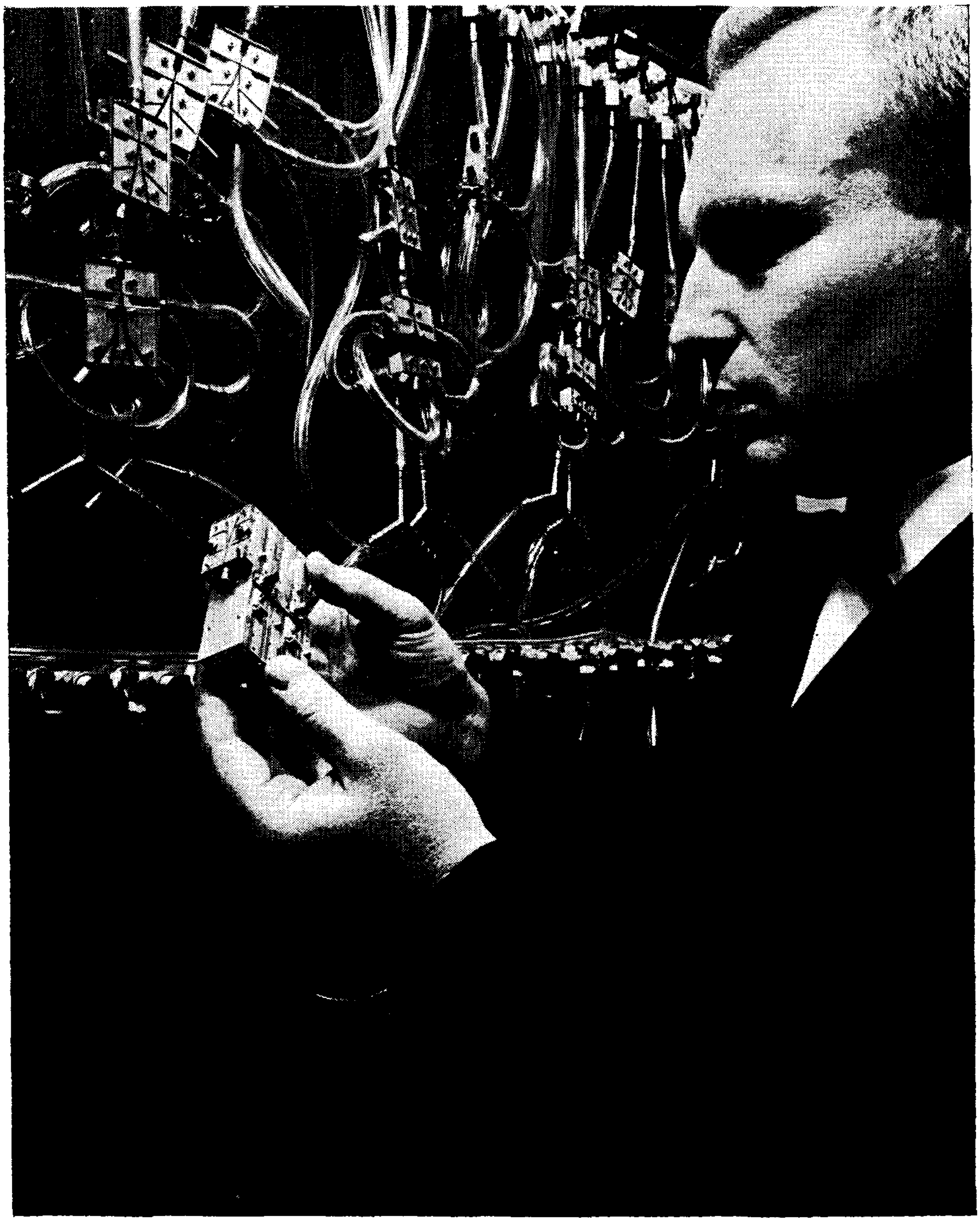

FIG. 11—A FLUIDIC BREADBOARD ARRANGEMENT

means considerable power amplification can be obtained, The control system designer's problem is therefore to string together the basic devices into a workable system. The problem is exactly analogous to the electronic designer's problem. The basic devices, amplifiers (transistors), fluid resistor (resistors), volume chambers (capacitance), are all available as components. The circuits employed in analogue control systems may be either direct-flow systems (D.C.) or pulsed flow systems (A.C.), while the logic systems can be regarded as simple on/off systems where the exact level of signal is not important (relay interlocks). Designers of the complex analogue systems used for applications such as speed control of engines are already involved in amplitude modulation (AM) and frequency modulation (FM) as techniques. The problems of electronics are also present in these circuits namely: noise, which can be self-generated, and drift.

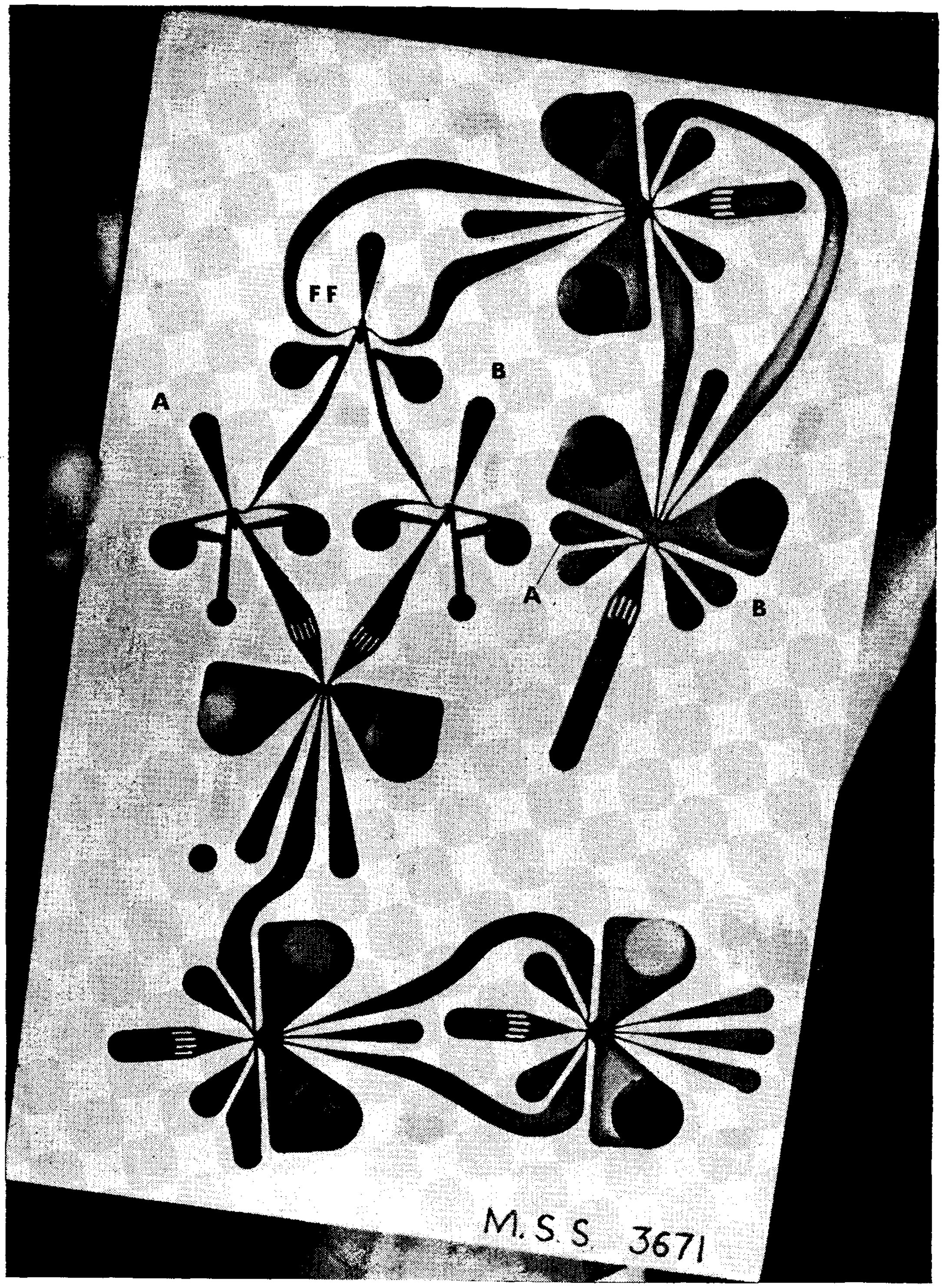

FIG. 12—INTEGRATED CIRCUIT PLATE

The correct sizing of components is important, and due regard must be paid to the venting arrangements to prevent back pressures affecting the performance of other components.

It is also possible for the basic devices to be purchased as components, to be strung together with plastic tubing, and the 'breadboard' design of a system produced. Certain firms are now offering a service to purchasers of their components, in that they will produce an integrated circuit from an initial 'breadboard' arrangement. Shown in FIG. 11 is a 'breadboard' arrangement of a four-bit

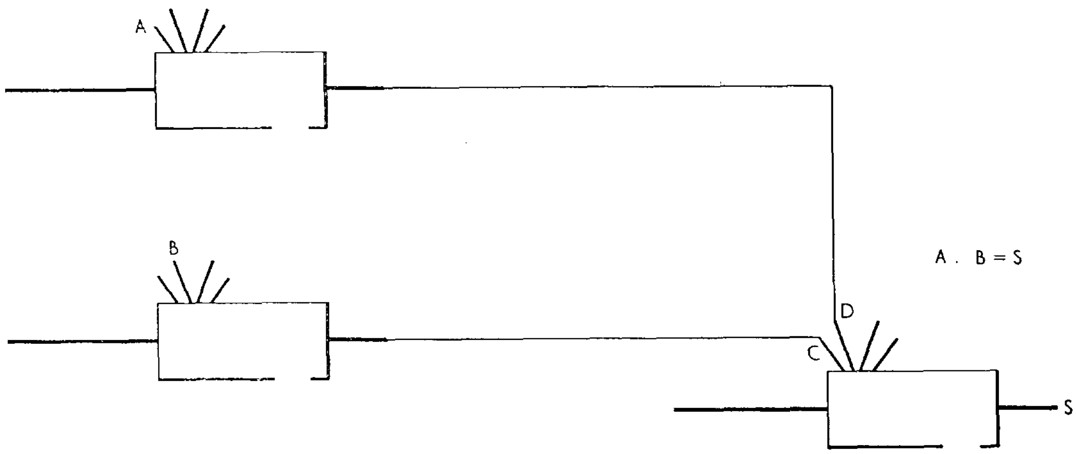

FIG. 13—TURBULENT AMPLIFIERS AND LOGIC STATE AND

binary counter together with the final packaged version. The packaged version uses smaller amplifiers with jet dimensions of 0·020 in. × 0·040 in.

FIG. 12 shows an integrated circuit plate and is a typical example of fluidic circuitry. This direct-flow circuit determines which of two signals is the minimum signal and amplifies that signal. The circuit works as follows. Signal A is applied to the power nozzle of one of the two OR gates and to one of the control nozzles of the initial stage of a two-stage analogue amplifier. Signal B is also applied at two similar locations. The output of the two-stage amplifier, which is proportional to the difference between these two signals, drives a flip-flop (FF). The larger of the two signals determines the state of the flip-flop and drives the OR-gate switch on the side of the maximum signal to the 'off' position. The next element after the OR gate therefore receives only the minimum input signal, which is amplified by the final two-stage amplifier to bring the circuit to the desired gain. These circuit plates form the basis of amplifier modules, which consist of either a single or multiple stacked circuit plates so engineered to present a uniform presentation of inputs and outputs. In the general concept these modules are similar to the amplifiers used in certain electronic computers. In a similar manner they can be inserted into racks or cabinets and form a compact control system.

This circuit (FIG. 12) could be used, for example, in a boiler control system where it is desired to limit the fuel entering the boiler to be proportional to the minimum of either the air flow being produced by the blower or the desired fuel signal. Such a system ensures that on increasing power, when the blower lags, only the fuel proportional to the air supply present is fed into the boiler, while on decreasing power the fuel follows the desired value signal and is always less than the air supply present. This type of system is quite common in commercial boiler control systems with conventional controls components.

A simple example of logic using turbulence amplifiers is shown in FIG. 13, in which basic NOR elements have been used to produce an AND gate. Here, in order that the output S is obtained, both the control signals A and B must be present. (In logic terminology A.B = S.) This circuit might well be employed in controlling a machine operation where the power operator, controlled by S, is not allowed to function until both the safety guards are closed as indicated by control signals A and B.

Applications of Fluidics

In the U.S.A. the money necessary for the development of fluidics and the application of this technology to hardware problems has almost entirely come from the U.S. Government. This has been both in the form of pure research contracts and also to develop hardware applications. The money spent is very

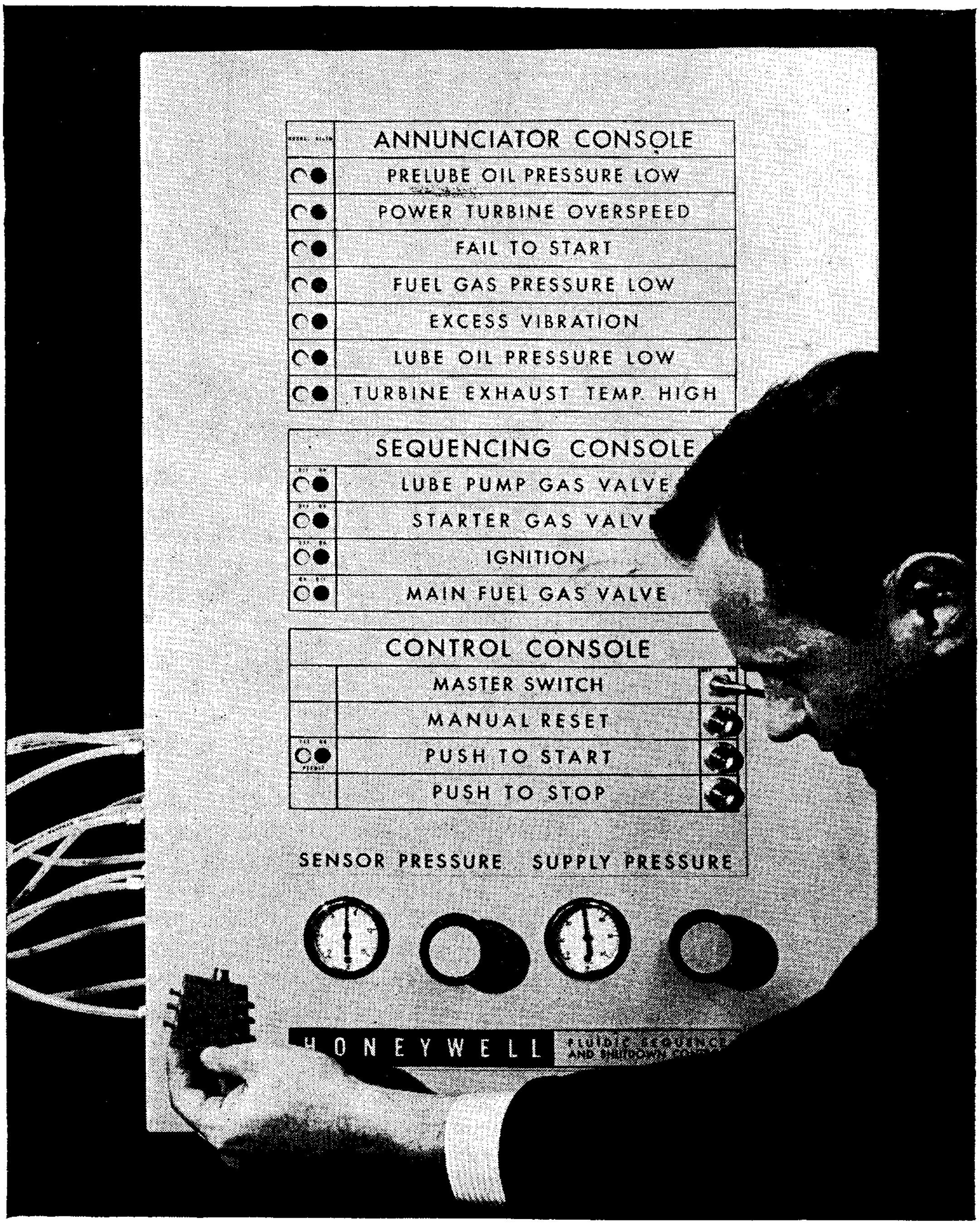

FIG. 14—AUTOMATIC SEQUENCE STARTING PANEL

large by U.K. standards. Honeywell, for example, have a $2·7 million contract for jet engine control. The exact amount spent each year in the U.S. is not known as it is hidden in defence projects. In 1964, the total market was only some $14 million. It is confidently predicted, however, that the gross market in 1970 will be of the order of $200 million. A few of the more interesting projects which have been published will be briefly described in the following paragraphs.

Boiler Control

At the U.S. Navy Boiler and Turbine Laboratory in Philadelphia the existing automatic control systems on water level, fuel and air have been replaced by fluidic control systems. The project is still under development but it is anticipated that control equally as good as from conventional systems will be obtained.

Gas Turbine Control

Control systems for gas turbines have been produced which will control the speed, thrust, inlet guide vanes and gas inlet temperature of jet engines. This work is leading to an aircraft control system which is completely integrated with the engine control. Sensors to determine aircraft altitude and stalling speed will all be linked to the engine controls.

Aircraft Pitch-Rate Control

In 1963 the pitch rate gyro system in a light aircraft was replaced by all-fluidic system. The sensor used was on the same principle as the vortex amplifier already described. In this application there were no control ports and the supply fluid entered the vortex chamber over the whole of its 360 degrees periphery through a porous wall. Under normal zero rate of pitch conditions therefore the fluid flowed in a radial path to the central output duct. The vortex was created by the pitching of the sensor; the angular velocity of the fluid in the output port being a measure of the rate of pitching of the sensor. A pick-up device in the output port measured this velocity and this was amplified to produce the control signal to the elevators. This system occupied less space and gave better performance (faster response) than the system it replaced.

Diesel Electric Control for Railway Engine

A development engineer on the staff of New York Central Railways replaced the electric relay system which controlled the electric driving motors on a standard Diesel electric locomotive by an all-fluidic control system. An outstanding gain in reliability resulted.

Rocket Control

Developments in this field are highly classified and as a result very little has been published. It is known, however, that most U.S. space missiles usually employ a fluidic system in one form or other. Known applications are a main engine thrust diverter and a roll stability system. It is from the space industry in the U.S.A. that a large proportion of the technical developments have been and are being derived.

Automatic Sequence Starting

It is in this field that the majority of applications have been made. This is, of course, due to it being the simplest system to develop, and automatic start systems are now available as commercial equipment. The control panel for the automatic starting sequence for a natural gas pipeline pump control is shown in FIG. 14. This system uses the relatively inexpensive injection moulded plastic components of the type shown and can be run on either compressed air or on the natural gas itself. Also of interest are the fluidic indicator 'lamps'. These consist of a tiny cylinder, the end of which is transparent plastic, containing a free piston which moves from end to end in response to a small air signal. The piston face is coated with a coloured light-reflecting surface (usually red or green as appropriate) which produces an outstandingly effective indication. The air circuit to this indicator is tapped from the power circuit of the amplifiers and hence there are no relay troubles. The provision of a sound warning with such a system also presents little problem, a simple whistle being all that is necessary.

In addition to the above projects there are many others which have been or are being developed, including:

(*a*) A hydrogen/steam ratio detector for a fuel cell

(*b*) A heart pump

(*c*) A respirator

(*d*) Automatic tank and bottle filling

(*e*) Machine tool control

(*f*) A submarine hovering control system using liquid jets

(*g*) Digital computation

(*h*) Self-cleaning air filter.

Possible Future Naval Applications

In the foregoing paragraphs a variety of different applications have been mentioned; what, then, are the possible naval marine applications that could be in service in the next few years? To gaze into the crystal ball it would appear that the first ones will be in the field of automatic start sequencing of auxiliary machines. Control systems are already pneumatic and it is a logical step to include automatic start systems using the same medium in future designs. No research is necessary to adopt this technique which is largely one of engineering application. As a natural follow-on from this it is reasonable to expect fluidic systems to be employed in the automatic watchkeeping role with the necessary shut-down on failure. These would probably first appear where they are now traditional, i.e., Diesel generators. The requirements for all the devices as regards the cleanliness of the air, when using air as the fluid, is the same as for existing pneumatic control systems.

The prospect of the increased use of gas turbines for main propulsion in the Royal Navy leads one also to think that as gas turbine controls change to fluidic, the existing pneumatic controls for main engines will more readily be combined with the gas turbine controls to produce an integrated ship control system. Existing gas turbines used in marine applications are usually adapted from aircraft type gas turbines. These almost invariably use electro-hydraulic control systems and, as a result, adaptations are necessary in order to meet naval requirements. With fluidic controls the necessity for such adaptation should be reduced.

There will also come into use as part of the SYMES range, gas turbine/electric generator/waste heat boiler units. These would appear to be a natural application for fluidics, where the starting, being an emergency generator, must be from air bottles. The run-up sequence could be fluidic from the same air bottles and, when running, the supply of air for the control system would be obtained from the gas turbine compressor. Claims are also being made that the speed of a gas turbine generator can be governed with greater accuracy by fluidic means than by present methods, while the response of a fluidic sensor for control of maximum gas temperature is claimed to be some 2,000 times faster than the response of a temperature sensor.

In the case of automatic control of boilers, when all the characteristics of the boiler and control equipment are known, a difficult closed loop problem exists in Royal Naval installations due to the rapid rates at which it is desired to vary the power level. It will probably be some time therefore before sufficient is known in industry about fluidics to employ them in this application. As already mentioned, this system has been successfully controlled in the U.S.A. but whether a system can be produced which would be acceptable for service use has yet to be fully ascertained.

Gazing deeper into the crystal ball there may be possibilities for fluidic controls in the field of evaporators, lubricating oil temperature control and F.F.O. heating systems. These will need close examination and investigation.

Advantages of Fluidics

As there is a vast amount of money and effort being spent on fluidics, what therefore are the main advantages? To summarise, they are as follows:

(*a*) *Reliability*—There are no moving parts and therefore nothing to wear out. The components do not 'age' or have any limited life if properly designed. No maintenance is involved. No damage results from overloading.

(*b*) *Simplification*—Compared with conventional methods the equipment has reduced weight and bulk.

(*c*) *Ability to operate in adverse environments*—The equipment can be designed to operate in any temperature or environment. Unaffected by nuclear radiation. No explosive or fire risk.

(*d*) *Rugged Construction*—The equipment in production models is largely constructed out of solid material and requires no special mountings.

(*e*) *Reduced cost*—Production units give promise of being extremely cheap compared with conventional units.

Factors Against Fluidics

Obstacles which have prevented the wider acceptance and application of fluidics are as follows:

(*a*) The difficulty of predicting and achieving satisfactory performance particularly when using combinations of devices in closed loop systems. This leads to long and expensive development. It is rumoured that two firms in the U.S.A. have developed a completely 'operational' amplifier. If this is so this difficulty could disappear.

(*b*) The lack of suitable transducers to feed information into and out of a system. Those concerned with system development usually have to produce their own. Very little is available for 'off-the-shelf' purchase.

(*c*) The lack of immediate large-scale production prospects for these systems. In the long term they will make control systems cheaper, longer wearing and with little requirement for a spares service. Commercially these systems will tend to reduce the total turnover of control firms in the form of hardware. In this light they are not economically attractive as they require at present a greater ratio of skilled design to production output in man-hours than existing control systems. Firms in the U.S.A. have, in articles in the technical press, been accused of deliberately holding back development for this reason.

(*d*) The low efficiency of the devices. Most devices use maximum power the whole time whether in use or not. Each device may only use a watt or two of energy but with multiple devices, as in a computer, a measurable amount of energy is wasted.

(*e*) The lack of all-round knowledge of the technology, which either for defence or commercial reasons is not generally available. In this respect in this country the British Hydromechanics Research Association at Cranfield has been doing pioneer work in sponsoring conferences.

Progress in the United Kingdom

Progress in this country in this technology has been very slow. There are several reasons for this state of affairs. The first is, of course, money; no large-scale research or development studies have been sponsored by the Government as has been done in the U.S.A., although some minor ones have been placed with industry by the Ministry of Technology. Industry in this country is mainly interested in production and exporting, rather than research and development. With the present state of this country's economy this is understandable.

Universities are encouraging work by students in this field and a few of the larger firms maintain a watching brief on the general state of progress. The general result is, however, that as a nation we are making slow technological progress in this field.

Conclusions

Fluidics as a technology will come into increasing use in control systems. There is great promise of simpler and more reliable systems with no maintenance. The understanding of the techniques involved in the design of such systems involves knowledge of the phenomena of fluid flow. Increasing attention needs to be given to making all engineers aware of this new technology and its implications. This new technology is only as yet in its infancy, there will undoubtedly be more discoveries and applications as experience is gained. At present Fluidics is a challenge to all concerned with the design and applications of control systems.