United States Patent

[11] **3,550,604**

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[54] **HIGH SPEED FLUIDIC DEVICES**
25 Claims, 13 Drawing Figs.

[52] **U.S. Cl.** **137/81.5,** 235/201; F15c/1/14
[50] **Field of Search** 235/200, 201; 137/81.5

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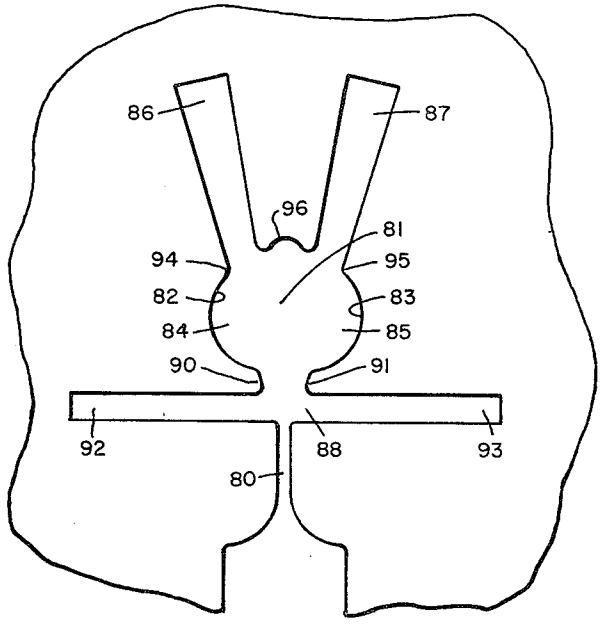
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ABSTRACT: This invention relates to a high speed fluidic element configured to have at least one cavity in which low pressure is developed as a result of a stream of fluid flowing close by, such low pressure acting to hold the stream flowing into a desired receiver. Our cavity concept may also be employed in conjunction with a feedback flow injector for causing some of the fluid flowing toward the receiver to curve around and act against the stream at a location adjacent its source, thus helping stabilize the stream in the desired position. Significantly, our device can be switched much faster and has much more stability than ordinary Coanda effect devices.



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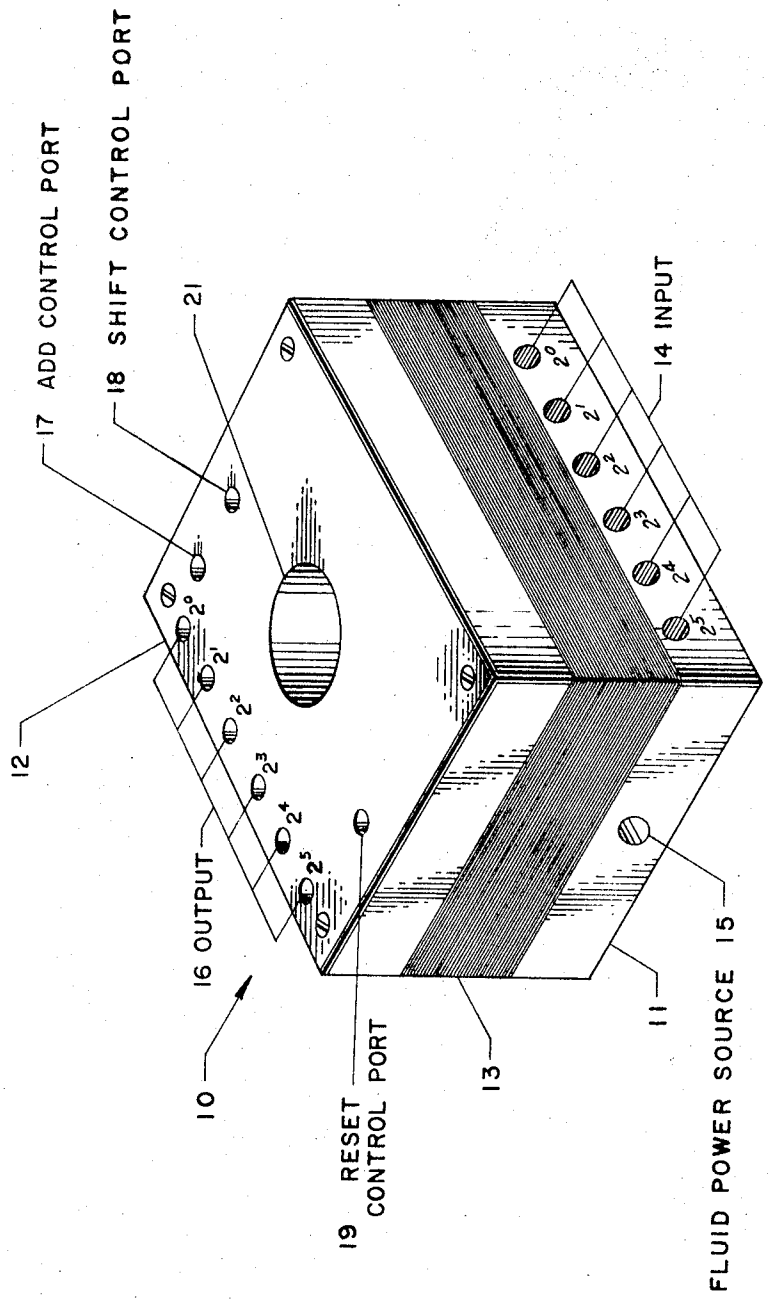


FIG. 1

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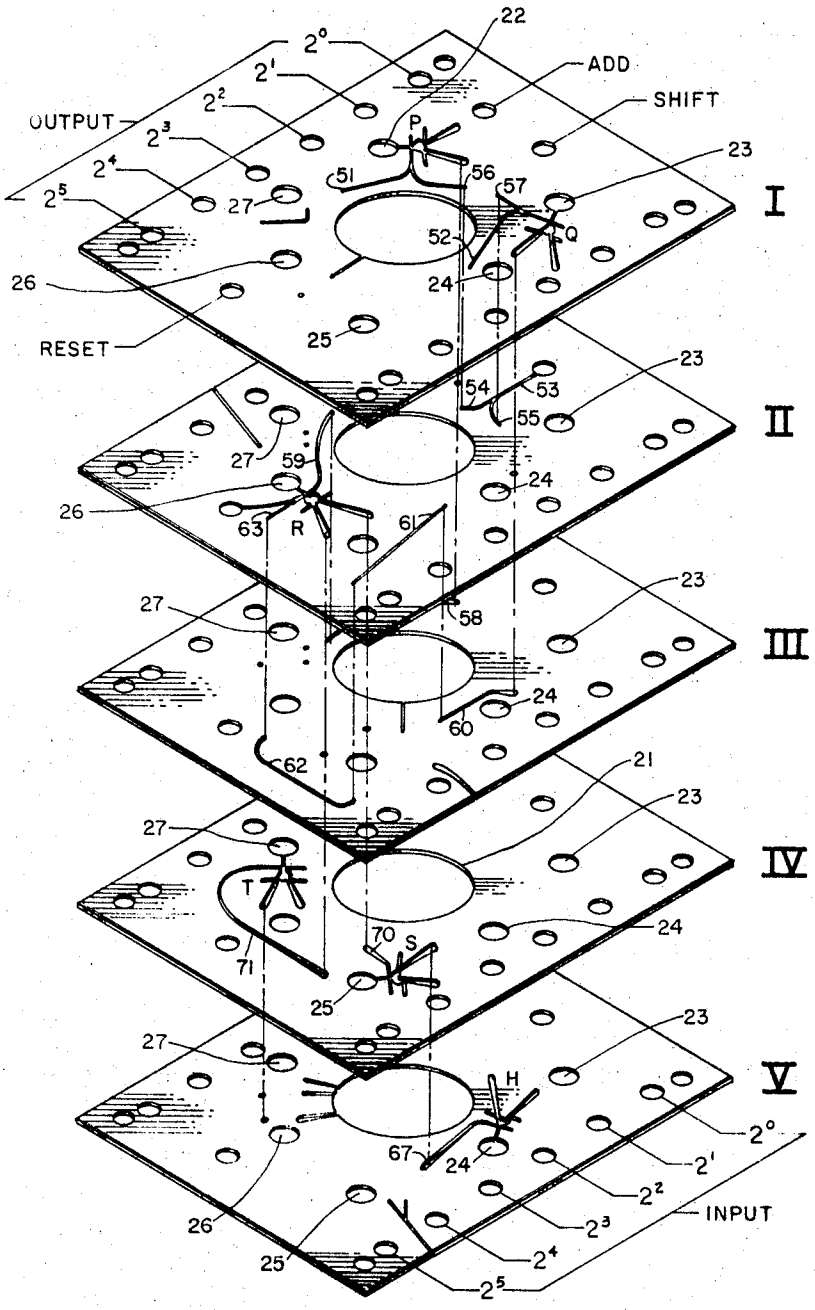


FIG. 2

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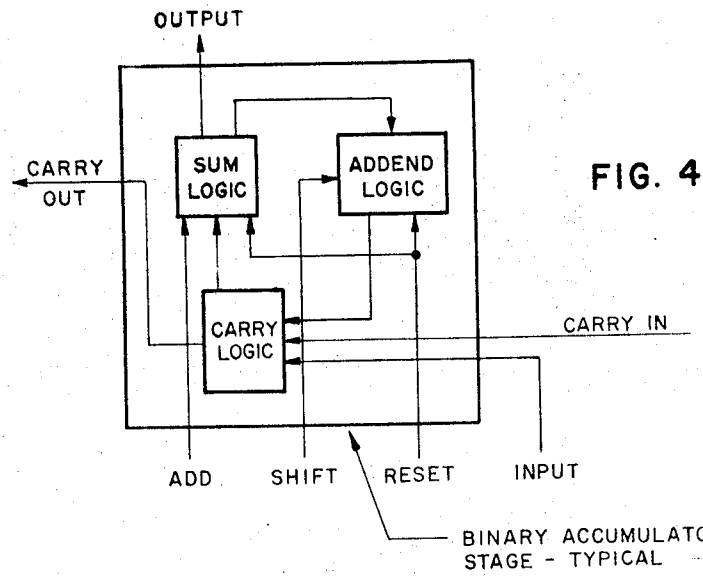


FIG. 4

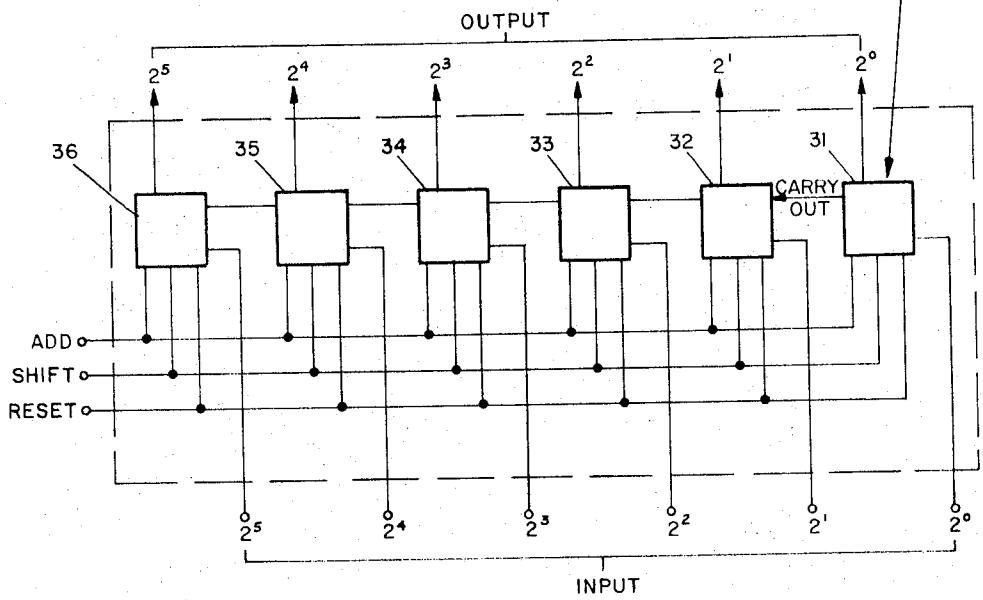


FIG. 3

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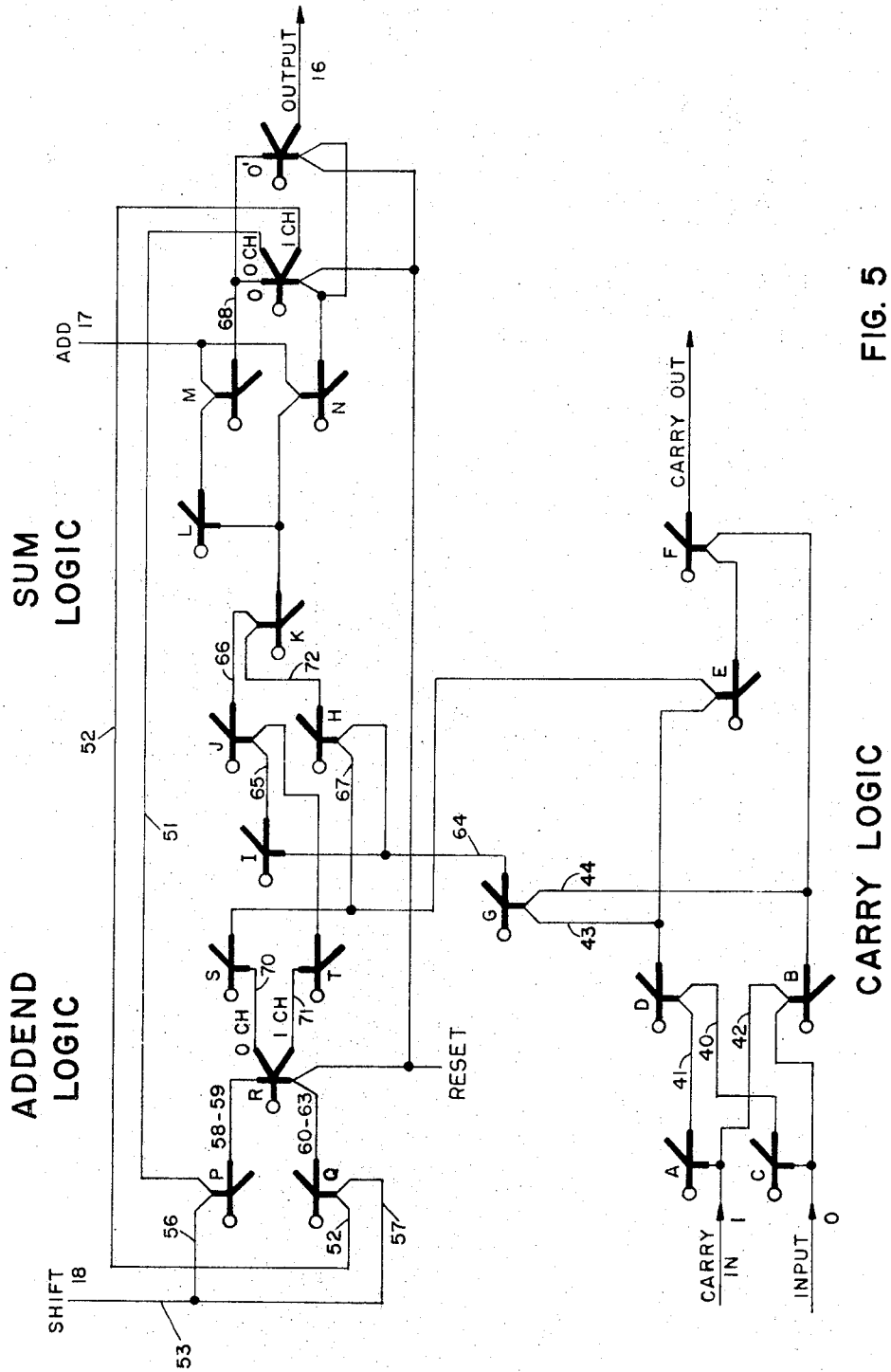


FIG. 5

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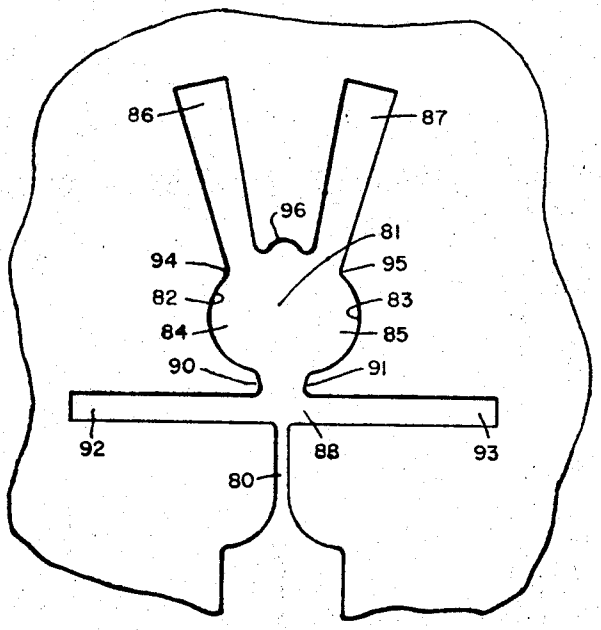


FIG. 6

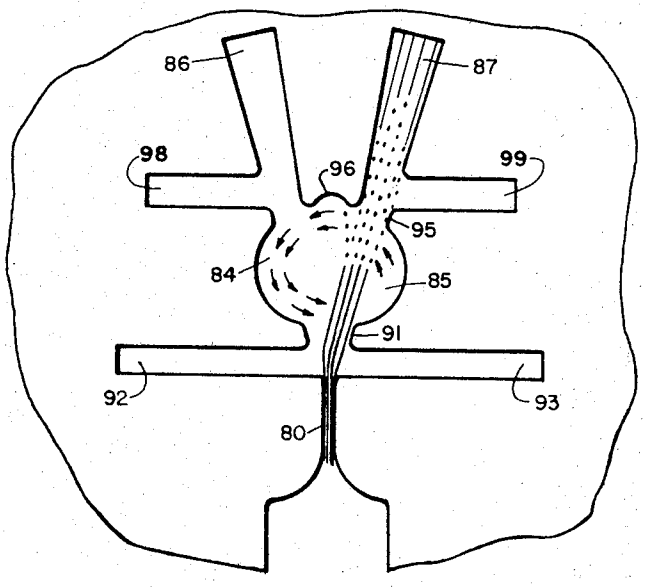


FIG. 7

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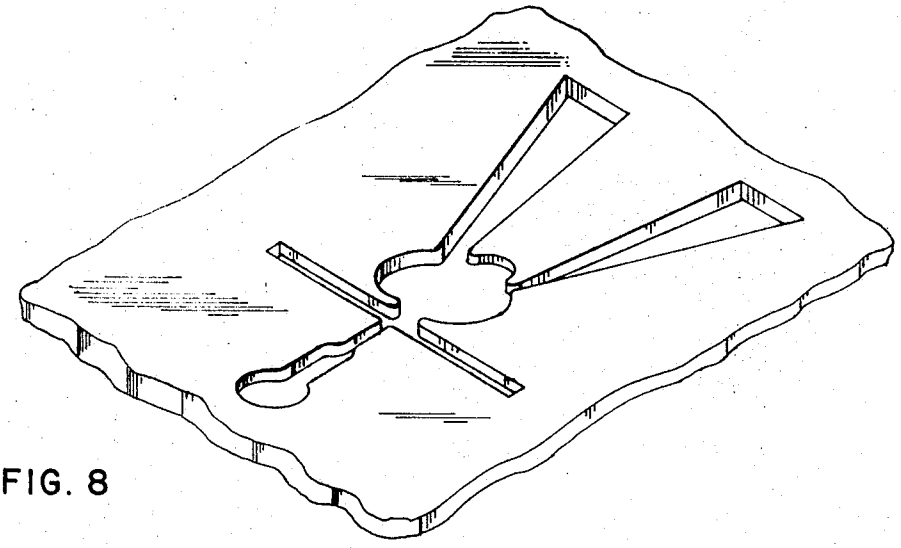


FIG. 8

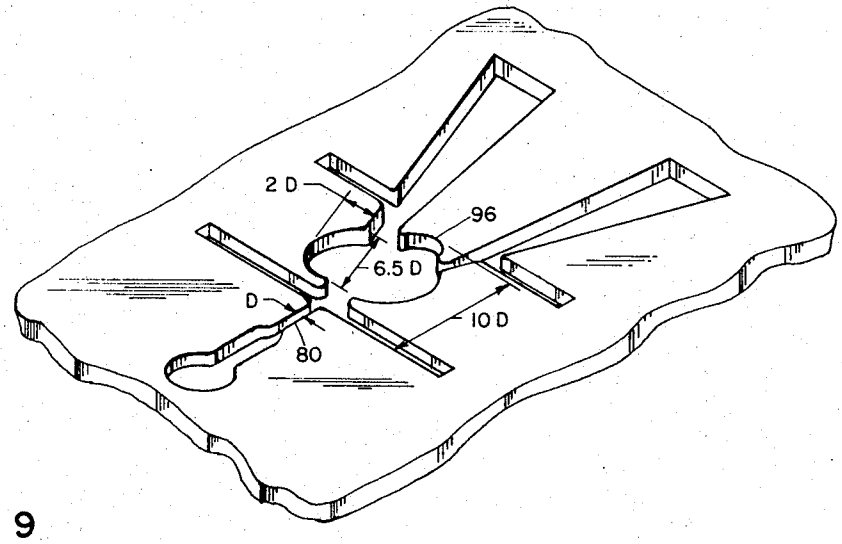


FIG. 9

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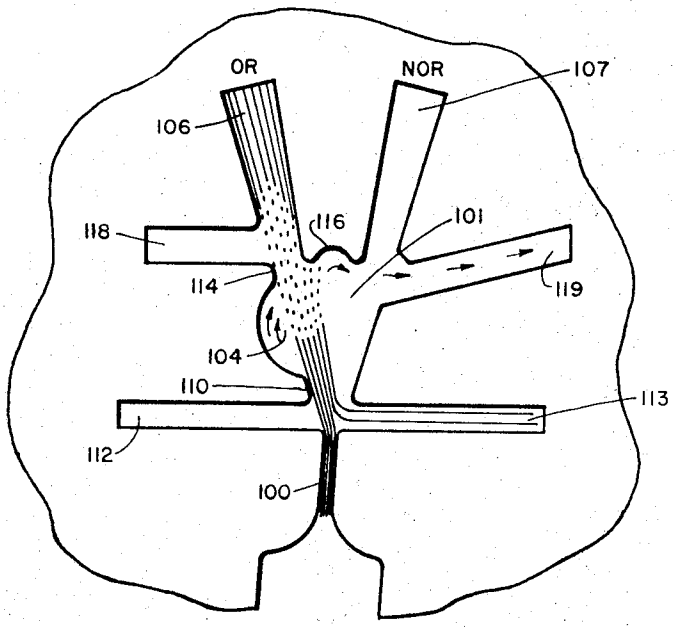


FIG. 10

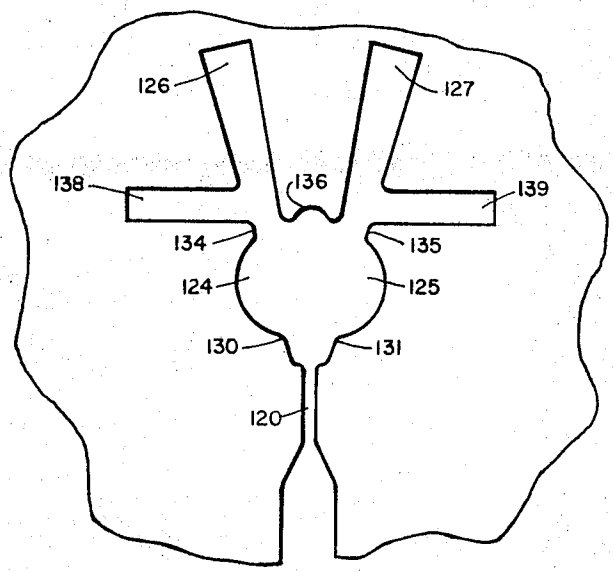


FIG. 11

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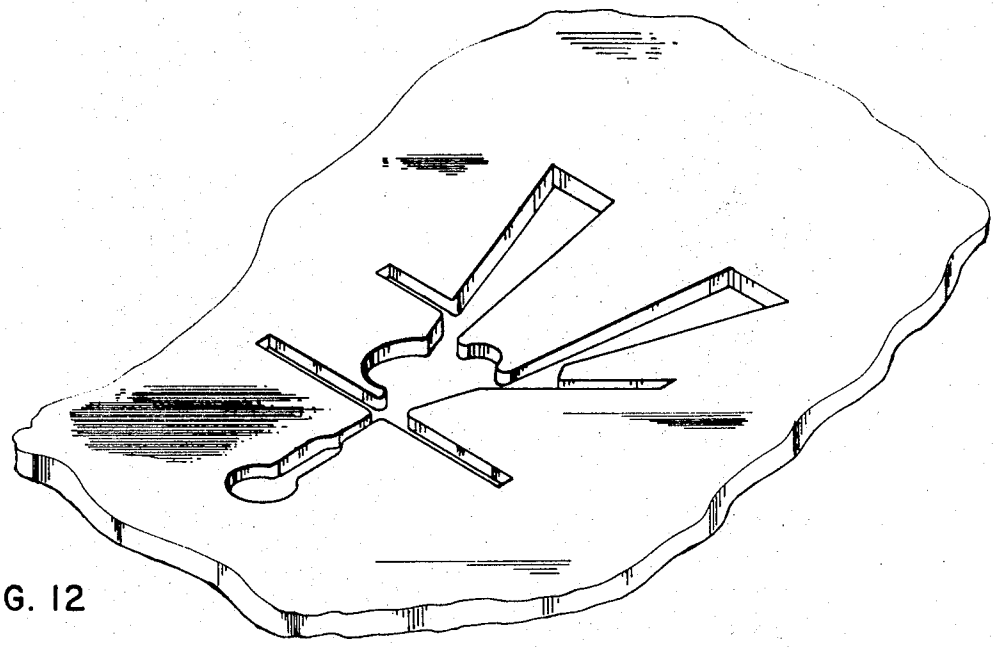


FIG. 12

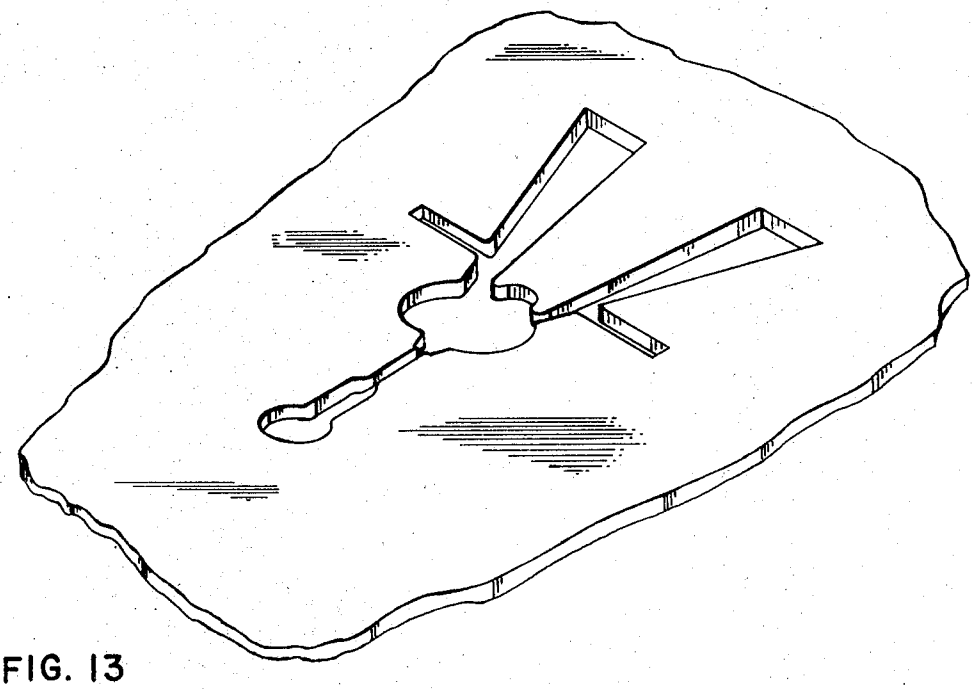


FIG. 13

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HIGH SPEED FLUIDIC DEVICES

This invention relates to fluidic digital logic devices, and more particularly to novel miniature fluid elements capable of highly acceptable performance at fast operating rates and requiring only small amounts of power, which elements can be made at low cost and packaged to a high density. By fluidic or fluidics we mean that field of technology which treats of the behavior and effects of fluid phenomena, and the use of fluids, either liquid or gaseous, in motion to perform functions such as signal amplification, sensing or detecting, logic or computation, and control. We intend also that this term will embrace such systems and devices presently known as pure fluid systems and devices, fluid amplifiers, fluid transistors, fluid power systems and fluid jet systems and devices.

In the past a number of so-called pure fluid devices have been proposed, but these have been characterized by their relatively large size and slow operating rates, and for these and other reasons, such prior art fluid devices were not suitable for complex logic applications.

These earlier devices have typically involved utilizing a stream of fluid under pressure, and at least two receivers, into one or the other of which receivers the stream of fluid can be caused to flow, with control means being positioned so as to deflect such stream into the desired receiver. Such devices have been the subject of numerous patents and many publications, with their proposed uses by industry becoming larger each successive year. However, all known prior art devices of this type are either analogue devices or digital Coanda effect devices, and their operating rates have been very much slower than the comparable electronic devices. As a result, it has not heretofore been feasible to perform the complex functions normally associated with electronic logic by the use of fluidic devices.

As is known, a network of logic elements for sequencing, computing and control system applications must complete a data cycle within the time interval defined by the intended use. Therefore, the number of logic elements that can be effectively utilized in a given application depends upon the operating rate. In other words, the number of logic elements defines the numerical accuracy and functional capability of the digital device, so therefore the operating rate of logic elements is of vital importance in that it establishes directly the capability of the digital mechanization. It is known that in a fluid device, the operating rate is directly related to size, and although the velocity of propagation by fluid signals is limited, by employing very small elements, quite adequate response times can be obtained.

Whereas prior art fluid logic devices have been large and slow, suitable only for primitive logic networks, we have dramatically extended the utility of the fluid logic technology by making our logic elements small and fast acting, so as to make them highly useful in complex logic devices.

We have created a new fluid element configuration utilizing a novel cavity past which a jet of fluid from a nozzle can flow. Because of the unusual properties of this cavity configuration, laminar nozzle flow can be used and the device made much smaller than was ever previously possible. As is known, it is only by virtue of a turbulent flow that any substantial entrainment of adjacent fluid can occur, but advantageously, the laminar flow emanating from our nozzle is caused to turn to turbulent flow before the confines of the cavity are passed, which means that a desirable entrainment of the fluid from the cavity can take place, thus reducing the pressure therein and holding the jet of fluid in the desired position.

More specifically, our novel concept makes possible a new class of miniaturized fluid logic devices that significantly can operate on initially laminar jets.

In our elements, the novel interaction area geometry is used to induce desired bistable or monostable operation without dependence on sidewall attachment. In this class of device, miniaturized sizes can be employed, where laminar power jets are encountered. Laminar power jets interact with boundary fluid through viscous forces only, so there is no appreciable momentum exchange. As a result, there is insufficient entrainment of fluid as is necessary to develop an adequate pressure gradient by proximity to a sidewall. However, the necessary pressure gradient is established in this class by internal feedback, and/or selectively inducing turbulence in a portion of the jet.

In other words, our novel concept makes possible a new class of miniaturized fluid logic devices that can operate on initially laminar jets, and the fact that turbulent nozzle flow is precluded in small sizes due to the high ratio of surface to cross section in small channels is overcome by virtue of the fact that our novel cavity configuration desirably induces turbulence in the initially laminar jet at a location close to the nozzle exit. Several other desirable effects are also brought about, with the net result being to provide fluid logic devices in a smallness of size heretofore considered impractical. The aforementioned cavity is disposed between the control port and a receiver, which cavity includes an upstream edge and a downstream edge. The relationship of the upstream edge with respect to the jet is such that the control cavity is in effect isolated from the control port except when switching pressure is applied thereto. That is to say, when the jet is flowing past the upstream and downstream edges, the cavity portion of the chamber is in effect isolated, with the entrainment of fluid being such that a negative pressure is created in the cavity, which lowered pressure causes the jet to stay in the selected position.

Upon the arrival of the control signal at the control port, this causes the jet to move away from the upstream edge or point, thus to allow flow to take place from the control port into the previously evacuated cavity. This of course serves to dissipate the lowered pressure therein and thereby to cause the jet to tend to move away from the cavity. Switching thereafter takes place very rapidly, such as within 20 microseconds.

By virtue of the fact that we can achieve highly satisfactory performance with only a very small supply nozzle, such as a nozzle of a width dimension of .004inch, it is possible for us to resort to printed circuit techniques in the creation of our elements, and to employ copper foils that are .004 inch thick. As will therefore be seen, our nozzles are .004 inch on a side, or have an aspect ratio of 1. This is of course to be contrasted with the smallest nozzle heretofore known, which was some .014 deep and .008 wide.

Our small nozzle makes possible a number of additional advantages, such as the fact that each logic plane can be very thin and thereby make possible the stacking of dozens or even hundreds of logic planes into a single logic device. Whereas the aforementioned prior art nozzle that was .014 deep could be made by the use of say seven foils of 2-mil stock, we can make self-contained logic planes that are each .004 inch thick, utilizing a single foil thickness for each logic plane, thus of course circumventing the alignment and registration problems that accompany devices whose elements are made of a plurality of layers.

It is significant to note that the application of a control signal to the control port brings about switching of the jet to the other receiver in a very rapid manner by virtue of the fact that the distance from the control port to a receiver can be very short. This is to be contrasted with the prior art configurations, in which the nozzle was thought to be necessarily large in order to obtain the initially turbulent flow required in fluidic elements.

Accordingly, it is a principal object of this invention to provide miniature high speed fluid logic elements that can be quite successfully employed in sophisticated, yet very small logic networks. Further, since the operating rate in accordance with our invention allows the use of a large number of elements in a given size package, it is another object of this invention to provide high density element packages and fluid logic that can be produced at very low cost.

A further object of this invention is to provide fluid logic elements with practical circuit characteristics such as

adequate fan-in, fan-out capability, low power consumption, and reliable operation over a wide range of supply pressures and loading characteristics.

Our invention provides a substantial improvement over Coanda effect devices in that through the use of our novel control cavity configuration, initial turbulence in the fluid jet is manifestly not necessary. Our cavity enhances stability of the fluid jet with respect to the selected receiver in a most significant manner, and because wall attachment is not required, our logic device is operable over a wide range of supply pressures. This is to be contrasted with a Coanda effect device, whose attachment point undesirably varies with supply pressure as well as other input parameters.

As will therefore be seen, in a fluidic device in accordance with our invention, a source is employed from which a fluid jet issues, and control port means are provided for switching the fluid jet between one or the other of two alternative receivers. As earlier mentioned, means define a novel control cavity between the control port means and a receiver, which cavity serves to generate a low pressure with respect to the jet so as to hold same in a stable position with respect to the respective receiver. This cavity includes an upstream edge contacted by the jet in such a manner that the control cavity is isolated from the control ports except when switching pressure is applied thereto. Switching pressure applied at the control port serves to move the fluid jet away from such upstream edge and produce a comparatively high pressure within the cavity so as to effect a switching of the jet to the other receiver in a very short time, such as in 20 microseconds.

As will be obvious to those skilled in the art, this novel utilization of a cavity to bring about low pressure to hold the fluid jet in a stable position with respect to a selected receiver can be utilized in a number of configurations, such as one in which a pair of cavities is used in symmetrical fashion, with each cavity being associated with one of two receivers, thus to form a fluidic flip-flop device or a pulse relay. As an alternative, however, a single cavity can be used to form a fluidic OR-NOR logic gate, for example.

In each of these instances it will be noted that the use of our novel cavity concept for developing the pressure gradient that holds the fluid jet in a selected position amounts to a substantial improvement over the prior art devices wherein a wall was employed for holding the jet in the selected position. This is of course because a high operating rate simply cannot be obtained in the large sizes required by wall attachment-type devices. Further, by virtue of the fact that in accordance with this invention no wall is used to which the jet is to attach, switching can be brought about in an extremely rapid manner by merely causing the jet to move away from a cavity-defining position. It should be noted that our so-called wall-less concept possesses quite acceptable stability standards inasmuch as low pressure is developed in even a single cavity tending to hold the stream of fluid in the desired location. When a pair of cavities is used, the cavity opposite the jet in any instance serves to increase the fluid pressure on the jet and thus operates with the low pressure to hold the jet in the desired position.

These and other objects, features, and advantages will be more apparent from a study of the drawings in which:

FIG. 1 is a perspective type view of a logic device in accordance with our invention, illustrating the logic matrix in conjunction with top and bottom manifold plates secured in position;

FIG. 2 is an exploded view of several logic circuit planes of the type used in the logic device of FIG. 1, with the interconnecting fluid passages between elements being indicated;

FIG. 3 is a block diagram of an exemplary fluid circuit in accordance with this invention, in this instance a 6bit binary accumulator;

FIG. 4 is a block diagram of a typical binary accumulator stage of the block diagram of FIG. 3;

FIG. 5 is a logic diagram in accordance with this invention, revealing in schematic form the logic elements of FIG. 4.

FIG. 6 is a fluid element in accordance with our invention, in this instance a two-cavity arrangement that is particularly suitable from the standpoint of simplicity of description;

FIG. 7 represents a device along the lines of FIG. 6 but possessing the configuration of a fluidic flip-flop presented to a scale much larger than that of the actual device;

FIG. 8 is a perspective view of the device shown in FIG. 6;

FIG. 9 is a perspective view of the device shown in FIG. 7;

FIG. 10 represents a single-cavity version of our novel concept, this particular device being a fluidic OR-NOR logic gate:

FIG. 11 is another symmetrical cavity arrangement in accordance with our invention, this device being in the form of a load-controlled fluidic pulse relay;

FIG. 12 is a perspective view of the device shown in FIG. 10; and

FIG. 13 is a perspective view of the device shown in FIG. 11.

Referring to FIG. 1, logic device 10 is there depicted, which comprises bottom manifold plate 11, top manifold plate 12, and logic matrix 13 disposed therebetween. As will be seen hereinafter, the logic matrix 13 comprises a comparatively large number of logic circuit planes which together form the logic of this device. In this instance, the device is a 6bit binary accumulator, such as could be an integral building block of a digital computing mechanism. A similar assembly could contain logic for a sequencer or other digital control device.

As will be apparent from FIG. 1, the INPUTS or augend 14 as well as the fluid power source 15 are disposed in bottom manifold plate 11, with the OUTPUTS 16 as well as the sequencing control ports 17, 18 and 19 being disposed in the top manifold plate 12. All of these inputs and outputs could be provided by controllable (manually or automatically) interface devices or could be a consequence of other signals where this device acts as a subassembly of a more complex digital mechanization.

The fluid power source 15 is a continuous pressure with a flow capacity adequate for the device, with pressurized gases such as, for example, air, nitrogen, or the like being usable.

The INPUT 14 is so configured as to allow a series of fluid pressures applied as a binary coded number. For example, the number 3 could be applied at the INPUT 14 by pressurizing the 2^0 and 2^1 ports, with zero pressure simultaneously being maintained at the 2^2, 2^3, 2^4, and 2^5 ports. Similarly, the number 15 could be applied to the INPUT 14 by pressurizing the 2^0, 2^1, 2^2, and 2^3 ports, with no pressure applied at the 2^4 and 2^5 control ports.

The top manifold plate 12 contains the ADD control port 17, SHIFT control port 18, and RESET control port 19, as mentioned earlier, which ports are used to sequence the logic device. Here momentary pressure pulses are selectively applied which control the logic operations. On the side of the top manifold plate, the OUTPUT set 16 is located, with this set serving to transmit the result of the logic device operation to a readout or to a subsequent similar logic device. In other words, this output can be used in controlling and/or sequencing mechanisms or applied to another similar logic device to perform a more complex computing function. Each port of the OUTPUT set 16 is selectively pressurized as a consequence of the logic device operation, and as an example, this output set could represent a binary coded number. For instance, the number 29 would be presented by having pressure at 2^4, 2^3, and 2^2, and 2^0, with zero pressure at ports 2^1 and 2^5.

The hole 21 in the middle of the top manifold plate extends down through the logic matrix to provide a chamber which is used for venting the internal logic devices. The outer boundaries of the logic matrix are similarly used to vent the logic devices, such as to the atmosphere or a low-pressure plenum.

Turning to FIG. 2, it will be noted that in this exploded view of a typical fluidic logic assembly in accordance with our invention consists of five exemplary circuit planes I through V containing our novel logic elements and their interconnections, arrayed in the approximate relationship that they are disposed in the logic matrix. It is of course to be understood

that the logic matrix in accordance with this invention may comprise dozens or even hundreds of logic planes, with it also being understood that the five planes shown herein are typical planes that may be juxtaposed in the illustrated relation in a preestablished location in a typical logic device. Each circuit plane is preferably made of copper foil, because of the comparative ease with which known etching techniques may be employed to create logic elements in accordance with this invention. Also, copper foils are preferred from the standpoint of manufacture, for a desired number of foils may be satisfactorily secured together in a preestablished relationship either by clamping, screwing, or suitable bonding techniques. However, it is within the contemplation of our invention to use foils of brass, copperbrass alloy, or even stainless steel if such be desired, with these of course being used in the thickness desired.

As will be apparent, each logic plane is prepared in accordance with a preestablished standard and basically involves the use of three types of interconnections; power supplies, vents, and signal passages, with it also being evident that several logic elements may be disposed in each logic plane. These elements will be discussed in detail hereinafter, and it should at this point suffice to say that the elements used on the planes of FIG. 2 are either flip-flop of the type appearing in FIGS. 7 and 9, or else OR-NOR gates of the type appearing in FIGS. 10 and 12. The element configurations are designed so that the metal foil after etching does not fall apart. This is made possible by the fact that stepping between elements often takes place between two or more adjacent planes, with the arrangement being such that appropriate communication among the elements is conveniently made possible.

As will also be apparent, the logic pattern in each instance is arranged circularly around the common vent 21 to facilitate simultaneous venting on the inside as well as on the outside of the stack. Power supply ports 22 through 27 are disposed adjacent the elements, or perhaps more accurately, the elements are disposed in such a manner as to partake of the fluid pressure available at power supply ports. For example, elements P & Q are disposed in Plane I connected to ports 22 and 23, element R is disposed in Plane II connected to port 26, etc. The power supply ports will be noted to continue through all five illustrated planes. As well be understood, the Fluid Power Source 15 of FIG. 1 is connected to the supply ports by appropriate power supply interconnections and passages disposed in bottom manifold plate 11, and in a similar manner, the input ports, output ports and control ports are connected to the matrix 13 formed of the standardized circuit planes by means of other appropriate passages disposed in the manifold plates. By standardized it is meant in this context that the power supply ports, the central vent, and the indexing holes are in a preestablished location, and that the material size is the same.

FIG. 2 also reveals how fluid logic elements can be interconnected in complex sequencing and computing circuits. Each of the logic elements employed in this matrix must operate at a high enough rate so that the composite speed of the complete logic device is suitable for the intended application. In addition, a number of the logic elements must be capable of fanning out to a multiplicity of other elements and simultaneously being controlled by a fan-in from a multiplicity of elements. Interconnections among logic elements can be made either in a horizontal plane or by transferring vertically from stack to stack, the decision in each instance largely depending on good design practice. Since as is apparent, a large number of discrete digital logic elements is required to mechanize digital devices in most practical applications, this imposes a requirement in addition to the other characteristics of the logic circuits, which is that they must be suitable for low cost fabrication techniques such as by certain photo etch processes.

Our invention will be explained by next referring to FIG. 3, which is a block diagram of a logic device, in this example a 6bit binary accumulator employing stages 31 through 36. As indicated earlier and shown here, the input to this device is a binary coded set, and the three controls, ADD, SHIFT and RESET, are used to sequence its operation. Similarly, the output is another binary coded set. Associated with each binary bit there are blocks containing the CARRY LOGIC, the SUM LOGIC and the ADDEND LOGIC, as indicated in FIG. 4. In this example, the binary input set is added in a parallel fashion to the existing binary coded number on the ADDEND LOGIC and the result transferred to the SUM LOGIC. Whenever necessary as the consequence of the addition operation, digital logic is employed to transmit a carry to the next higher ordered bit. This addition operation is controlled by a momentary removal of the fluid signal to the ADD control channel. This binary coded set is then transmitted and/or displayed at the OUTPUT ports.

To prepare the device for the next add operation, the binary coded number of the SUM LOGIC is transferred to the ADDEND, in this instance by momentary removal of the pressure signal at the SHIFT control port. In this case, element O of the SUM LOGIC, and elements P, Q & R of the ADDEND LOGIC cooperate to perform the function of a shift register, where the state of the first bistable element O is shifted to the second bistable element R without changing the condition of element O. The result of this automatic, or manually applied sequence of ADD and SHIFT commands is to accumulatively add the binary coded number applied as the INPUT set. The INPUT set can of course be changed at any time, as for example from a binary function generator or an interface associated with the application of this device.

The RESET control port can be used at initiation of the operation and/or intermittently to reset each bit of the device to zero. The OUTPUT is continuously presented and presents the binary number existing at any point in time in the SUM LOGIC.

Turning now to FIG. 5, this is a schematic of the logic in each bit of the accumulator. Element O is the SUM flip-flop, element O' the OUTPUT flip-flop and element R is the ADDEND flip-flop. Element R of course appeared in FIG. 2, and the precise operation of this (and the other) bistable devices will be set forth in connection with FIGS. 7 and 9. Similarly, the OR-NOR elements of FIGS. 2 and 5 will be discussed in detail in connection with FIGS. 10 and 12. It should be noted from FIG. 5 that removal of the SHIFT signal to the control ports of OR-NOR elements P and Q results in the transfer of the state of element O to element R. Similarly, removal of an ADD signal to the control ports of OR-NOR elements M and N results in adding the ADDEND, CARRY IN, and INPUT, displaying the result on element O and O', and transmitting a CARRY OUT through element F as required. Monostable elements A through G of FIG. 5 represent the CARRY LOGIC, elements H through O' the SUM LOGIC, and elements P through T the ADDEND LOGIC.

In the device shown in FIG. 1, assume that signals are normally present at the ADD CONTROL PORT 17 and the SHIFT CONTROL PORT 18, and that both the ADDEND LOGIC and SUM LOGIC of FIG. 5 have been reset to 0. In this initially assumed condition, all OUTPUT signals 16 will be zero. Now assume that an INPUT signal 14 is applied to the first bit or the 2^0 INPUT port.

In order to add this number, which represents 1 in this case, to the number in the ADDEND LOGIC, which is now 0, one must momentarily remove the ADD control signal at port 17. This process sets the elements 0 and 0' in the SUM LOGIC in the first bit to the 1 channel which indicates 2^0 or 1. The signal to the ADD control port 17 is then reapplied and the number 1 in the SUM LOGIC of the first bit is then shifted to the ADDEND LOGIC of the first bit. This is accomplished by momentarily removing the SHIFT control signal 18 which sets the ADDEND flip-flop R of the first bit from the 0 channel to the 1 channel. This in conjunction with the 2^0 input set signal generates a CARRY OUT signal from bit 1 which is applied to bit 2 as a CARRY IN. The second add operation will then add the number existing in the ADDEND LOGIC, in this case 2^0 or

1, to the number existing in the INPUT, again in this case 2^0 or 1. This is accomplished by again momentarily interrupting the signal at the ADD control port which results in setting the elements 0 and 0' in the SUM LOGIC of the second bit from the 0 channel to the 1 channel, and simultaneously setting elements 0 and 0' of the SUM LOGIC of the first bit from the 1 channel back to the 0 channel. This results in changing the condition of the OUTPUT signals 16 from a 2^0 state to a 2^1 state. This is equivalent to saying that the sum of $2^0 0 + 2^0 = 2^1$ or 2.

The exact mechanics of how this is accomplished may be seen by referring to FIG. 5 and it is described in the following discussion.

In this situation assumed for the purpose of explanation, let FIG. 5 represent the second bit of the 6 bit binary accumulator. Because all input signals except the 2^0 signal are absent, the input to bit 2 will be in the 0 state, thus explaining the 0 at the INPUT near the bottom of FIG. 5. As a result of the first addition and shift, a CARRY OUT was generated from bit 1, thus explaining the 1 condition existing here at the CARRY IN of bit 2. The ADDEND flip-flop R of bit 2 was previously set to the 0 channel by the initial premise of the problem. Now, in order to explain how the second addition process sums these three signals, the INPUT 0, the CARRY IN 1, and the ADDEND 0 to provide a 2^1 OUTPUT, the following discussion is presented.

As previously indicated, it is to be realized that the arrangement of OR-NOR gates and bistable elements shown in FIG. 5 represents one bit of an exemplary logic device designed to receive, shift and add binary logic signals. Each element of FIG. 5 is connected to the fluid power source 15 of FIG. 1 and each element is designed to perform a discrete logic function in a manner described in detail hereinafter. As will be apparent, the control ports of monostable logic elements A and B receive the CARRY IN signals and the control ports of elements C and B are designed to receive the INPUT signal. The control port of element D is designed to receive the output from the receivers of elements A and C when the control ports of latter elements are receiving no signal and such elements are therefore in the on condition. Similarly, the outputs of elements D and B are directed to the control ports of elements E and F, respectively, as well as to the control port of monostable element G.

SHIFT pulses supplied through port 18 of FIG. 1 are directed to the control ports of elements P and Q of the ADDEND LOGIC of FIG. 5, with these elements also on occasion receiving inputs on lines 51 and 52 from bistable element O, the presence of a signal on a given line depending of course upon the state of latter element. ADD pulses supplied to port 17 of FIG. 1 are received by a control port of elements M and N, which elements are directly responsible for switching bistable element O. One of the outputs of related bistable element O' represents the OUTPUT 16.

As earlier mentioned, the CARRY IN to the CARRY LOGIC is from the CARRY OUT from the preceding stage, and conversely the CARRY OUT depicted in FIG. 5 becomes the CARRY IN of the succeeding stage.

An input present in the CARRY LOGIC can be transferred to the output 16 by means of operating the SHIFT and ADD control signals through ports 18 and 17 of FIG. 1. It should be noted that a change in the state of the CARRY LOGIC can be brought about without affecting the state of the output. Operating the SHIFT and ADD input control signals, the new input will be added to the quantity already present in the SUM LOGIC block. All the logic functions in this device are performed in binary logic fashion, and provisions are made to carry the necessary signals to the next bit of the device.

Referring to the CARRY LOGIC, the INPUT is set by control port 14 of FIG. 1 to either a 1 or a 0, and as just reiterated, the CARRY IN represents the 1 or the 0 CARRY OUT from the previous bit. In this example, the INPUT is a 0, so element C is in the on position, and a pressure signal flows through line 40 to a control port of monostable element D. This of course causes a switching of element D to the off condition during the continuation of the pressure signal, thus preventing at this time the transmission of a signal to the control ports of elements E and G.

In this case, a 1 is present in the CARRY IN, and this turns off element A, but this is irrelevant in this instance insofar as element D is concerned, for whether or not there is a signal from A to element D on line 41 will not change the state of element D when as here it has already been switched to the off position by the signal from C.

The CARRY IN signal is also sent on line 42 to a control port of element B and turns it off, thus in this instance making the presence of an INPUT at the control port of element B irrelevant.

As will now be apparent 0 (zero) signals exist on lines 43 and 44 as a result of B and D being in the off condition, so element G will be in the on position and will provide a pressure signal on line 64 to the control ports of elements H and I of the SUM LOGIC, turning them off. Since element I is now off, there will be no signal on line 65 connected to the control port of element J, so that the state of element J will be decided by the state of element T of the ADDEND LOGIC.

Assuming element T is on, element J is turned off and therefore no signal will exist on line 66, thus allowing the state of element K to depend upon the state of element H. Since element H was turned off by element G, there will be no signal in channel 72 to element K, so element K will be on and therefore element L will be off. Assuming no pressure is provided at this moment by the ADD input port, element M will be on and will provide a signal in line 68 to the control port of bistable element O, causing it to have an output in the 1 channel and thereby provide a signal on line 52 to the control port of element Q.

Since element K is now on, element N is off, thereby allowing element O as just mentioned to provide a signal on line 52 that will turn element Q off. The signal on line 68 further flips element 0' to the OUTPUT 16 position. As will be seen, we have performed the binary addition of three signals, the ADDEND a zero, the CARRY IN a 1, and the INPUT a zero, with the result being a 1. Since this was assumed to be the second binary bit in the system, this 1 appears at the OUTPUT represents the value 2, which is the sum of the INPUT 2^0 or 1, and the value that was in the SUM LOGIC, also a 2^0 or 1.

It should be noted that simultaneously with the change of the state of the second bit from a 0 condition to the 1 condition, the state of the output of the first binary bit of the device is shifted from the 1 state back to the 0 state. This is accomplished through somewhat related logic operations to those previously described for the change of state for the second bit.

In order to set the device up for the next add operation one must momentarily interrupt the SHIFT control signal 18, which essentially transfers the number existing at the OUTPUT 16 of the SUM LOGIC into the ADDEND LOGIC. This is accomplished by the ADDEND LOGIC block of FIG. 4 which involves elements P through T of FIG. 5.

In order to actually see how this is accomplished in the physical circuit, refer back to the exploded view of FIG. 2, which is relatable to a portion of FIG. 5. Since the output of bit 2 is now in the 1 channel as the result of the previous operation, a signal will be present on line 52, which appears in plane I of FIG. 2 as well as in FIG. 5. This of course is a control input to monostable element Q which holds this element in the off condition or 0 state. A shift control is normally present in channel 53, and as seen in plane II, this channel branches into channels 54 and 55 (not shown in FIG. 5). Channels 54 and 55 intersect channels 56 and 57, respectively, with these latter channels being control inputs to elements P and Q respectively. As long as the shift control signal is present, both of the latter elements will be held in the off condition. However, when the shift pulse is interrupted, element P will turn on since as was noted, no signal is present in line 51 from the zero channel of element O. Element Q, however, will remain off because of the signal that is present in channel 52. When ele-

ment P turns on, its output is applied through logic plane II into channel **58** of logic plane III and back to channel **59** of logic plane II, which is the control port of bistable element R of latter plane. This sets element R to the channel **1** condition. Since element R is a bistable element, it will remain in this condition even when the signal from channel **59** is terminated. This signal is terminated by reapplication of the shift pulse, which again turns element P off. Element R has now been switched to the **1** channel and the signal from the **1** channel is transferred through logic plane III to logic plane IV, where via line **71** it feeds the control port of element T. Contemporaneously, since element R was switched from the **0** channel to the **1** channel, the signal in the **0** channel was removed, which removes the signal from line **70** connected to the control port of element S, permitting this element to turn on. This chain of events sets up the remaining logic in the system for the next operation. It is to be understood that FIG. **2** was not depicted to have a sufficient number of logic planes in order for all of the operations set forth in FIG. **5** to be carried out. For example, a total of say **20** logic planes might well be involved in order for all of the logic operations of FIG. **5** to be performed.

Now to illustrate how element R is set from the **1** channel to the **0** channel, assume that a signal is present in line **51** to element P and that the signal in channel **52** has therefore been removed. This results when element O, due to successive addition processes, has been switched from the **1** channel back to the **0** channel. Now, when the shift control signal is terminated, element P will remain off due to the signal in channel **51**, but element Q will turn on since the signal in channel **52** is no longer present. When this occurs, the output from element Q travels through logic plane II, through channel **60** of logic plane III, back up to channel **61** of logic plane II, back down to channel **62** of logic plane III, and up to channel **63** of logic plane II, which is a control port of element R. This switches element R from the **1** channel back to the **0** channel and causes a corresponding change of state of the remaining elements driven by element R. Again, when the shift control signal is reapplied, element R will now remain in the **0** channel since it is bistable, even though the shift control signal again turns off element Q. This completes the detailed discussion of FIG. **2**.

Under the initially-assumed conditions, element F was not generating a CARRY OUT. However, when R is flipped to the **1** state, a **1** appears at the CARRY OUT.

As will be apparent from this exemplary circuit, element F will provide a **1** at the CARRY OUT if any two of the CARRY IN, INPUT, or ADDEND LOGIC represent a **1**, then element F is off, and a 0 is provided.

The foregoing description of a typical logic mechanization was presented in order to illustrate the way in which our novel fluidic elements can be employed in complex integrated fluidic circuits. By using our novel elements in a counter circuit in which simple interconnections were possible, a packaging density of approximately 500 elements per cubic inch was obtained, whereas in a computer circuit made in accordance with these principles, a number of interconnecting planes in the nature of plane III of FIG. **2** were required, and the packaging density fell to 200 elements per cubic inch.

As will be apparent to those skilled in the art, by effective design, certain logic devices having packaging densities of 1,000 fluidic logic elements per cubic inch or even higher can be built. As a result of the use of our principles, substantial improvement in overall operating rate can be effected relative to existing fluidic techniques.

Turning now to a detailed description of our novel fluid element configurations, and referring to FIGS. **6** and **7**, it will be noted that nozzle **80** is designed to provide a stream of fluid or jet that flows from a suitable source into control chamber **81**, which chamber is principally defined by arcuate sidewalls **82** and **83**. The dimension of the channel associated with source **80** can be quite small, such as .004 inch wide. As will be more apparent hereinafter, these sidewalls **82** and **83** in effect define cavities **84** and **85** that serve in a highly advantageous manner to hold the stream of fluid from **80** flowing into receiver **86** or receiver **87**, the particular receiver depending upon the direction of the most recent signal received in the control section **88** of the device.

As will be noted, the cavities **84** and **85** are of well-defined configuration, which start from a lower edge or point adjacent the control section **88**. This is upstream edge or point **90** in the case of cavity **84**, and upstream edge or paint **91** in the case of cavity **85**. It is most significant to note that when the stream of fluid from source **80** is flowing into receiver **86**, for example, the stream flows closely adjacent upstream edge **90** whereas when the flow of fluid is into receiver **87**, the stream of fluid flows closely adjacent upstream edge **91**. As will be obvious from the configuration exemplified in the FIGS. of drawing shown herein, when the stream of fluid is closely adjacent a point or edge, the respective cavity is in effect isolated from the rest of the chamber, and most significantly such cavity is isolated from the control port area. At such times as the jet flows closely adjacent one of these well-defined cavities, a comparatively low pressure is developed therein, as will be described more fully hereinafter, thus holding the jet in a desired position and eliminating the need for utilization of the Coanda wall attachment phenomena, as in prior art devices.

Control ports **92** and **93** are provided on opposite sides of the device as shown in FIG. **1** and arranged to open into the control section **88** of the device. A proper signal at control port **92** will be sufficient to rapidly switch the stream of fluid or jet from receiver **86** over to receiver **87**, and conversely, a proper at port **93** will be sufficient to rapidly switch the jet from receiver **87** over to receiver **86**. Exemplary FIG. **6** therefore represents a form of fluidic flip-flop.

Referring to FIG. **7** wherein a typical flow configuration is illustrated it is to be understood that a low pressure region is created in one or the other of the well-defined cavities **84** or **85** as a result of entrainment of cavity fluid by the jet when it is adjacent a particular cavity. The jet, which is initially laminar, seals off the cavity at upstream edge **90** or **91** as well as the respective downsteam edge **94** or **95** so that a small amount of entrainment creates a substantial decrease in pressure that is suitable for holding the jet very stably in that position. In this FIG., the flow is into receiver **87**, and two small arrows indicate the flow of fluid from cavity **85** as a result of this entrainment.

The cavities are also employed to quickly induce turbulence in an initially laminar jet. This is necessary since laminar jets do not entrain fluid effectively enough to create the desired low pressure region in the cavity. The transition to turbulence is effected by an initial disturbance from the respective upstream edge, in this instance edge **91**, transverse fluid interactions during flow across cavity **85**, and the sonic reflections from the respective downstream edge, in this instance edge **95**. These effects combine to induce turbulence in the initially laminar jet at a point between the upstream and downstream edges of the cavity, as illustrated, and it is the turbulent portion of the jet that entrains fluid from cavity **85** to create a low-pressure region in portion of the chamber defined by the arcuate wall **83** and the stream of fluid when such stream is adjacent this cavity. In other words, when the jet or stream is on the right-hand side of the chamber as viewed in FIG. **7**, it seals off the cavity **85** and thus isolates this low pressure region from the control section **88** of the device. This advantageously prevents dilution of this low-pressure region by flow through the control port and enhances the stability of the element as well as eliminating undesirable interactions with other elements connected to the control zone by means of attachment to control ports **92** or **93** as the case may be.

It should be noted that the stability of the jet that is achieved as a result of the low pressure created in cavity **85** when the stream of fluid is disposed on the right-hand side of the chamber is not derived entirely by virtue of cavity **85**, for a desirable high-pressure region is created on the opposite side of the stream of fluid as a result of the feedback flow injector **96** operating in conjunction with opposite **84**. The immediate-

ly foregoing statement is based upon the fact that the feedback flow injector **96** returns a portion of the power jet along the arcuate upper and side boundaries of chamber **81** to react against the jet in the vicinity of its upstream edge, as is depicted by some eight small arrows in FIG. **7**. In addition to this reaction, the reinjected velocity head is converted to static pressure which acts against the entire jet to help maintain it on the selected side. Thus it will be seen that whether the stream of fluid is flowing into receiver **86** or receiver **87**, the feedback flow injector **96** will serve in concert with the cavity that at that instant is farther from the stream of fluid to create a positive pressure buildup serving with the low pressure created in the cavity nearest the jet to hold such stream of fluid in the selected position.

It is not to be assumed that because of this combination of high and low pressures serving to hold the stream of fluid in the desired position that switching is difficult to bring about, for in reality the converse is true; switching is quite easily and very rapidly brought about in accordance with our novel design. Significantly, the pressure required to direct the jet from one receiver to the other is substantially lower than the pressure recovered in the receiver, which of course defines the gain of the element and establishes the fan-out capability of our device. Fan-out of course refers to the number of downstream logic elements that can be controlled from one element.

Assuming the stream of fluid in the right-hand position as illustrated in the bistable device depicted in FIG. **7**, upon the application of a control pressure at control port **93**, such acts on the jet upstream of edge **91** and establishes an initial deflection. This serves to open a low resistance path between edge **91** and the jet control cavity **85**, allowing the control signal to flow rapidly into the low-pressure region and distributing the switching pressure along the entire span of the cavity. The result of this is a nearly instantaneous snap action switching of the jet over to receiver **86**, this being accomplished in 20 microseconds or so rather than requiring one or more milliseconds in accordance with prior art devices wherein the control pressure had to "walk" along the length of an attachment wall in order to bring about switching of the jet away from that wall to the alternate position. Since the switching control forces act on the upstream of the cavity, switching is accomplished in accordance with our invention without the necessity of having to overcome the stabilizing forces.

The fluidic flip-flop illustrated in FIG. **7** should be noted to bear a resemblance to the illustrative device depicted in FIG. **6**, but differs in that it utilizes bleed ports or channels **98** and **99** connected to the left and right receivers **86** and **87**, respectively. As will be seen, these bleed channels serve to enhance stability of the element with respect to output impedance changes, increase pressure recovery, permit stable operation into a blocked load condition, and provide signal isolation in circuit interconnections.

Assuming the jet is entering the right-hand receiver **87** of FIG. **7**, if the load impedance of this receiver is increased, pressure would rise throughout the right-hand receiver if a bleed channel were not present, and eventually a pressure value would be reached that would cause the jet to separate from downstream edge **95**, which would unseal the low-pressure region existing in cavity **85** and allow receiver pressure to feed back into this region. This of course would serve to raise the pressure on the right-hand side of the jet and undesirably cause switching.

When in accordance with the embodiment shown in FIG. **7** bleed channels are incorporated, the pressure at point **95** is prevented by channel **99** from rising to a level that would cause separation of the jet from this point and the jet remains stable on the right-hand side of the device, even if the right-hand output channel **87** is blocked. It is therefore to be seen that in accordance with this facet of our invention, stability is increased substantially.

In addition, since the jet remains stable in the right-hand receiver in this circumstance, the pressure that can be recovered at the output of this receiver is also considerably increased, these factors contributing to the excellent stability and excellent gain characteristics of the device. By the placement of the bleed port **98** adjacent lefthand receiver **86**, a similar advantageous operating characteristic is obtained when the fluid jet is disposed to flow into the opposite receiver.

As another point with respect to this novel configuration, when the jet is flowing into say the right-hand receiver, the bleed channel of the left-hand receiver acts as a vent for any signals that may be impressed on the receiver, thus tending to provide a desirable isolation of the high-pressure region from such signals. A similar advantage is also obtained of course when the jet is flowing into the left-hand receiver, by virtue of the location of the right-hand bleed channel.

Although we are not to be limited to certain foil thicknesses, we generally prefer the use of comparatively thin foils, of a thickness of .010 inch or less, and highly satisfactory results have been obtained by using .004 inch foils. An approximate relationship between foil thickness and preferred cavity size may be deduced from FIGS. **8** and **9**, which of course correspond to FIGS. **6** and **7** respectively. Like FIGS. **6** and **7**, FIGS. **8** and **9** are primarily provided for the purpose of illustrating the chamber relationships, and do not purport to show as FIG. **2** somewhat did, the inlet and outlet connections or orifices associated with the control ports and the receivers. These orifices are of course to be understood to be connected to appropriate channels in the same plane, or in adjacent planes.

As revealed in FIG. **9**, if the nozzle **80** is presumed to be of a width dimension D, the chamber dimension from the nozzle outlet to the feedback flow injector **96** may be **10** times D, the width of a cavity in the direction of flow may be **6.5** D, and the depth of the cavity **2** D. These dimensions are quite satisfactory over a wide range of source pressures, but we of course are not to be limited to same, for the chamber configuration can be varied somewhat if preestablished source pressures are to be used.

Turning now to FIG. **10**, we illustrate in detail an OR-NOR device in accordance with our invention. In this device, a geometric bias exists, so that an output is provided in NOR receiver **107** at all times except when a control signal is present. When any combination of one or more control inputs is applied to the control port **113**, the device will switch so that an OR output is provided in lefthand receiver **106**. Therefore, this device is monostable and can satisfactorily perform the aforedescribed OR-NOR LOGIC FUNCTION.

As to the functional operation of the OR-NOR device of FIG. **10**, and presuming the presence of a control signal at port **113**, a turbulent jet is created from the laminar flow emanating from nozzle **100** as a result of a combination of excitations produced by the step expansion at the nozzle exit, the upstream edge or point **110**, the downstream edge or point **114**, and the complex flow interactions in the jet control chamber **101** in essentially the same manner as that described earlier for the symmetrical jet control chamber. The transition to turbulent flow is depicted in FIG. **10**. However, in this embodiment, the jet is biased, as previously mentioned, so that it always establishes itself in the right-hand receiver **107** when a control signal is not present. This biasing is accomplished by rotating the power nozzle **100** through a small angle from the center line of the device so that it points more toward the right-hand receiver **107** than to receiver **106**. The jet remains in this position as a result of its momentum and the force developed along its lefthand side due to the high-pressure region resulting from the action of the feedback flow injector described earlier. In this case, provision is not made for a sealed low-pressure cavity on the right-hand side of the jet since the forces developed by the high-pressure region on the left-hand side of the jet and the jet's momentum are adequate to normally hold the jet in the right-hand receiver. In this instance, the right-hand bleed channel **119** serves the same purpose as in the corresponding description of the fluidic flip-flop

it enhances stability of the device with respect to output impedance fluctuations, increases pressure recovery, and permits stable operation into a blocked load. The left-hand bleed channel **118** provides isolation from signals that may be impressed on the lefthand receiver **106**.

As to the details of switching the OR-NOR device, assume, as illustrated, that a signal is applied to the control port **113**. This signal will raise the pressure on the right-hand side of the jet to a point where the force developed by this pressure will overcome the jet's momentum and the force resulting from the high-pressure region on the left-hand side of the jet due to the feedback flow injector **116**, and the jet will switch to the left-hand receiver **106**.

The jet is held in this position by a combination of two forces. These are the force resulting from a high-pressure region on its right-hand side due to the control signal, and a force resulting from a low pressure region developed in the sealed cavity **104** disposed between points **110** and **114** located on the left-hand side of the jet. The reasons for establishment of this low pressure region were of course discussed in detail earlier.

In this state, the left-hand bleed channel **118** now provides the required stability with respect to output impedance variations, resulting in increased pressure recovery and stable operation with blocked receiver outputs. Again, the right-hand bleed channel **119** serves to isolate the jet control chamber from spurious signals that may be impressed on the right-hand receiver **107**. However, in this case, the right-hand bleed channel serves another very important function. As shown in FIG. **10**, the beginning of channel **119** is located upstream of the tip of the feedback flow injector **116**. This allows the flow from the feedback flow injector **116** to be dumped out the right-hand bleed **119** during the illustrated conditions, which prevents establishment of a high-pressure region due to feedback flow injection on the right-hand side of the jet. This enhances return switching to the right-hand receiver when the control signal is removed, thereby increasing frequency response.

Another bleed channel, channel **112**, is used in this embodiment, and is located opposite to the control port **113**. This channel is identical to the left-hand control port described earlier in the discussion of the fluidic flip-flop. Although it is not used as a control input in the OR-NOR logic gate, channel **112** serves a twofold purpose. First, assume the jet is in its normal position feeding into the right-hand receiver **107**. Bleed channel **112** then prevents the pressure resulting from feedback flow injection in the high-pressure region to the left of the jet from reaching an excessively high value. This in turn permits switching to the left-hand receiver with a lower magnitude control signal than would be the case if this bleed channel were not used. This feature then provides increased gain and frequency response.

In addition, bleed channel **112** enhances return switching from the lefthand to the right-hand receiver. To illustrate this, assume the jet is switched to the lefthand receiver and then the control signal is removed. As the control signal is removed, the power jet deflects toward the right because of the angle of the nozzle, and breaks the seal between it and point **110**. This opens the low pressure region **104** on the left-hand side of the jet to the bleed channel **112**, which provides a source of flow to fill the low-pressure cavity **104** and raises the pressure in this cavity to ambient level. This results in easier and more rapid return of the jet to the right-hand receiver than if bleed channel **112** were not used. This feature also tends to increase frequency response.

As is therefore to be seen, the arcuate cavity **104**, in a manner analogous to that of the bistable device, facilitates the transition to turbulent flow and isolates the resultant low-pressure region from both downstream and upstream effects, thus to enhance pressure recovery. The very fast response of our device is of course a consequence of the fact that we can operate with very small elements, in which laminar jets are employed.

FIG. **11** depicts a device called a load controlled fluidic pulse relay. It is used in digital counter circuits and other pulse operated devices. Its configuration is essentially the same as the fluidic flip-flop described earlier except the left- and right-hand control ports have been eliminated. Unlike the fluidic flip-flop however, the power nozzle **120** of the fluidic pulse relay is powered by intermittent pulses rather than by a continuous power source. Also, the output receiver in which the jet is established is controlled by a pressure differential applied across the receiver outputs rather than by conventional control ports.

Consider first operation of the device when the nozzle is powered. Assuming the jet is set to the right-hand receiver **127**, a turbulent jet is developed due to the combined influence of disturbances that occur at the nozzle exit, point **131**, point **135**, and the complex flow interactions in the jet control chamber **125** in a manner similar to that described previously. A low-pressure region will be developed on the right-hand side of the jet, and a high-pressure region on its left-hand side in exactly the same manner as these pressures are developed in the basic jet control chamber. If the jet is established in the left-hand receiver **126**, the pressure forces acting across it are of course reversed. The right- and left-hand bleed channels **139** and **138** serve the same purpose as the corresponding bleed channels of the fluidic flip-flop.

The unique feature of this embodiment is the manner in which the jet is directed toward a certain preselected receiver. Consider the device when there is no pressure applied to the power nozzle, and apply a pressure differential across the output receivers with the pressure applied to right-hand receiver **127** greater than that applied to lefthand receiver **126**. This pressure differential will establish a flow pattern in the device such that flow travels down the right-hand receiver, across the jet control chamber from right to left, and up through the left-hand receiver. Of course, some flow also escapes through the vent channels, but a substantial amount is passed across the jet control chamber from right to left.

Now consider what occurs when a pulse is applied to the power nozzle **120**. Initially a low energy jet begins to issue from the nozzle exit and the circulating flow in the jet control chamber deflects this jet to the left. As the power jet builds in intensity it develops a low-pressure region in left cavity **124** and a high-pressure region on its right in a manner described previously, and the forces resulting from these pressures hold the jet stably in left-hand receiver **126**. The jet will remain in this position until the pulse at the power nozzle is terminated. Once the power pulse is terminated, a control pressure differential can be reestablished across the output receivers. Suppose that in the next case the pressure applied to the left-hand receiver is greater than that applied to the right-hand receiver. This will establish a flow in the jet control chamber from left to right. When a pulse is again applied to the power nozzle, this left-to-right flow circulation will direct the jet to the right-hand receiver **127**, where it will remain until the power pulse is terminated. Therefore, this device transmits a power pulse to a particular output receiver, such receiver being selected by a pressure differential supplied from the load device during the off portion of the nozzle power pulse.

As is therefore to be seen, we have provided a new, useful and unobvious contribution to the fluidic art, in the form of a fluid jet device utilizing elements with unique chamber configurations. At least one cavity in accordance with this invention is disposed in such chamber, between the control port and receiver sections of the element, and by generating low pressure on one side of the fluid jet flowing into a receiver, and a high pressure on the other side, this novel cavity brings about the stable maintenance of the jet in a desired position in the chamber until such time as a control signal is applied to the control port section.

This invention can manifestly be utilized in monostable as well as bistable forms, and makes possible the utilization of elements so small that only laminar flows can emanate from the fluid nozzles of the elements. However, by virtue of the

fact that our novel cavity plays a vital role in bringing about the turbulent flow desired in the element chamber, elements with comparatively large jet nozzles are not required, thus making possible the construction of fluidic devices of a small size not heretofore thought possible, with much higher switching speed.

Six or so of such elements may be disposed on a single logic plane of foil smaller than one inch on a side, and by the use of appropriate interconnection and stacking techniques, dozens if not hundreds of such foils can be arrayed into a highly versatile device in which element density of several hundred per cubic inch is obtained.

As mentioned earlier, the logic planes are designed to conform to a standard layout. With this layout each logic element is placed in one of six or so corresponding positions in all planes containing logic elements, so that when these planes are stacked, a vertical column of elements is created. These columns of elements are arranged in a circular fashion around a common center vent **21** extending through the central area of the stack, which arrangement permits each column of elements to be powered from a common vertical supply passage formed from aligned ports, **22, 23, 24** etc. It also permits short, direct, and properly oriented interconnections from element column to element column. In addition, element bleed passages on the outside of the element ring can be ported directly to the edge of the stack, while vents on the inside of the element ring are ported directly to the center vent, eliminating the crossing of bleed and signal passages and simplifying circuit design.

As will be understood by those skilled in this art, a given device in accordance with our invention may involve some degree of repetition of plane design, and for example, one device on 160 planes used some 40 different plane designs constructed to the aforementioned standard layout principles. However, as the device involved becomes more complex, there generally is less repetition of plane design in a device.

As will be apparent, by utilizing the aforementioned standard configuration principles, several different basic logic planes can be made in large numbers utilizing certain etching techniques. These logic planes are typically made of foil as previously mentioned, and because each foil is an inch or less on a side, such logic planes can be made in large sheets that are thereafter separated to form the individual logic planes. Quite obviously each logic element is of quite small size, and, for example, may be 1/32 of the size shown in FIGS. **7, 10** and **11**.

As pointed out earlier, it is not necessary that every plane contain an element, for as was noted in connection with logic plane III in FIG. **2**, some of the planes may contain only interconnecting passages. Further, not all the logic planes of a given fluidic device need be of the same thickness, for if such be warranted, thicker or thinner planes than a standard thickness may be incorporated in a given fluidic device. Further, it is not necessary that the logic planes constituting a fluidic device be bonded together, for other techniques such as screwing the planes together may be employed. Furthermore, the planes need not be of metallic material, for in some instances thin planes of dimensionally stable plastic or even glass may be employed.

With regard to the recovery obtained by our elements, we have found that a pressure recovery of 25 percent is typical, with better values than this being obtained on many occasions. Flow recovery under certain conditions may actually exceed nozzle flow. As to pressure gain, which may be defined as recovered pressure divided by the pressure required to switch the element, values from 5 to 10 can be expected, depending on element design. Flow gain, as defined in an analogous manner, may also range from 5 to 10. These values when multiplied together represent power gain, which therefore may range from 25 to 100.

We claim:

1. In a bistable fluidic element, a source from which flows a stream of fluid, switching control means adjacent each side of said source, and at least two receivers into which said stream can flow, the flow into a particular receiver being on a selective basis as a result of an appropriate control fluid signal appearing at said control means, and a pair of edges interposed between said source and each of said receivers, said edges cooperating to render said flow of fluid turbulent, one of said edges of each pair being upstream of the other, with each upstream edge being closely adjacent the respective control means, a cavity defined between each pair of said edges, in which a comparatively low pressure is generated as a result of said turbulent flow, such low pressure being isolated by said upstream edge in each instance so as to prevent, when said stream of fluid is flowing into the respective receiver, inflow from the respective control means, said low pressure serving to hold said stream of fluid in a stable position until such time as a control signal appears at said control means and causes said stream of fluid to move away from said upstream edge and thus expose said low pressure to control fluid.

2. The element is defined in claim **1** in which the switching of said stream of fluid is brought about by flow into said switching control means from a related fluid element.

3. The element as defined in claim **1** in which feedback flow injector means is provided between the entrance to said receivers, to redirect a portion of the flow not entering a given receiver, around the cavity adjacent the other receiver and into direct contact with the stream of fluid at a location closely adjacent said source, the redirected flow tending to supplement the efforts of said cavities in stabilizing the flow into such receiver.

4. A fluidic element in which a stream of fluid flows from a source, across a chamber and thence into one or the other of a pair of receivers, control port means connected to said chamber, means defining a cavity in said chamber disposed between said source and the entrance to one of said receivers, said cavity being on the opposite side of said chamber from said control port means and including upstream and downstream edges adjacent which said stream flows when entering said one receiver, feedback flow injector means disposed adjacent the entrances to said receivers and arranged in such a relationship to said cavity as to redirect a portion of said stream flowing into a receiver so as to cause it to flow in a generally circular direction about said chamber, said cavity on occasion serving to help redirect such flow somewhat back toward said source so as to act directly against the stream adjacent the source in a direction tending to help maintain said stream stably in one of two possible positions, said control port means, upon receiving an input signal, being responsible for causing said stream to shift so as to enter a different receiver, at the same time causing a cessation of flow of the previously recited stream in the generally circular direction through said cavity, said cavity thereafter tending to develop a relatively low pressure therein as a result of the stream flowing closely adjacent said upstream and downstream edges, which low pressure tends to hold said stream adjacent such upstream and downstream edges so that said stream will flow into the receiver adjacent such cavity, said fluidic element further including an additional cavity, such that a cavity is associated with each of said receivers, said feedback flow injector means being disposed between the entrances to said receivers so as to function to redirect a portion of the stream of fluid around said chamber, regardless of which receiver such stream of fluid is entering, thereby assuring the buildup of pressure in whatever portion of said chamber at any instant is opposite the cavity in which said stream of fluid is causing the relatively low pressure.

5. A fluid logic element comprising a fluid interaction chamber for confining fluid flow therein to planar flow, a nozzle for issuing a well-defined stream into one end of said chamber, at least a pair of output passages having the entrances thereof located downstream of said nozzle for receiving the stream therefrom, said entrances defining the other end of the said chamber, control means adjacent said nozzle and responsive to an input signal for causing said stream to be

deflected from one passage into the other of said passages, said chamber including means defining a cavity proximate said entrance to said other passage for creating a comparatively low pressure during the time said stream flows close by, for the purpose of stably holding said stream in said other passage, and means for scooping off and redirecting a portion of said stream while said stream is directed into said one passage for creating a flow around a substantial portion of said chamber and through said cavity, the flow through said cavity helping direct a flow of fluid against the stream at the location where it emanates from said nozzle, thus to assist said stream remaining stably in said one passage.

6. The element as defined in claim 5 in which a straight wall is associated with said one passage, along which wall said stream normally flows except during the duration of an input signal.

7. The element as defined in claim 5 in which two cavities are utilized in said chamber, each of which serving to hold said stream flowing in a stable manner into the adjacent passage.

8. The element as defined in claim 7 in which said nozzle provides an intermittent flow, said passages being arranged on occasion to have unequal back pressures thereon, thus to cause a flow from one passage, across said chamber, and thence into the other passage, said nozzle directing said stream into the passage into which flow is taking place at such time as it recommences issuing a stream.

9. A fluid logic element comprising a fluid interaction chamber for confining fluid flow therein to planar flow, a nozzle for issuing a well-defined stream into one end of said chamber, at least a pair of output passages having the entrances thereof located downstream of said nozzle for receiving the stream therefrom, said entrances defining the other end of said chamber, means for causing said stream to flow into a preferred passage of said pair of passages, means responsive to an input signal for deflecting the stream from said preferred passage into the nonpreferred passage, an arcuate cavity located on a side of said chamber corresponding to said nonpreferred passage, feedback flow injector means disposed between said entrances to said output passages, and serving to redirect part of the flow intended for a given passage, said cavity acting in conjunction with said feedback flow injector in the absence of a control signal to provide circulation throughout a major portion of said chamber and hence a positive pressure on the stream at a location immediately adjacent said nozzle tending to hold it on said preferred side of said chamber, but in the presence of a control signal, said arcuate cavity providing a negative pressure which enhances stability of said stream in flowing into said nonpreferred output passage, and means defining a vent in a portion of said chamber for discharging the flow redirected by said feedback flow injector means when said stream is directed into said nonpreferred output passage, thus to eliminate any positive pressure on said preferred side and facilitate rapid return of said stream to said preferred side.

10. In a fluidic device having alternate receivers, a source from which an initially laminar flow of fluid issues, control port means for switching said flow of fluid between said alternate receivers, means defining a cavity located between said control port means and a receiver for establishing on occasion the flow of fluid into one of said receivers, said cavity having an upstream edge, said flow of fluid becoming turbulent upon flowing past said upstream edge and said cavity, and causing entrainment of fluid such as to bring about a comparatively low pressure in said cavity, the low pressure existing in said cavity contributing to hold said flow of fluid in a stable position flowing into said one receiver, the fluid from said source at times flowing into the other of said receivers, and feedback flow means in said chamber for bringing about a flow of fluid around a substantial portion of said chamber and through said cavity at such times as fluid flows into such other receiver, latter flow adding to the stability of the flow by being directed at a location immediately adjacent said source.

11. The fluidic device as defined in claim 10 in which a straight wall is associated with the other receiver, said other receiver and wall representing the preferred position for said stream of fluid, said control port means being adjacent said straight wall for causing said stream of fluid to switch to said position closely adjacent said cavity during the continuation of said signal.

12. The fluidic device as defined in claim 10 in which a cavity is provided in conjunction with each of said receivers, so that said flow of fluid will be held by a cavity in a stable position with regard to either receiver, the cavity opposite the cavity closely adjacent the flow at any instant serving to develop a comparatively high pressure therein, which serves to reinforce the stabilizing effect provided by the comparatively low pressure existing in the cavity nearest said flow of fluid.

13. The fluidic device as defined in claim 10 in which a feedback flow injector disposed between said receivers is responsible for recirculating fluid not entering a given receiver, thus to bring about such comparatively high pressure.

14. A fluidic device comprising a substantially circular chamber, means for issuing a stream of fluid under pressure so that said fluid flows across substantially the central portion of said chamber, and a pair of receivers on substantially the opposite side of said chamber from said means, into one or the other of which receivers said stream of fluid can flow, control means for selectively switching said stream of fluid between receivers, a pair of edges on each side of said chamber so that despite which receiver receives said stream of fluid, said stream will flow past a pair of edges, one of said edges of each pair being upstream of the other and tending to bring about turbulence in said stream of fluid, the presence of the respective downstream edge cooperating to assure the transition to turbulent flow by the time said stream of fluid enters the adjacent receiver, a cavity defined between each pair of said upstream and downstream edges, in which a lowered pressure is created as a result of said turbulent flow occurring nearby, thus bringing about a force tending to hold said stream of fluid stably in either position undertaken by the stream of fluid, and feedback flow injector means between said receivers for redirecting a portion of said turbulent flow, said redirected turbulent flow impinging upon said stream just as it enters said chamber and thus tending to create a high pressure on the opposite side of said stream of fluid from the cavity closely adjacent which said stream may be flowing, therein tending to reinforce the stability of said stream of fluid in flowing into the respective receiver.

15. The fluidic device as defined in claim 14 in which said control means serves to supply control fluid to move said stream of fluid away from close proximity to an upstream edge, thus exposing the respective cavity to the control fluid in such a manner that control fluid will be drawn into said cavity and bring about switching of said stream of fluid by virtue of the creation in said cavity of a pressure greater than that in the remaining portion of said chamber.

16. The fluidic device as defined in claim 14 in which said means for issuing a stream of fluid issues an intermittent flow, and a separate flow occurring through said chamber between said receivers, whereby upon a flow taking place from said means for issuing a stream of fluid, such stream flows into the receiver in which said separate flow is flowing.

17. In a high speed fluidic element, a jet source, a chamber, a pair of receivers disposed on an opposite portion of said chamber from said source, into one or the other of which receivers said jet on occasion can travel after flowing across said chamber, a feedback flow injector disposed between the entrances of said receivers, said feedback flow injector being arranged to redirect a portion of the fluid flow intended for a receiver around at least a portion of said chamber, at least one cavity defined in said chamber, said cavity being disposed between said jet source and the entrance to one of said receivers, and having upstream and downstream edges across

which said jet can flow when directed into said one receiver, said cavity tending to develop therein a lowered pressure upon fluid flowing past, thus tending to help hold the jet of fluid flowing into said one receiver, said cavity on occasion receiving flow from said feeback flow injector, and on such occasion helping direct a fluid flow against the jet at a location immediately adjacent the location where it emanates from said source, to help hold it in its then position, and control means adjacent said jet source and upstream of said cavity for controlling positioning of said jet into the desired receiver.

18. The high speed fluidic element as defined in claim **17** in which a pair of cavities are utilized on opposite sides of said chamber, with each cavity being disposed so as to be able on occasion to receive the flow from said feedback flow injector, and thus function to help hold the jet flowing stably into whichever receiver it happens to be flowing into a given time.

19. The high speed fluidic element as defined in claim **17** in which only a single cavity is utilized, said element having monostable characteristics.

20. A fluidic element in which a stream of fluid flows from a source, across a chamber and thence into one or the other of a pair of receivers, control port means connected to said chamber, means defining a cavity in said chamber disposed between said source and the entrance to one of said receivers, said cavity being on the opposite side of said chamber from said control port means and including upstream and downstream edges adjacent which said stream flows when entering said one receiver, feedback flow injector means disposed adjacent the entrances to said receivers and arranged in such a relationship to said cavity as to redirect a portion of said stream when flowing into the other of said receivers so as to cause it to flow in a generally circular direction about said chamber, said cavity on such occasion serving to help redirect the flow back toward said source so as to act directly against stream closely adjacent said source in a direction tending to help maintain said stream stably in one of two possible positions, said control port means, upon receiving an input signal, being responsible for causing said stream to shift so as to enter said one receiver, and at the same time causing a cessation of flow of the previously recited stream in the recited generally circular direction through said cavity, said cavity thereafter tending to develop a relatively low pressure therein as a result of said stream flowing closely adjacent said upstream and downstream edges so that said stream will flow into said one receiver adjacent such cavity.

21. The fluidic element as defined in claim **20** in which a comparatively straight wall is provided in said chamber adjacent one of said receivers, said source of fluid being geometrically biased so as to cause said stream of fluid normally to enter said receiver adjacent said comparatively straight wall, said feedback flow injector means being disposed between said receivers and serving, when said stream is flowing into the receiver adjacent said wall, to redirect a portion of the stream latter-mentioned entering lattermentioned receiver in a generally circular direction through said chamber so as to build up a comparatively high-pressure region tending to supplement the effect of said geometrical bias.

22. The fluidic element as defined in claim **21** in which said control port means is provided adjacent an upstream portion of said stream of fluid, with a proper signal at said port causing said stream to switch from the preferred position in which it flows into said receiver adjacent said wall, to a position in which it flows into the nonpreferred receiver adjacent said cavity, the comparatively low pressure created in said cavity as a consequence of the flow of said stream contributing to stably hold said stream in the position in which it flows into the nonpreferred receiver during the continuation of said signal.

23. The fluidic element as defined in claim **22** in which a bleed port is provided between said comparatively straight wall and its respective receiver, said bleed port representing an orifice through which flow can take place, said feedback flow injector means serving to redirect a portion of flow into said port when said stream is flowing into the nonpreferred receiver, thereby to prevent an undesired buildup of pressure of said chamber remote from said cavity, thus to enable said stream to switch back promptly to the preferred receiver when the signal at said control port means is terminated.

24. A bistable fluid logic element not dependent upon wall attachment principles, comprising a fluid interaction chamber for confining fluid flow therein to planar flow, a nozzle for issuing a well-defined fluid stream into one end of said chamber, a pair of output passages at substantially the opposite end of said chamber, and having entrances disposed such that flow from said nozzle can take place into one or the other of said passages, a pair of generally symmetrically placed cavities in said chamber, with control port means being disposed on the opposite sides of the chamber, each cavity being disposed downstream of said control port means and upstream of the nearest output passage, feedback flow director means disposed between said entrances to said output passages for scooping off and redirecting a portion of said stream while said stream is directed into one or the other of said passages, said flow director means thus creating with either of said cavities a configuration responsible for directing fluid flow around a substantial portion of said chamber, with the configuration and placement of each cavity being responsible for directing such fluid flow against the base of said stream flowing from said nozzle at a location closely adjacent where it passes the downstream edge of its control port means, the flow of said stream past one of said cavities and into the respective output passage thus causing through the action of said feedback flow director means, flow through the other of said cavities and establishing a positive pressure tending to hold said stream flowing from the nozzle in the position in which it flows stably into the one output passage, the upstream edge of said one cavity causing said flow of fluid from said nozzle to become turbulent upon flowing past, and causing entrainment of fluid such as to bring about a comparatively low pressure in said one cavity, the low pressure existing in said one cavity contributing to hold said flow of fluid in a stable position flowing into said one output passage, said low pressure being destroyed when flow is introduced through the respective control port means, thus causing said stream to be directed into said other output passage.

25. A fluid logic element not dependent upon wall attachment principles, comprising a fluid interaction chamber for confining fluid flow therein to planar flow, a nozzle for issuing a well-defined fluid stream into one end of said chamber, a pair of output passages at substantially the opposite end of said chamber, and having entrances disposed such that flow from said nozzle can take place into one or the other of said passages, at least one cavity in said chamber, with control port means being disposed on the opposite side of the chamber from said cavity, said cavity being disposed on downstream of said control port and upstream of the nearest output passage, feedback flow director means disposed between said entrances to said output passages for scooping off and redirecting a portion of said stream while said stream is directed into said one passage, said flow director means thus creating with said cavity a configuration responsible for directing fluid flow around a substantial portion of said chamber, with the configuration and placement of said cavity being responsible for directing such fluid flow against the base of said stream flowing from said nozzle at a location closely adjacent where it passes the downstream edge of said control port means, the flow through said feedback flow director and said cavity thus establishing a positive pressure tending to hold said stream flowing from the nozzle in the position in which it flows stably into said one output passage, said fluid logic element further including an additional cavity, such that a pair of cavities are employed and said element has bistable characteristics, said cavities being disposed on opposite sides of the chamber between said source and output passages, each cavity having an upstream edge immediately adjacent a control port, each upstream edge with the cooperation of a fluid jet, when flowing closely by, isolating the respective cavity from the adjacent

control port except when a control signal is applied to such control port to bring about a switching of the stream from one output passage to the other.