W. F. Voit, Jr.

Digital Pneumatic Logic Using Coded Tapes

A number of exploratory studies have been made during the past five years on the use of fluid logic elements to replace conventional electronics in certain applications. IBM began to study fluid logic at the Zurich Research Laboratory about 1956. This work was initially directed toward using a spool valve to perform the logic function[1] but was rapidly expanded to investigate other elements. Most of the present interest in fluid logic is a result of the invention of the fluid jet amplifier (wall interaction amplifier) in 1959 at the Harry Diamond Laboratory. This amplifier consists of a high-energy stream of fluid passing through a nozzle into a cavity which contains two diverging walls. Control channels are located perpendicular to the nozzle, enabling low-energy control streams to switch the high-energy stream from one wall to the other.[2] This element can be made either monostable or bistable and has been constructed to produce several logic functions (AND, OR, NOR, etc.). By combining these into a system, one can produce some rather sophisticated logic. Although the element by itself appears to be simple, considerable expertise is required to connect a number of elements together into a reliable system.

Numerous other fluid logic elements have been developed, both with and without moving parts; these include ball valves, spool valves, vortex chambers, impacting jets and laminar-turbulent jets.

Initial work by the author and his co-workers, together with the knowledge of some specific applications, has led to the development of a class of elements that use a coded flexible strip as the valving member. The actuation of this strip is performed pneumatically by deflecting the strip into a profiled cavity, thereby producing a controlled displacement of the coded portion of the strip. For the lack of a better name, we shall refer to these as tape elements, since in practice a Mylar tape has been the flexible member. Several characteristics of the element are given below:

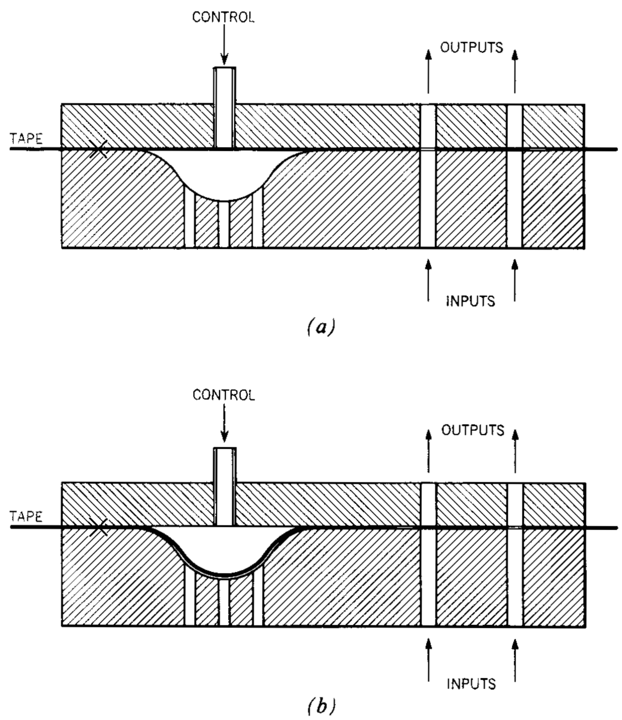
- The element is capable of controlling many outputs.
- The control input is isolated from the output.
- Variation in the output impedance will not switch the element.
- Moving parts are involved, but they are lightweight.
- The element is simple and inexpensive.
- For obvious practical reasons, the element operates with air as the working medium.

The following sections describe several tape logic elements and a pneumatic actuator, which together form the basic building blocks for a complete logic system utilizing pneumatic techniques.

Monostable element

Figure 1a shows a monostable element that consists of a lower block with an actuating cavity at one end, a coded tape and a cover block. The lower block contains a groove along which the tape is free to move. The tape is clamped at one end with the coded end free. A pneumatic signal applied to the control channel creates a pressure differential

Figure 1 (a) Monostable element—tape horizontal; (b) Monostable element—tape in cavity.



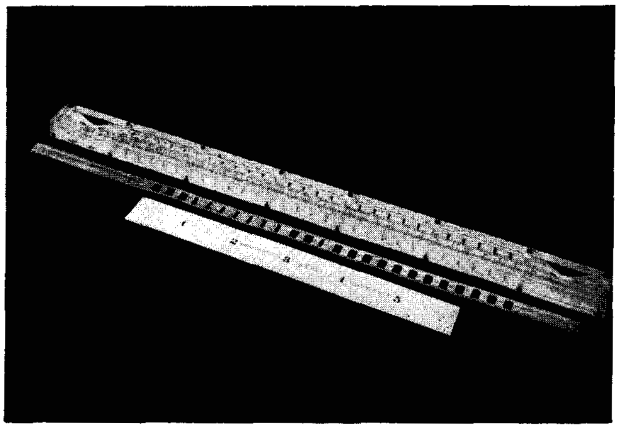


Figure 2 Storage element and tape.

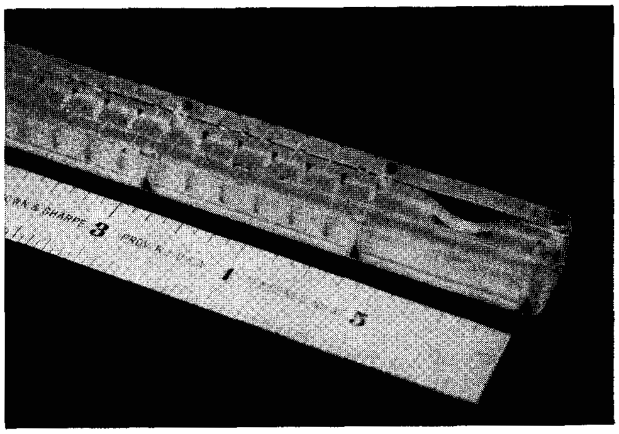


Figure 3 One end of the storage element showing the actuating cavity.

across the tape, deflecting it into the actuating cavity and producing a displacement of the coded end. Figure 1b shows a tape deflected into the actuating cavity with the coded portion controlling the various output channels. When the control signal is removed, the tape, because of its elastic properties, snaps back to the horizontal position, producing a monostable action. It should be noted that channels vent the bottom of the actuating cavity to atmosphere, permitting the air which leaks by the edges of the tape to escape. Maximum control signal leakage occurs during switching, since the tape in the deflected position seals the vent.

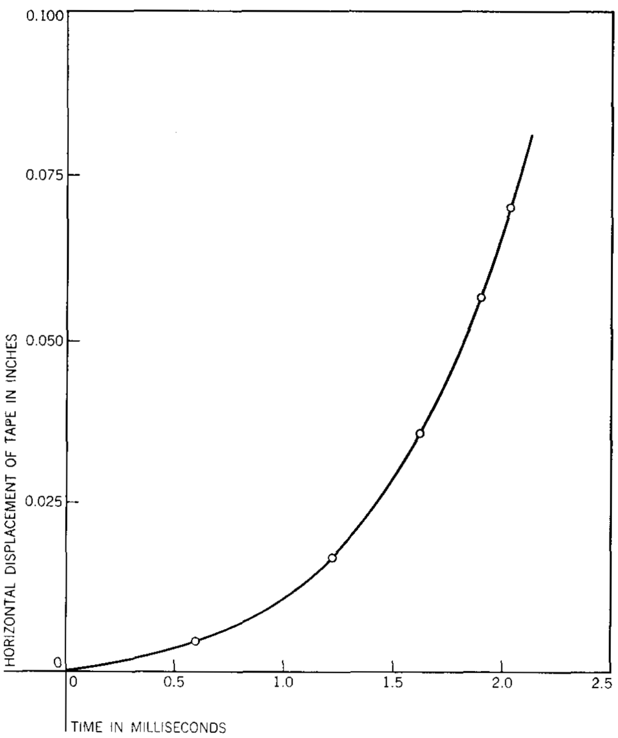
Storage element

A storage element, Fig. 2, consists of a coded tape and a block with an actuating cavity, Fig. 3, at either end. These cavities are connected by a groove in the surface of the block, and a series of output channels is located between them. The tape is clamped at both ends with sufficient slack to conform to one of the cavities while bridging the other. The tape can be deflected into either cavity by applying the appropriate control signal and will remain in the cavity after the removal of the signal, thereby producing the storage function. The control signal leakage characteristics of this element are similar to that of the monostable element.

A displacement-time relationship for a particular element, operating at a pressure of 20 inches of water, is given in Fig. 4. The element is considered to be operating in the pulsed mode; that is, the output channels are pulsed after the element is switched. (The reason for operating in this fashion will be explained later in this discussion.)

The storage action for this element can be explained in the following manner: When the tape is bridging a cavity, it is essentially a slender column with built-in ends. The force-displacement relationship for a typical tape, under a column load, shows the force to be constant over the displacement under consideration. The magnitude of the force is given by the critical load from the Euler equation[3] for a column with built-in ends. Considering the forces acting on the center section of the tape, we have a force F acting on each end, regardless of the cavity into which the tape is deflected, and a frictional force F_f opposing motion. Thus, $F + F_f > F$ ensures the storage function. In practice, the forces F and F_f are extremely

Figure 4 Displacement-time relationship for tape element switching.



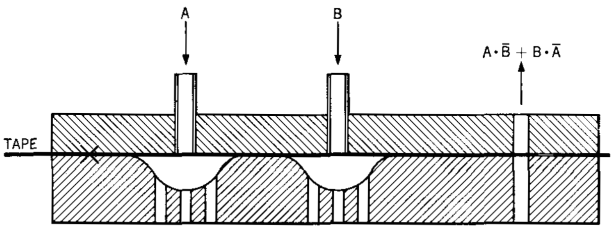


Figure 5 EXCLUSIVE OR element.

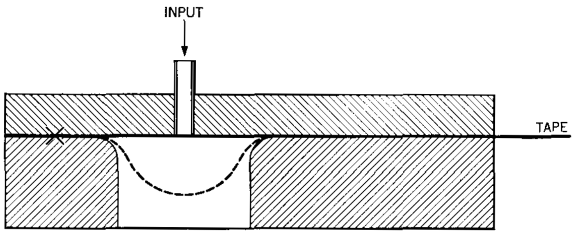


Figure 7 Sketch of actuator.

small. The frictional force F_f results from the contact of tape and groove and occurs as the deflected portion of the tape makes the transition from the cavity to the groove.

Other elements

Elements using the aforementioned techniques can be constructed to produce an array of logical operations. For example, Fig. 5 shows an element used to obtain the EXCLUSIVE OR function. It consists of two actuating cavities in series and is shown as a monostable element, although it could be constructed with memory. The control inputs are denoted A and B. With the tape coded to produce an output when deflected into only one cavity, an output is obtained only if the inputs are $A \cdot \bar{B} + B \cdot \bar{A}$.

Logic circuits

The ability of a single tape to control many outputs enables one to generate some very simple, yet powerful, logic arrangements. Figure 6 shows a number of memory elements stacked to produce a circuit for code translation. The translator receives parallel pneumatic inputs in one code and produces parallel outputs in another code. The sequence of events for translation is as follows:

1. All tapes are reset into one cavity.
2. The desired tapes are set in parallel.
3. The output channels are pneumatically pulsed.

The tapes are arranged in such a fashion as to minimize the length of the interconnecting channels, thereby decreasing line losses and improving the system's response. Also, with a minimum of leakage paths, the power transfer efficiency is quite high. (Power transfer efficiency is defined as the power recovered from the output channels divided by the power supplied to the output channels.)

Most of our translator circuits to date have operated in the pulsed mode in which a series of tapes are set; then the output channels are pulsed. This mode of operation has been chosen, for translator circuits with parallel inputs, to eliminate possible transient outputs which could otherwise occur during tape switching. In contrast, most of the control circuits constructed are sequential circuits and do not operate in the pulsed mode.

Actuator

In many pneumatic system applications, the desired output is mechanical work; that is, a force is to act through some distance in order to actuate a mechanical system.

Figure 6 Translator assembly.

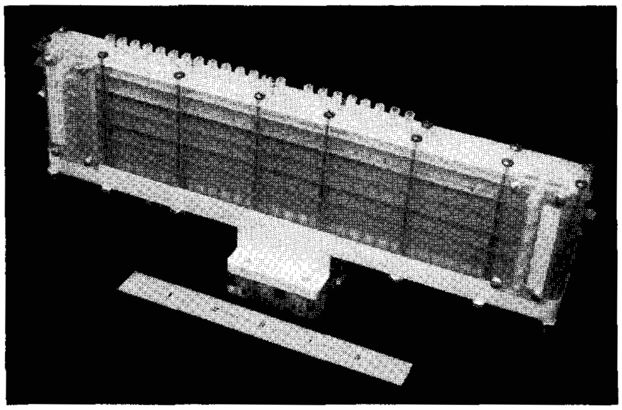
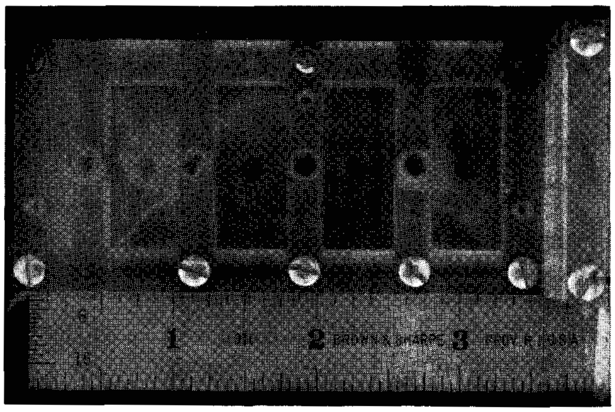


Figure 8 Actuator assembly.



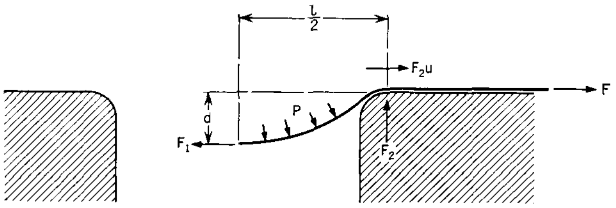


Figure 9 Forces acting on tape segment.

An actuator has been developed as shown in Fig. 7. It consists of an actuating block with a cavity and tape groove, a tape and a cover block. The tape is anchored at one end, the other end remaining free. Figure 8 shows a number of these actuators in an assembly. A pneumatic signal applied to the actuating cavity deflects the tape and produces a displacement and corresponding force at the free end of the tape. The force is a function of the pressure differential across the tape, the geometry of the tape cavity, the amount the tape is deflected into the cavity and the coefficient of friction between the materials used for the tape and that used for the housing.

Figure 9 shows a portion of the actuator tape with the forces acting on the tape. Assuming F_2 as the vertical reaction force, the output force F is represented by the equation:

$$F = Pw\left(\frac{l^2}{8d} - \frac{d}{2} - \frac{l\mu}{2}\right),$$

P = average pressure differential across the tape,

w = width of tape,

l = length of tape exposed to pressure differential,

d = deflection of tape, and

μ = coefficient of friction between tape and cavity.

Experimental results have verified this expression.

The force-displacement relationship for a particular actuator is shown in Fig. 10. Two interesting characteristics of this actuator should be noted.

- The output force is a maximum at zero displacement and decreases with increasing displacement.
- Force amplification is obtained over the initial portion of the displacement due to the nonlinear relationship between tape deflection and motion of the free end of the tape.

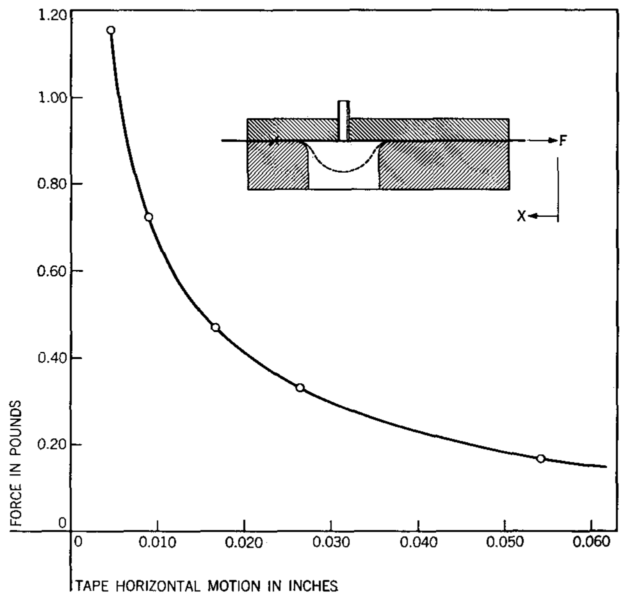


Figure 10 Force-displacement plot for actuator.

Remarks

Our experience to date indicates that tape elements offer a simple and low-cost technique for performing pneumatic logic. A minimum number of lightweight, moving parts can be built into a system that is logically quite powerful.

Acknowledgments

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