LINEAR PIEZO-ACTUATOR AND ITS APPLICATIONS

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ABSTRACT

The electromagnetic machine has long been used as one of the main devices to produce rotary and linear movement. Generally, electromagnetic actuators have a good frequency range and have excellent force and displacement output. But they usually are heavy and require significant electrical power. It is also difficult to obtain accurate displacements of under one micrometer without special design, measurement and compensation methods. Usually complicated close-loop control has to be used where high speed and high positional accuracy are needed. On the other hand, piezo-actuators are known for their excellent operating bandwidth and can generate large forces from a compact size. With piezo actuators it is relatively easy to get positional accuracy of under several nanometers. But the problem with piezo-actuators is that their application is limited because they have very small displacements. This paper reviews different structures that have been developed to increase the displacement of piezo-actuators.

1.0 INTRODUCTION

When certain types of crystal are subjected to tensile or compressive forces, the resulting strain causes a polarized state in the crystal, and an electric field is created. Conversely, if a crystal is polarized by an electric field, strains along with the corresponding stresses are created. Together, these two effects are known as the piezoelectric effect. The two aspects are sometimes distinguished as the positive and reverse effects [1]. The latter has been used for linear actuation which can directly convert the input electrical energy into output mechanical energy and linear movement. Until now linear actuation has been dominated by hydraulic and pneumatic cylinders, electromagnetic solenoids, voice coil motor and by linear electromagnetic motors. These motor devices are widely used in different applications, such as machine tools, automotive control systems and aircraft. But piezo actuators can easily supply super-precision linear movement, which is generally difficult for other methods of linear actuation to achieve [1][2].

One of the problems of piezo actuation is that the single piezo element can only produce expansion in the range of several micrometers. To reduce this limitation, a useful multi-layer design has been developed called the piezo stack actuator. Stack actuators can generate linear movement reaching displacements of 250 micrometers and forces up to 10 KN with very high speed. Although the stack design has made the piezo actuator practical, the displacement of the piezo stack is still very limited for some applications [1-4]. For example, a piezo driven control valve still cannot directly replace solenoid driven pneumatic valves in motor vehicles because of their small displacement. However, the piezo stack actuator can often produce much bigger output forces than required for some applications. It is then possible to develop mechanical amplifier structures that increase the displacement of the stack actuator but with a corresponding reduction in force.

This paper reviews some typical mechanical amplifier structures for the piezo stack actuator. Application examples are also given.

2.0 PRINCIPLES OF PIEZO ACTUATION

There are two basic types of piezo actuator; the stack and the bender. Based on these two types of actuator, amplifier structures have been designed to increase the available displacement.

Both the stack and the bender work on the same underlying principles. If we ignore the hysteresis effect, the relationship between strain and electric field strength for a single piece of piezo element can be expressed as $\frac{\Delta l}{l} = dE$. The proportional constant d is called the piezoelectric strain constant (mV^{-1}). Where E is the electric field strength and $\frac{\Delta l}{l}$ is the strain. Because of $E = \frac{U}{l}$, then we get $\Delta l = dU$. So, we can deduce that the deformation Δl is independent of the dimensions, where U is the applied voltage (v).

As piezoelectric strains are generally extremely small, with the strain constant d typically around 10^{-10} to 10^{-9} mV^{-1}, a practical piezo actuator can be manufactured by putting many thin slices of piezo ceramics together to produce large deformation. This type of arrangement results in the stack actuator. Figure 1(a) shows the structure of a stack actuator.

The stroke of piezo stack actuator can be calculated by:

$$l_{stroke} = Nd_{33}U$$

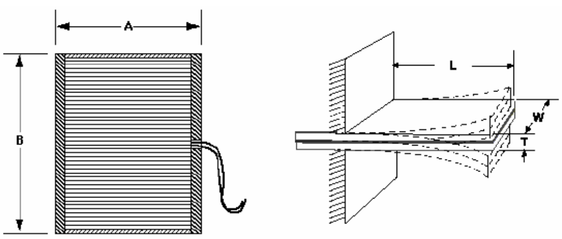
And the blocked force:

$$F = \frac{l_{stroke}.A}{NtS_{33}{}^{E}}$$

Where, N is the Number of thin piezo layers, d_{33} is the piezoelectric constant (m/v), U is applied voltage (v), A is the section (m^2) of the piezo actuator, t is the layer thickness (m). $S_{33}{}^{E}$ is the elastic constant (m^2/N), l_{stroke} is the total stroke (m) and F is the blocking force (N).

Figure 1(b) illustrates the typical structure of the bender actuator. Usually, the bender consists of two piezo plates which are joined together. During actuation, one piezo plate is extended and the other one is simultaneously contracted. This produces a bending action which results in the desired output force and displacement. Table 1 shows the equations describing the bender's force and displacement.

Compared with the stack piezo actuator, the bender piezo actuator can give only very small output forces (typically about 1 N) and about +/-1mm maximum displacement. It is the cheapest practical piezo actuator and has been successfully used in inkjet printers, hard-disk drives, micro pumps and small valves.



(a) (b)

Figure 1 The structures of the stack (a) and bender (b) actuators.

Table 1 Displacement and force for bender

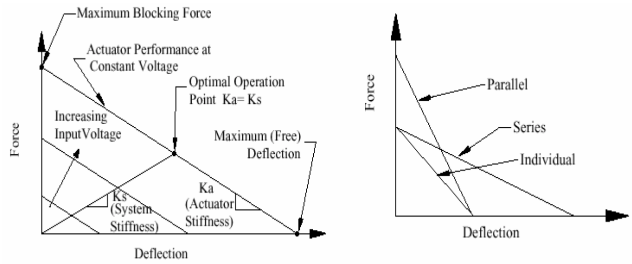
Displacement	Blocking force
$\Delta l_s = \frac{3T}{2L^2} d_{31}U$	$\frac{3TW}{8L} Y_{11}{}^{E} d_{31}U$
$\Delta l_p = \frac{3T}{L^2} d_{31}U$	$\frac{3TW}{4L} Y_{11}{}^{E} d_{31}U$

Piezo elements have the property of being able to produce large forces but with a very small displacement. When developing new actuators, engineers have to address this trade-off between force and displacement. The relationship between force and deflection of piezo actuators is shown in Figure 2.

At the point where the system stiffness equals the stiffness of the actuator, the actuator system can get maximum outside output energy. The output displacement δl_F, under force F is

$$\delta l_F = \frac{1}{1 + {k_s}/{k_a}} \delta_{\max} .$$

Where $\delta_{\max}$ is the unloaded maximum displacement of the actuator; k_s and k_a are the stiffness of the system and the actuator respectively. Figure 2(b) shows the behavior of the actuator system when two or more piezo actuators are connected in serious or parallel [4].



(a) (b)

Figure 2 Force vs. deflection of piezo actuators

3.0 ACTUATION PRINCIPLES

This section reviews typical arrangements used for applying the piezoelectric effect to actuation. The different approaches to developing piezo actuators may be classified as follows.

- **Piezo actuator with mechanical amplifier.** Because the displacement of the stack piezo actuator is too small in many applications, it is increased using a mechanical amplifier such as a lever. This type of actuator can produce more than 10 times the displacement typically obtained directly from a stack type actuator but its force and frequency are decreased accordingly. Amplifying mechanisms are described in more detail in Section 3.1.
- **Inertial drive actuator.** These actuators use friction and inertial forces to produce large displacements. They are described in Section 3.2.
- **Inchworm actuator.** In theory, the inchworm piezo motor can produce unlimited linear displacement, but with limited force and response frequency. Inchworm actuators are described in more detail in Section 3.3.
- **Ultrasonic motor.** The ultrasonic motor is similar to the inchworm actuator, but works at its resonant frequency and so can produce a larger output force. The performance of an ultrasonic

motor depends heavily on its design and its structure. Ultrasonic motors are described in Section 3.4.

The remainder of this section describes these typical arrangements in more detail.

3.1 Piezo actuators with mechanical amplifiers

Stack actuators can produce very large output forces but with a correspondingly short displacement. On the other hand, the bender has a large deflection, but its force is very small. Consequently the direct application of the simple stack and bender actuator is sometimes limited. To use the advantages of stack actuators and to increase the displacement, special designs are needed.

3.1.1 Mechanical lever

The simplest way to amplify the movement is using a mechanical lever. Figure 3 shows an example. The lever must be made of rigid and light materials to provide good efficiency and high resonant frequency for fast operation [4]. The amplified output displacement proportional to the lever ratio.

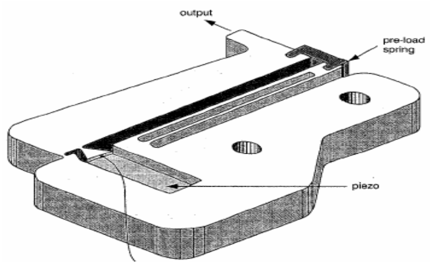


Figure 3 Piezo actuator with lever amplifier

3.1.2 Diamond flexure amplifier structure

Figure 4 shows the typical structure of the diamond flexure amplifier [5]. The amplified ratio is about l/h, where h is the height of the triangle. Then if the original piezo stroke is δ, the amplified displacement is $\delta\, l/h$. The advantage of this kind of actuator is that it can produce high displacement and high force with high frequency. Typically, more than 10 times displacement can be obtained with this arrangement than by using a stack alone.

Researchers have made the diamond structure using a monolithic piece of ceramic [6] (Figure 5).

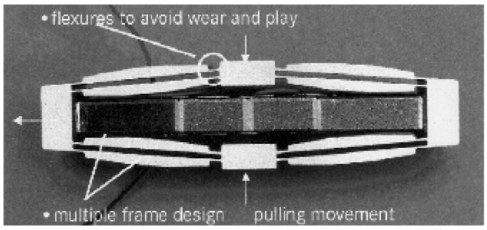


Figure 4 Flexure amplifier structure

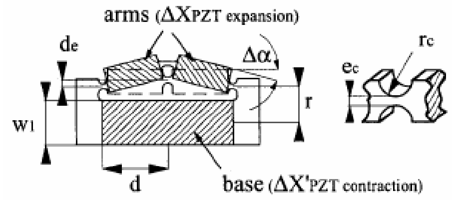


Figure 5 Monolithic piezo actuator

3.1.3 CYMBAL transducer

Figure 6 shows another kind of structure called the CYMBAL. The CYMBAL is similar to the diamond structure in that it features large displacement and large force but with more cost effective manufacturing. The shape of the CYMBAL is round (whereas the diamond is oblong) and the end caps can be manufactured by model punching. The piezo ceramic and end caps can be put together by super glue. An example of a CYMBAL of diameter 12.7mm by thickness 1.7mm can produce a 40 μm displacement and 15 N output force [7,10].

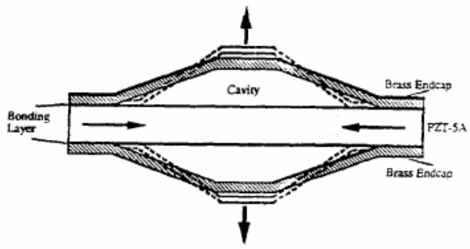


Figure 6 CYMBAL Piezo Actuator

3.1.4 Hydraulic amplification mechanisms

Figure 7 shows hydraulic amplification structures for use with piezo actuators [3, 8]. Hydraulic fluid in a reservoir is actuated by a piezo actuator and drives a small piston cylinder. The small cylinder is hydraulically connected to a larger one to produce the amplified displacement.

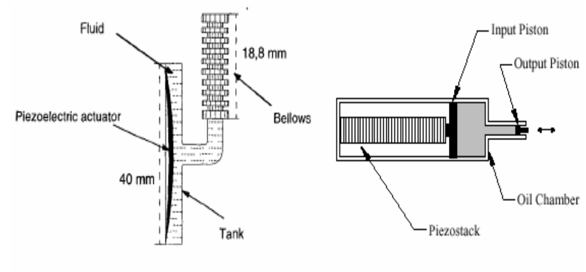


Figure 7 Hydraulic amplification mechanisms

As a piezo bender is too weak to directly drive a big valve, a two-stage piezo driven structure has been developed [9]. Figure 8 shows its principle. The bender actuator controls the flow of air between pipe lines 5 and 6 and the atmosphere. The balance of the pressures in pipe lines 5 and 6 then controls a large piston which can be seen in the center of Figure 8 which controls the flow of air between pipe line 7 and the load.

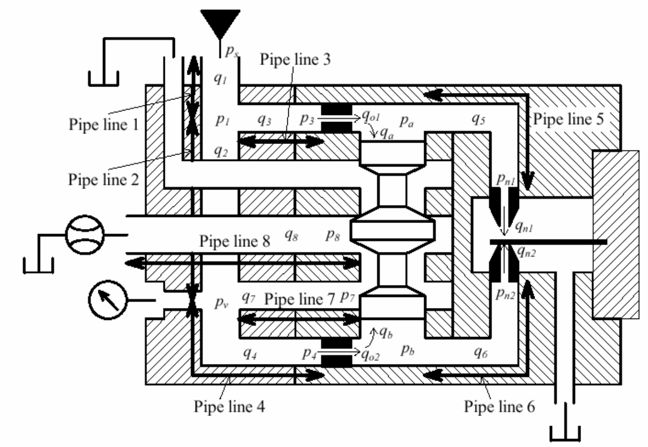


Figure 8 A 2 stage piezo actuated pneumatic valve.

3.2 Inertial Drive Piezo Actuators

The method of inertial drive uses the relationship between friction and inertial forces. Figure 9 illustrates the principle [11].

There are two steps in the working principle of the inertial drive actuator. Firstly, when the stacked ceramic actuator slowly expands, the counter mass moves to the right but the cramps do not. Next, when the stacked actuator quickly contracts, the cramps move to the right and the counter mass moves to the left a little. Because the inertial force is bigger than the friction force, the machine moves incrementally to the right. By repeating the above two steps, the machine moves to the right. . Reversing the action results in movement to the left. The structure has been used in a micro inspection machine with a weight of 1g.

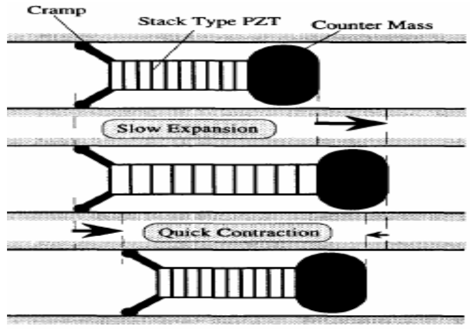


Figure 9 Principle of inertial drive with piezo

Another actuator, called a stick and slip actuator [6], uses a similar principle and is showed in Figure 10. Each step movement consists of a slow deformation of the legs followed by an abrupt jump backward. The typical speed with this structure is about 5 mm/s.

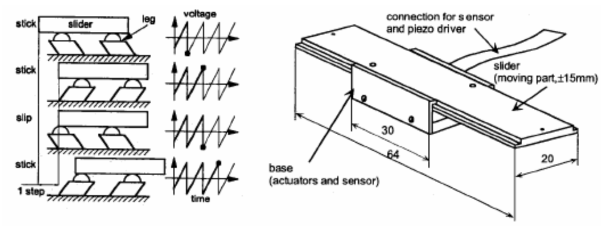


Figure 10 Stick and slip actuator

3.3 INCHWORM LINEAR MOTOR

Piezo ceramic inchworm motors are linear motors generally used in micro-positioning applications due to their ability to make very small, accurate movements. The concept is shown in Figure 11. There are two clamps (actuators 1 and 3) and one extensional element (actuator 2). The clamps are designed to work on a central rod. Movement is achieved by coordinating the activation of the clamp and extensional elements:

1. Clamp 1 is turned on and it grips the rod.
2. Clamp 3 is turned off, relaxing its grip on the rod.
3. The extensional element, actuator 2, is turned on, thus moving the rod to the left.
4. Clamp 3 is turned on so that it grips the rod.
5. Clamp 1 is turned off.
6. The extensional element, actuator 2, is turned off. This element contracts and moves clamp 1 to its original position relative to clamp 3.

This sequence is repeated many times and the rod moves to the left. Reversing the clamping sequence can make the rod move to the right. These devices can be operated at high frequencies to achieve millimeter per second motions. One of the challenges of inchworm devices is in achieving high precision in manufacturing so that the clamps work properly.

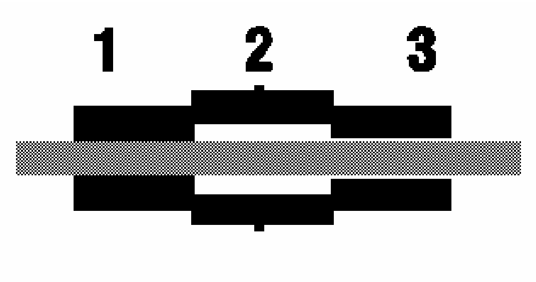


Figure 11 Principle of inchworm actuator

3.4 Ultrasonic Linear Motor

Figure 12 shows the structure of an ultrasonic linear piezo motor [1]. The stator vibrator (shown beneath the moving table in Figure 12) is fitted with bending and longitudinal piezoelectric actuators. They are driven by two electrical sources of identical frequency, but with a phase difference that is carefully controlled. At the vibration tip, an elliptical motion is thus created, resultant of the elliptical and longitudinal motion. The bending actuators convert a large electrical power to mechanical output and the longitudinal actuator dynamically changes the force along the pre-load direction to adjust the frictional force between the stator and the rotor. A vibration circuit working at resonant frequency is used to cause the longitude and bending ceramic components to vibrate.

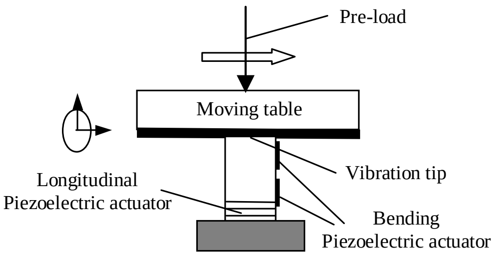


Figure 12 Ultrasonic linear piezo motor

4.0 CONCLUSIONS

Compared to other linear actuators, piezo linear actuators have several advantages. They can easily reach micrometer range precision and nanometer range resolution. They have very good dynamic performance. On the other hand, they tend to suffer from small displacement. Though developing and using new piezo materials is one route to solving this problem, current high strain piezo materials and manufacturing technology still cannot meet industrial requirements. To overcome the limitations of small displacements, piezo actuated inchworm and ultrasonic linear motors have been developed. There are many different kinds of structures and designs based on the inchworm and ultrasonic principles with different features. Their design is complex and is highly dependent on the specific application. Designing new amplifiers based on basic piezo actuators is currently an effective method to overcome the limitation of the small displacement inherent in piezo actuation.

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