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From Piezoelectric Actuators to Piezomotors

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Abstract-This paper discusses the ways to achieve a macroscopic motion from the very small strain generated in basic piezoelectric actuators. The first part reviews the operating principle and force-displacement characteristics of some types of piezoelectric actuators, bulk-type, multilayer, benders, flextensional and Langevin transducers. The second part focuses on the different ways to convert this small displacement into macroscopic sliding motion, usually through friction forces. Regardless of the actual use of the active piezoelectric elements, it is shown that the characteristics of each motor can be derived from the trajectory of the contact point between the active stator and the slider, either with a reversible or hysteretic motion. Finally, the third part shows two recent prototypes of piezomotors that have been built and tested in our lab: an Inchworm and a linear-traveling-wave motor.

1. INTRODUCTION

Piezoelectricity is a well known phenomenon that allows a direct generation of motion when an electrical field is applied with a rather high power density. However, the resulting strain has an order of magnitude of some micrometers for centimeter-sized piezoelectric elements. This particularity creates the need for complementary mechanical systems that allow obtaining suitable strokes for general applications.

Piezoactuators are devices that amplify the motion of active piezoelectric elements to the range of millimeters. They are the brick elements of piezomotors which are devices that transmit motion with potentially unlimited stroke.

A review of the main types of commercially available piezoelectric motors is presented in [1]. Several surveys over specific types of piezomotors are available in [2] [3].

Piezoelectric motors show characteristics such as high actuation forces, low speeds, which often render the use of gear unnecessary and high efficiency at a small scale. These features make of them an interesting solution to many applications in which the available space is limited. Additionally, the presence of friction forces in the transmission of motion often ensures a blocked position at rest. As for the small displacement amplitudes of some kinds of motors, it may lead to a very accurate motion capability. Application fields include watches, camera zoom actuators, valves for precise injection systems, and micropositioning devices.

2. PIEZOELECTRIC ACTUATORS

Piezoelectricity can be described as a linear phenomenon linking mechanical properties such as stress (T) and strain (S) to electric properties such as electric field (E) and electrical displacement (D) in some particular classes of materials, the most widely used being lead-zirconate-titanate (PZT) ceramics. When first poled, PZT ceramics are subject to longitudinal, transverse and shear efforts depending on the direction of the applied electrical field. Considering strain and electrical displacement as independent variables, the equations of

piezoelectricity read:

$$\begin{cases} S = s^E T + d^T E \\ D = dT + \varepsilon^T E \end{cases}$$

where d is a 3*6-matrix with only 5 non-zero coefficient when computed in the frame where the third direction is that of poling. The coefficient d_{33} then accounts for longitudinal displacement, $d_{31}=d_{32}$ for transverse displacement and $d_{15}=d_{24}$ for shear strain. It is to be noted that longitudinal and transverse displacements always occur simultaneously when the electrical field is applied along the poling direction, whereas shear strain appears alone when the field is applied orthogonally. The order of magnitude of these coefficients is 10^{-10} m.V⁻¹.

The reverse piezoelectric effect is used in actuators that provide a limited displacement with potentially high forces. Piezoelectric ceramics can be used directly when they are sandwiched between two electrodes, as bulk-type piezoactuators. In order to achieve displacements of some tens of nanometers, the voltage applied to the piezoelement must be high (hundreds to thousands of Volts). This voltage has an upper limit imposed by the disruptive field of the material and a lower negative limit at which the natural polarization of the ceramic is reversed. Due to these constraints, several techniques are often employed to amplify the movement and reduce the applied voltage.

Most piezoelectric actuators can be characterized by their free stroke and blocking force at a given voltage. In this case, a linear behavior between the maximum values of these parameters is observed.

1) Multilayers

The multilayer actuators are composed of stacked layers of piezoelectric ceramic of some tens of micrometers sandwiched between very thin electrodes, mounted electrically in parallel and mechanically in series. Compared to the bulk-type actuator, this configuration allows an increment in the electric field applied to a single layer resulting in higher strains for lower applied voltages. Typical strokes of these actuators are in the range of the tens of micrometers. Blocking forces can reach the 10 kN range. Due to layers bonding characteristics, these devices are much weaker when they are subject to tensional forces than bulk piezoelectric ceramics. Therefore, they cannot be used at resonance. In addition, the capacitance of a multilayer actuator is rather high (up to tens of μ F) leading to important currents in dynamic operation.

2) Benders

The benders use piezoelectric transverse (d_{31}) mode. The extension or contraction of the ceramic occurs along one of the surfaces of a beam, causing a bending motion. Benders can be manufactured in different ways: unimorphs (a single piezoelement glued to a passive beam), parallel bimorphs (two piezoelements poled in the same direction, glued on each side of a passive grounded electrode, and powered with opposite voltages) and serial bimorphs (two piezoelements poled in opposite directions, glued to each other). The latter bimorphs present a smaller stiffness due to the absence of a passive beam. Consequently, they can provide higher strokes. The piezoelements can also be made of multilayer piezoelectric ceramics in order to limit the input voltage. Depending on the stiffness and the length of the beam, the achieved free stroke of this kind of actuators can reach several millimeters, but with very low actuation forces (less than 2 N).

3) Flextensional

The flextensional actuators work with the piezoelectric multilayer stacks clamped in a passive elastic structure,

whose deformation amplifies that of the ceramic in longitudinal mode. There are several designs of flextensional structures, most of which are elliptic or rhomboidal. The amplification factor in terms of displacement ranges between 2 and 6 according to their axis ratio. This allows higher strains in the direction of motion in detriment of mass and size in the orthogonal directions. Depending on the dimension of the flexible structure and the stack, the developed force can reach the kN range.

4) Langevin transducers

The Langevin transducers [4] are made of one piece of massive piezoelectric ceramic sandwiched between two masses whose shape and acoustic impedance are chosen to amplify the motion at the resonance. Due to the piezoelectric ceramic's weak resistance to tensional forces a prestress is applied by bolting all three parts together. This kind of actuator is optimized for amplification purposes at a specific resonant frequency and can only be used in longitudinal (d_{33}) mode. As they work at resonance, the blocked force and free displacement cannot be defined for the Langevin transducers, which are instead characterized by their operating frequency (in the 10-100 kHz range) and output power, that can reach the 100 W range for use in acoustic devices.

All the actuators presented in this part show interesting characteristics in terms of actuation force, but suffer from very limited strokes when it comes to macroscopic applications. They are either used alone (e.g. in adaptive optics), but more often assembled in more complex structures intended to provide high displacements.

3. DIFFERENT STRATEGIES TO ACHIEVE A SLIDING MOTION

Converting microscopic displacements into macroscopic ones can be done by transmitting periodically the movement generated in a stator to a slider through friction forces. The different types of piezomotors can be classified according to the movement of the contact point between the slider and the stator, which can be hysteretic or reversible. The latter category can be subdivided in permanent or discrete motion. The "contact point" is defined here as one particle in the stator that has had contact with the slider and has transmitted its movement to it, at a given instant in the past.

For non-hysteretic movements of the contact points, there must be a dissymmetry between backward and forward phases of the movement, in order not to cancel the transmitted motion.

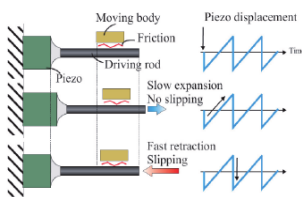


Figure 1: Stick-slip motor ([6])

Motors with permanent contact points rely on the stick-slip effect, which is based on the difference between static (μ_s) and dynamic (μ_d) friction coefficients. The principle is shown on figure 1. The piezoelement is driven slowly during the forward phase and rapidly during the backward phase. The forward force applied to the slider is given by:

$$F_F = \mu_s N$$

where N is the normal preload. The backward force is given by:

$$F_B = \mu_d N.$$

Due to the difference between μ_d and μ_s the movement can be achieved either in the backwards or in the forward direction.

Non-permanent-contact-point motors such as the impact-drive motor or the ultrasonic standing-wave motor use a geometric dissymmetry to achieve motion. The operating principle of this motor is shown on figure 2. On the forward phase, the slider is driven by the stator with an angle α that is inside the friction cone of the slider-stator interface, so the stator sticks to the slider while imparting motion. On the backward phase, the stator tip drives the slider with an angle of $\frac{\pi}{2} - \alpha$, which is outside the friction cone, so that the stator slips and similarly transmits a lower force in the backward direction. The main inconvenient of that kind of motors is the fact that it can only be driven one way.

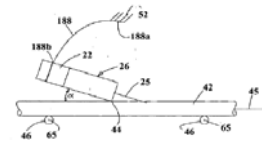


Figure 2: Impact-drive motor (US Patent 20050127789)

Finally, motors with hysteretic contact-point trajectory use this phenomenon to avoid exerting a force during the backward phase. One example of such a structure is the Inchworm-type motors, which use two piezoelements to clamp alternatively the slider and one between them to extend and contract. This results in a rectangular cycle during which one step is done. The process is explained on figure 3. This motor works in a quasi-static regime, but many other motors use resonance to achieve an elliptic motion of the contact point, for example in the famous traveling-wave ultrasonic motor.

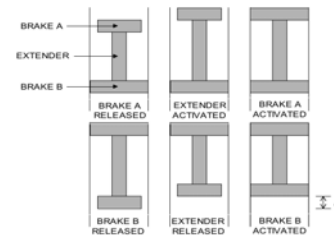


Figure 3: The operating principle of an Inchworm

4. EXAMPLES OF REALISATIONS AT LGEP

The LGEP has designed two piezomotors for different applications.

1) Inchworm

This work concerns the study of tissue regeneration that takes place between the existing gap of a cut bone while it is progressively separated. The actuation principle used to move one part of the bone with respect to the other the displacement has to be discontinuous performing small steps at a time in order to maintain a daily fixed gap between the two bone parts. The forces required are very weak because they only stretch the tendons that are elongated in a short distance. An inchworm (figure 4) has been designed and tested using multilayer actuators [6].

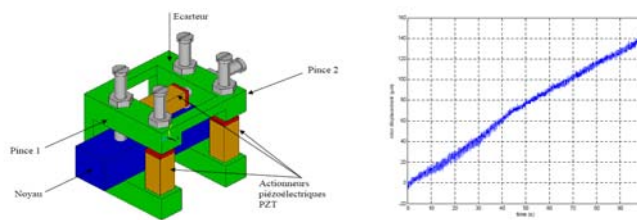


Figure 4: Designed structure and test (displacement versus time)

2) Travelling-wave motor

This work was aimed to perform a micropump. Here, Langevin transducers have been used to create a travelling wave on a beam, as shown in figure 5. The wave's energy has the ability to move a slider. Different strategies to create the travelling wave have been tested [7].

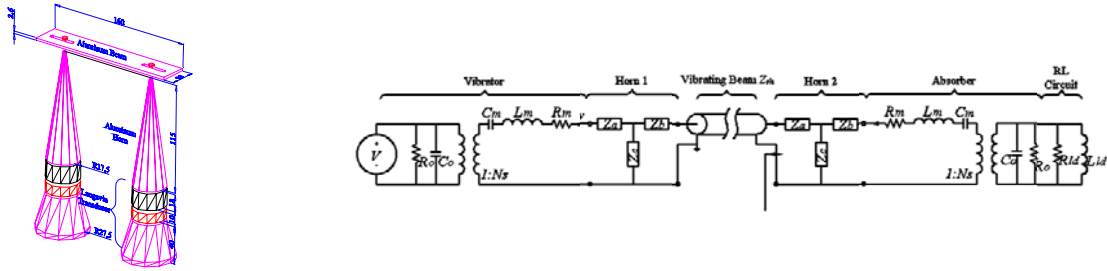


Figure 5: Designed structure and modeling for the travelling-wave motor

5. CONCLUSION

In this article, the evolution of the basic piezoelectric ceramic and its extraordinary ability to generate microscopic displacements into a more elaborated structure capable of producing large or even unlimited strokes is presented.

As first stage element in the evolution there is the piezoelectric actuator. Here, different geometries have been reviewed (multilayer, benders, flextensional and Langevin). According to their principle, they favour certain aspects of the piezoelectric actuation like the force or displacement. For example, when high forces are required, it is recommended to use piezostacks whereas for important strokes benders can be the solution.

The linking between piezoelectric actuators and piezoelectric motors which compose the last element of the evolutionary chain has been effectuated by studying the motion of the contact point between the motion-generating element and the moved one. In this manner, it has been possible to classify piezomotors. The classification unveiled in this paper presents the advantage of embracing all sorts of piezoelectric motors. In addition, with the proposed categorization it is possible to establish easily differences and relationships between motors presenting very different operating principles.

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