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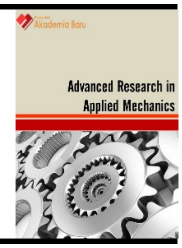

Review on the application of Piezoelectric materials in the development of ultrasonic motors

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ABSTRACT

This paper reviews the application of piezoelectric materials in the development of piezoelectric ultrasonic motors, Piezoelectric materials has vast applications in the manufacture of ultrasonic motors, as they use the converse piezoelectric effects to generate vibration which is finally converted to the type of motion required resulting from the standing or traveling wave generated earlier. Piezoelectric materials are the most important mechanism of piezoelectric ultrasonic motors, as they remain the main motion generating mechanism in the whole system. Piezoelectric ultrasonic motors can be driven via standing or traveling wave, different forms of motions can be generated such as linear or rotary motion, and also the output motion can be used to drive a single or double rotors. The nature of the output motion can either be single or multiple degree of freedom.

1. Introduction

The development of ultrasonic motors is a highlight in the application of piezoelectric materials. Ultrasonic motors take advantage of converse piezoelectricity of piezoelectric materials to yield mechanical output from converting electrical energy. It is no doubt that piezoelectric materials are in the central position that controls the performance of the devices.

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The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry. The piezoelectric effect is a reversible process in that materials exhibiting the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electrical field) [1-4].

Piezoelectricity is the ability of materials to develop or vary electric polarization when they are mechanically stressed has been known as piezoelectricity. When a piezoelectric is strained with external stress, charges displace from their equilibrium position to both surfaces, causing bound charges on the surfaces of the material. The produced charge density is proportional to the stress. This effect is the direct piezoelectricity and its mechanism is shown in Fig. 1a, and the mechanism of the converse piezoelectricity is shown in Fig. 1b, where an external electric field induces elastic displacement of charges, producing deformation in the material [2].

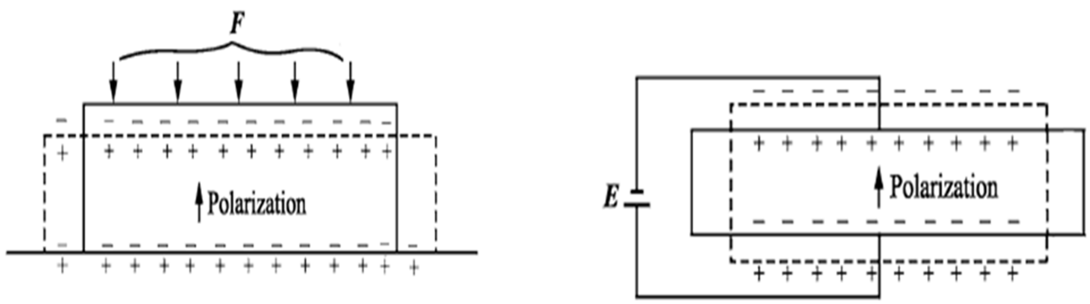

Fig. 1. Direct piezoelectric and Converse piezoelectric effect of a piezoelectric element responding to external force element and external electric field

2. Classification of Piezoelectric Ceramic Materials

The currently used piezoelectric materials cover three classes:

2.1 Inorganic Piezoelectric Materials

Including piezoelectric monocrystalline materials and piezoelectric ceramics which consist of massive fine crystals. Piezoelectric ceramics present advantages such as strong piezoelectricity, high dielectric constant and can be easily formed into various shapes. But they are usually with low mechanical quality factor, large electric loss and poor stability. These characteristics make piezoelectric ceramics suitable for high-power transducers, wide-band filters and so on. Piezoelectric single crystals provide high mechanical quality factor and excellent stability but low piezoelectric coefficient and low dielectric constant, and their shapes for devices arc restricted because of the difficulty in machining these crystals. Piezoelectric single crystals can be used in devices such as vibrators to control standard frequencies, high-selectivity filters (usually with high frequency and narrow-band), and high-temperature ultrasonic transducers and so on [3, 25].

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2.2 Organic Piezoelectric Materials

Also known as piezoelectric polymers, e.g. Polyvinylidene fluoride (PVDF). Unlike other polymers, piezoelectric polymers possess excellent flexibility, low density, small impedance, as well as reasonable piezoelectric coefficient. Piezoelectric polymers have been rapidly applied in devices for under water ultrasonic measuring, pressure sensing, and explosion igniting. However, the low piezoelectric stain constant of piezoelectric polymers has restricted their applications as active transducers [11, 25].

2.3 Piezoelectric Composites

This is a type of PZT material in which piezoelectric ceramics and polymers are incorporated together. As a result, the piezoelectric properties of the composites are enhanced comparing with their initial components. Furthermore, the composites may present novel properties that do not exist in these single components. Piezoelectric composites can have large piezoelectricity, strong strength and low density, and their outstanding machinability makes them easy to be fabricated into large area films or other complicated forms. Nowadays, piezoelectric composites have already been widely used in hydro acoustics, Electroacoustic, Ultrasonic and medical applications [25].

3. Applications of Piezoelectric Materials to Ultrasonic Motor

Piezoelectric materials play a key role in ultrasonic motors and other piezoelectric actuators because of their function to transform electrical energy into mechanical energy. Several parameters of some important piezoelectric materials are listed in Table 1. Since the properties of Piezoelectric can be widely adjusted by substituting or doping additives, the data show only a rough range. In the table, Tc is the Curie temperature and Ec is the coercive field.

The requirements in properties of piezoelectric materials have to be determined according to their specific purposes of the devices. These used in ultra-high frequency (UHF) and high-frequency devices require the material to have low permittivity and small high frequency dielectric loss. For energy transducer application, the coupling coefficient and acoustic impedance of the material arc often stressed. Materials with excellent frequency stability and high Q_m values can be used as standard frequency oscillators [43, 44].

Table 1
some main parameters of several typical piezoelectric materials

Materials	T_c/°C	εT_{33}	d_{33}/(pC/N)	d_{33}/(pC/N)	K_{33}	Q_m	E_c/(kV/cm)
Pb(Zr, Ti)O_3 (PZT)	330	1800	417	710	0.73	75	10-12
(BaPb) Nb_2O_3(BPN)	400	300	85	100	0.30	15	-
PbTi O_3 (PT)	490	190	56	68	0.45	1300	>40
Bi4 Ti4 O_{15} (NBT)	600	140	18	-	0.15	100	>50
($BiO_{0.5}$ $Na_{0.5}$) TiO_3 (BNT)	315	300	70	-	0.40	240	73
$LiNbO_3$ (LN) Crystal	1150	25	6	69	0.23	NR	200
SiO_2 (Quartz) Crystal	573	4.5	d11	-	NR	100000	-

4. Standing Wave Piezoelectric Ultrasonic Motor

There are two different designs of piezoelectric ultrasonic motors of the standing wave type. In the first class, only the longitudinal vibration of the piezoelectric actuator is excited (Figure 2). The oblique impact between the stator and slider/rotor elements causes an indirect bending mode excitation, converting longitudinal vibration into tangential vibration in the case of rotary motors [6, 9]. In the second class, two groups of electrodes on the vibratory pieces, such as on a ring, are excited in order to have clockwise and counter-clockwise rotation. Such a motor design was proposed by Tomikawa *et al*. [18] and the principle is illustrated in Figure 3.

The circular shape of the piezoelectric element shown in Figure 4 is divided into 12 parts of 1/4-wave lengths. The parts of each pattern are alternately polarized in positive (+) and negative (-) pairs. The six projections on the vibrator are placed on the border between parts of the same polarity and are adhered to the piezoelectric element.

When the shaded (Group A) electrodes are excited at the operating frequency of the motor, the projections leading to the left rise and ones leading to the right fall (the position of the hills and valleys alternate in half periods). The rotor is then driven to the left by the 3 rising projections. When the drive signal is applied to the non-shaded area (Group B), the entire process is reversed [45-50]. There are two different designs of piezoelectric ultrasonic motors of the standing wave type. In the first class, only the longitudinal vibration of the piezoelectric actuator is excited (Figure 2). The oblique impact between the stator and slider/rotor elements causes an indirect bending mode excitation, converting longitudinal vibration into tangential vibration in the case of rotary motors [6, 9]. In the second class, two groups of electrodes on the vibratory pieces, such as on a ring, are excited in order to have clockwise and counterclockwise rotation. Such a motor design was proposed by Tomikawa *et al*. [18] and the principle is illustrated in Figure 3.

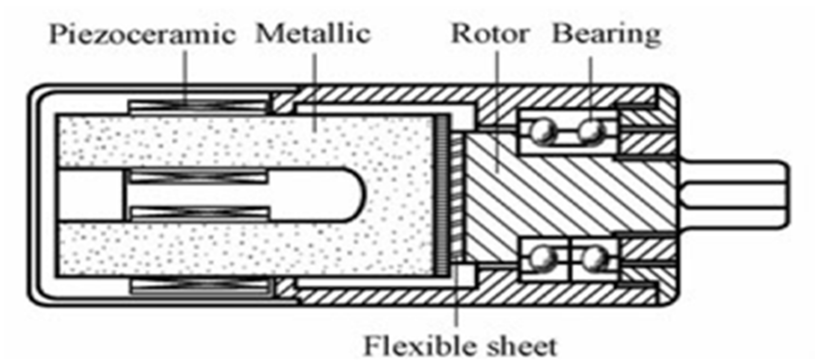

Fig. 2. Sashida's standing wave USM [9]

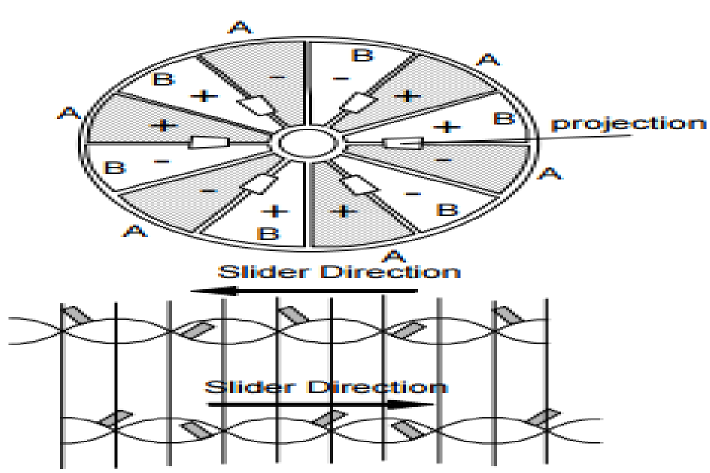

Fig. 3. Standing wave type ultrasonic motor operating mode [18]

The circular shape of the piezoelectric element shown in Figure 4 is divided into 12 parts of 1/4-wave lengths. The parts of each pattern are alternately polarized in positive (+) and negative (-) pairs. The six projections on the vibrator are placed on the border between parts of the same polarity and are adhered to the piezoelectric element.

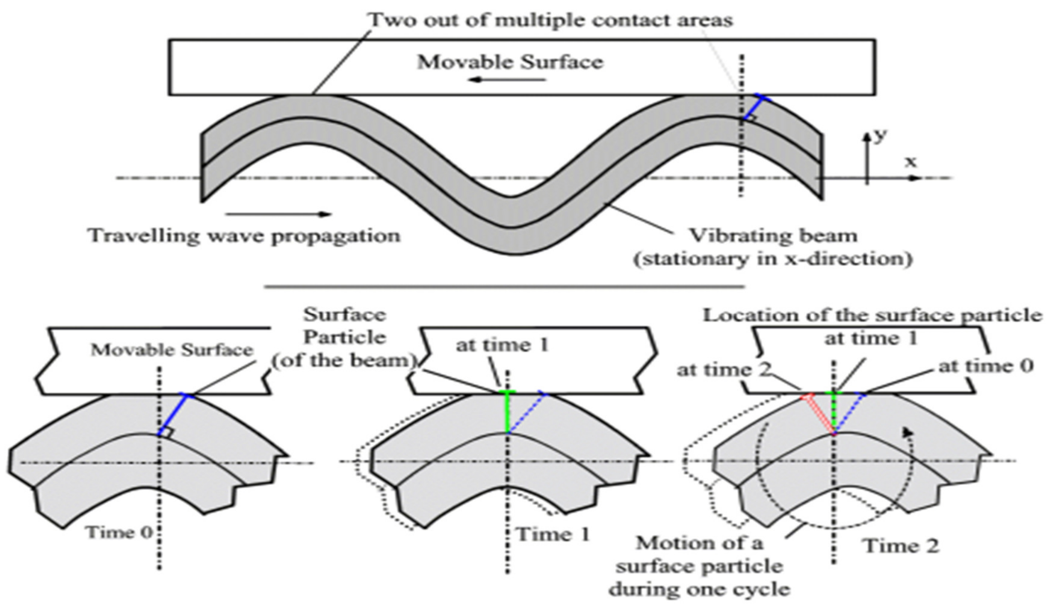

Fig. 4. Driving Process of Travelling Wave piezoelectric Motors [50]

When the shaded (Group A) electrodes are excited at the operating frequency of the motor, the projections leading to the left rise and ones leading to the right fall (the position of the hills and valleys alternate in half periods). The rotor is then driven to the left by the 3 rising projections. When the drive signal is applied to the non-shaded area (Group B), the entire process is reversed [45-50].

5. Traveling Wave Piezoelectric Ultrasonic Motors

Intensive research on piezoelectric ultrasonic motors started after the invention of Sashida's first practical ultrasonic motor in 1982. The elliptical motion on the stator surface is generated by a proper superposition of two orthogonal flexural waves. The piezoelectric ring has a segmented electrodes and the piezoelectric ceramic under each segment is polarized in such a way that one group of segments excites the sine mode and the other group excites the cosine mode.

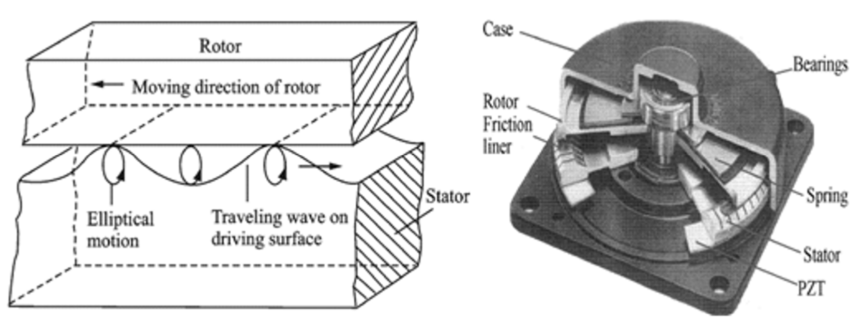

Fig. 5. Sashida's traveling wave USM [10]

Figure 5 shows the operation principal of a traveling wave motor. Intensive research on piezoelectric ultrasonic motors started after the invention of Sashida's first practical ultrasonic motor in 1982. The elliptical motion on the stator surface is generated by a proper superposition of two orthogonal flexural waves. The piezoelectric ring has a segmented electrodes and the piezoelectric ceramic under each segment is polarized in such a way that one group of segments excites the sine mode and the other group excites the cosine mode. Figure 5 shows the operation principal of a traveling wave motor.

6. Linear Piezoelectric Ultrasonic Motors

As a type of ultrasonic motor, a linear ultrasonic motor (LUSM) also utilizes the converse piezoelectric effect of piezoelectric ceramics and the ultrasonic vibration of an elastic body. It transfers the micro amplitude motion of a stator into the macro linear motion of a slider by the friction force between the stator and slider. Besides the common characteristics of rotary ultrasonic motors, linear ultrasonic motors also possess the following characteristics.

(a) The capability of a direct and straight drive;
(b) A high precision accuracy up to nanometer level;
(c) Good control characteristics due to no movement errors from auxiliary parts, such as linkage, ball screw, transmission belt, etc.
(d) A simple structure and the variability of shape, allowing easy miniaturization and weight loss. Linear ultrasonic motors have been developing rapidly in recent years.

Their applications are more and more widely used in the following areas:

(1) Semiconductor manufacture devices
(2) Aeronautic and astronautic appearances
(3) Precise position stages
(4) Biomedical equipment
(5) Optic fiber alignment facilities
(6) Miniaturization of information systems

7. Bar Type Traveling Wave Rotary Piezoelectric Motors

The bar-type traveling wave rotary piezoelectric ultrasonic motor includes two types: single degree of freedom (SDOF) and multi degrees of freedom (MDOF) ultrasonic motors. Both of them use the vibration of the bar type round stator to achieve conversion from electrical energy to mechanical energy.

This kind of structure makes the BTRUM possess a number of unique features, such as simplicity, cheapness, ease of processing, suitability for miniaturization, etc. Therefore, it promises a vast potential market in micro air vehicles (MAV), micro-robotics, precision instruments, medical equipment, and other industrial areas.

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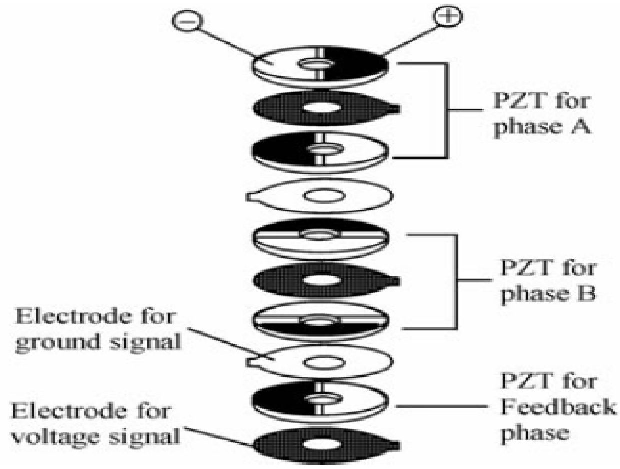

Fig. 6. Layout of PZT in BTRUM

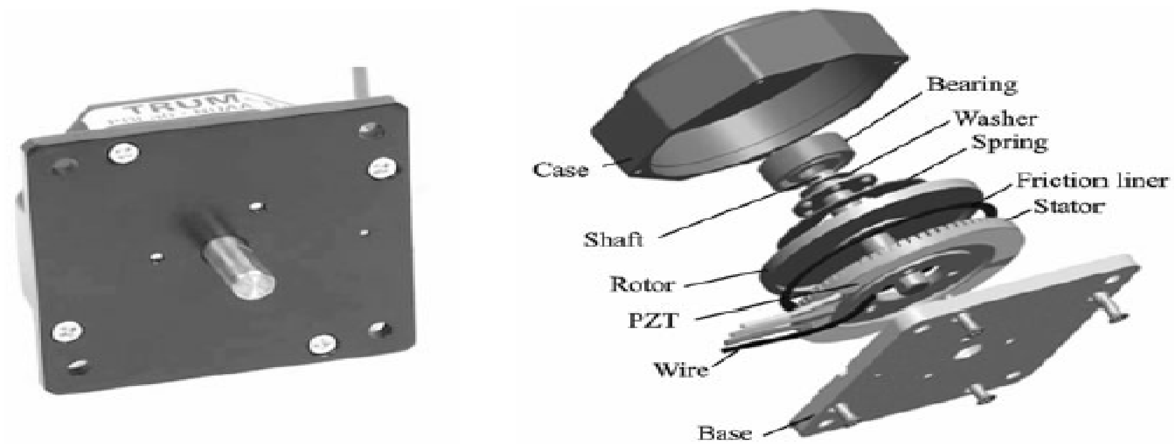

Fig. 7. Structure diagram of TRUM-60

8. Double Rotor Piezoelectric Ultrasound Motors

The successful design and manufacture of the BTRUM with single rotor pave a way for researchers in the field of ultrasonic motor technology by trying to come up with an idea of BTRUM with double rotor, many researchers have already developed USMs with double rotors which will be applied in the manufacture of robot arms, medical equipment and other industrial applications [53]. Sheng *et al*. [47] proposed a double-rotor ultrasonic motor with symmetrical longitudinal-torsional converter. According to the authors, “To obtain large torque, ultrasonic motors using longitudinal-torsional converters with diagonal slits should be used”. The converters have rather simple and tough structures and are driven by simply exciting the longitudinal vibration of the transducer. Stemming from the merits of such type ultrasonic motors, this paper proposes a double-rotor ultrasonic motor with a symmetrical longitudinal-torsional converter. The ultrasonic motor consists of four PZT-4 annular plates that vibrate longitudinally, two sonotrodes screw bonded atop the two end surfaces of the PZT plate stack, and two rotors pre-pressed against to the output surfaces of the sonotrodes by coil springs. To form identical directions of the output elliptical trajectory motions of the driving points, diagonal slits were symmetrically cut in the sonotrodes. To validate the proposed idea, principle description, FEM simulation, fabrication, and performance measurement of and prototype motor are presented. The tested performances of the prototype motor were no load revolution speed 30 rpm and maximum torque 1.8 Nm [49].

Chunsheng [33] proposed a Large-moment double-rotor stress type longitudinal-torsional composite ultrasonic motor; the invention discloses a large-moment double-rotor stress type longitudinal-torsional composite ultrasonic motor and an electric excitation method thereof, belonging to the technical field of ultrasonic motors. The motor comprises a stator assembly and a rotor assembly, wherein the stator assembly comprises a friction sheet, a first group of longitudinal vibration piezoelectric ceramics, a first balance weight block, a first group of torsional vibration piezoelectric ceramics, a flange, a second group of torsional vibration piezoelectric ceramics, a second balance weight block, a second group of longitudinal vibration piezoelectric ceramics, a fastening bolt and two radial bearings; and the rotor assembly comprises a rotating shaft, a locking nut, a spring cover, a spring, a first rotor, a key, a friction material and a second rotor. The method is operated by the first-order torsional vibration in a stator and the second-order longitudinal vibration in the whole of the motor, and the longitudinal vibration piezoelectric ceramics are placed near the contact surface of the stator and the rotors, namely the pitch plane of the longitudinal vibration to fully excite and apply the longitudinal vibration of the motor. Compared with the prior art, the invention has larger rotor blocking torsion [51].

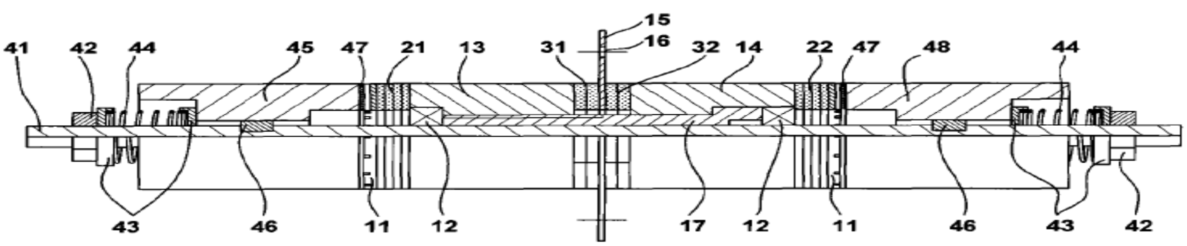

Fig. 8. Double-rotor stress type longitudinal-torsional composite piezoelectric ultrasonic motor

8. Conclusion

Piezoelectric ultrasonic motors are characterized by low speed and high torque, which are contrasted with high speed low torque of conventional electromagnetic motors. Thus, ultrasonic motors do not require gear mechanisms, leading to very quiet operation and space saving. Negligible effect from external magnetic or radioactive, and no generation of these fields making them suitable for the application to semiconductor technology (electron beam lithography), mechatronics (miniature robotics), information devices (silent alarm) and horology. Since the structure and poling configuration of the active piezoelectric elements used in the stator are simple, the proposed motor is very suitable for miniaturization. Moreover, a single driving source can excite two bending modes at the same time, thus generate a wobble motion. Therefore, this motor may find applications in aforementioned areas.

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