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ABSTRACT

The Kansas City Division of AlliedSignal Inc. has been investigating the fabrication and use of piezoelectric motors in mechanisms for United States Department of Energy (DOE) weapons applications for about four years. These motors exhibit advantages over solenoids and other electromagnetic actuators. Prototype processes have been developed for complete fabrication of motors from stock materials, including abrasive machining of piezoelectric ceramics and more traditional machining of other motor components, electrode plating and sputtering, electric poling, cleaning, bonding and assembly. Drive circuits have been fabricated and motor controls are being developed. Laboratory facilities have been established for electrical/mechanical testing and evaluation of piezo materials and completed motors. Recent project efforts have focused on the potential of piezoelectric devices for commercial and industrial use. A broad range of various motor types and application areas has been identified, primarily in Japan. The Japanese have been developing piezo motors for many years and have more recently begun commercialization. Piezoelectric motor and actuator technology is emerging in the United States and quickly gaining in commercial interest. The Kansas City Division is continuing development of piezoelectric motors and actuators for defense applications while supporting and participating in the commercialization of piezoelectric devices with private industry through various technology transfer and cooperative development initiatives.

INTRODUCTION

The fabrication and use of piezoelectric motors to replace solenoids and other electromagnetic actuators in mechanisms for DOE weapons applications has been an ongoing investigation of the Kansas City Division of AlliedSignal Inc. for approximately four years. The project has been successful as evidenced by the development of prototype processes for the complete fabrication of motors from stock materials and the establishment of electrical/mechanical testing capabilities to evaluate piezo materials and completed motors. The project is also supported by work being conducted at the University of Missouri at Rolla for mechanical analysis and advanced development of piezoelectric ceramic materials and fabrication processes.

Appreciation of the immense possibilities for piezoelectric devices, coupled with the present down turn in defense related production, has allowed project efforts to focus on evaluating the potential of piezoelectric devices for commercial and industrial use. A wide range of diverse motor types and application areas has been identified, primarily in Japan, where the Japanese have been developing piezoelectric motor technology for many years and have more recently begun commercialization.

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Commercial interest has spread to Europe and now appears to be gaining in the United States. The greatest potential in U.S. markets is for fractional horsepower intermittent duty devices. Application areas for this emerging technology include motors and actuators for 1) powering automobile windows, seats, sun roofs, windshield wipers, antennas, etc., 2) auto-focusing camera lenses, film winders and shutters, 3) optical lens and mirror positioning and adjustment, 4) computer disc drives, printer drivers and print heads, 5) watches and clocks, 6) space applications: adaptive space structures and gyroscopes, 7) fluid pumps, valves and fluid controls, 8) robotics: high torque/low weight finger and joint manipulation, 9) defense safing mechanisms, 10) powering devices in high magnetic fields, 11) medical devices and instruments and 12) many others.

In support of its primary mission as a prime contractor for the DOE, the Kansas City Division is continuing development of piezoelectric motors and actuators for defense-related applications while supporting and participating in the commercialization of piezoelectric devices with private industry through various technology transfer and cooperative development efforts.

TRAVELING WAVE PIEZOELECTRIC MOTORS

General

The first piezoelectric effect (conversion of mechanical or strain energy to electrical energy) was discovered by the Curie brothers (Pierre and Jacques) in 1880. It has been used extensively for a variety of transducers to sense pressure, impact, acceleration, etc., as well as other applications such as sonar, electric circuit oscillators, phonograph pick-ups, ignition systems and many others. The reverse effect, conversion of electrical energy to mechanical, was predicted by Lippmann in 1881 and verified by the Curies later that same year. This effect has also been exploited for application areas such as sonar, ultrasonic detection devices, microphones, speakers, smoke alarms, audio buzzers, and TV remote controls. More recently, intense interest and efforts have been focused on producing piezoelectric actuators and motors. These range from simple low frequency bending elements, stack (extension) actuators and inch-worm type linear and rotary motors to a number of unique concepts that exploit structural, resonant-frequency vibrations. The traveling wave motor is of the resonant frequency type and is one of a number of new concept piezoelectric actuators. The traveling wave motor is also frequently referred to in literature as an ultrasonic motor (USM).

Benefits

Traveling wave ultrasonic piezoelectric motors offer new design options and exhibit a number of advantages over conventional electromagnetic motors. Advantages have been demonstrated in output torque, response time, operation mode, motor noise and size. Benefits of traveling wave motors include the following:

- High Torque to Size Ratio
- High Torque @ Low Speed -- allows direct drive
- Reduced Inertia and Bounce
- Fast Response
- Precision Movement / Controllable
- Friction Locking with Power Off
- Flat Profile Enhances Packaging
- Non-Sparking
- Quiet
- Efficient
- Insensitive to Magnetic Fields

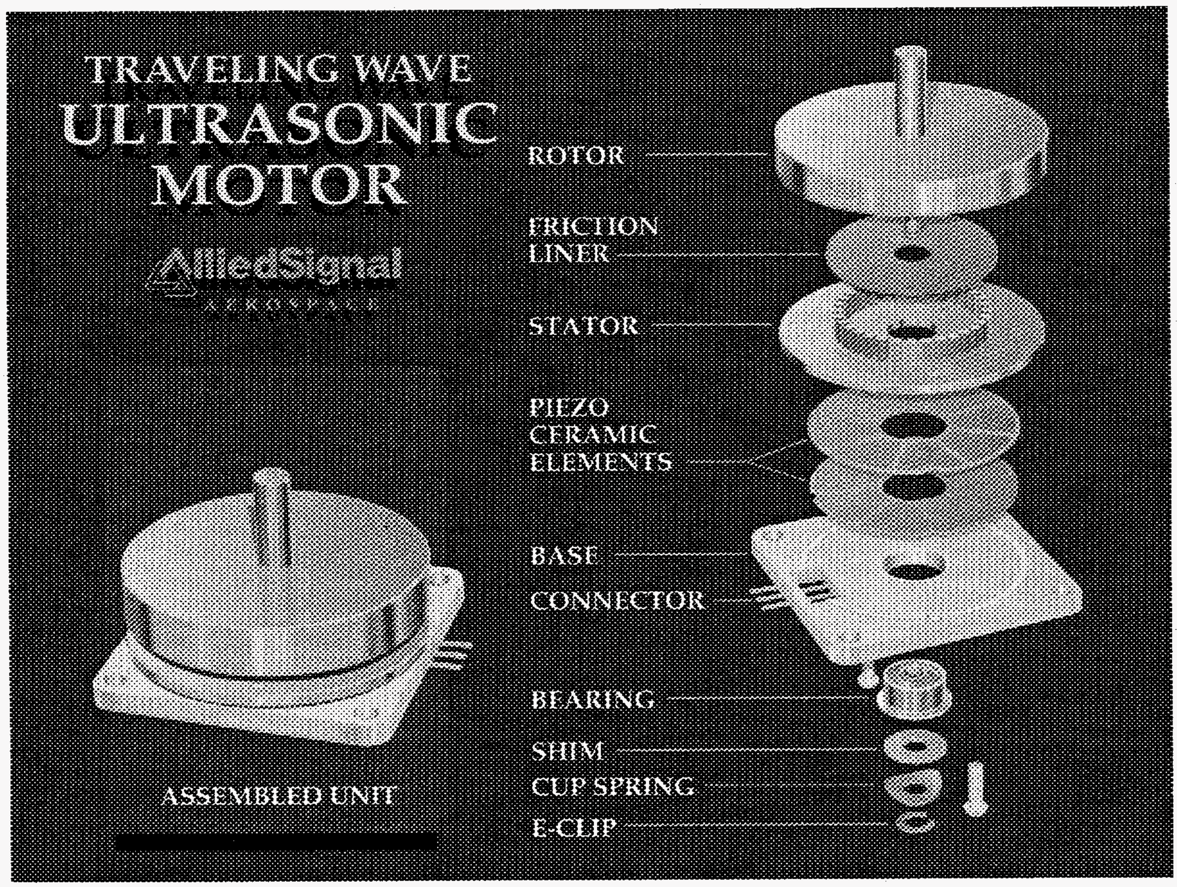

Figure 1. Assembled and exploded view of a traveling wave ultrasonic motor

Kansas City Division's Development

To date several prototype ultrasonic (traveling wave type) motors have been fabricated and tested. These include one linear motor and numerous rotary motors. The linear motor was utilized as an initial learning tool. The primary focus has been on the development and fabrication of rotor motors. Two sizes of rotary disc motors have been produced: 1.5-inch and 0.7-inch diameters. Torque and motion in each of these motors are produced by the generation of traveling waves with two piezoelectric ceramic disc elements. The most recent undertaking is the design and fabrication of a 0.315-inch diameter rotary ring motor. Torque and motion of this motor are produced by the generation of traveling waves with only one piezoelectric ceramic ring element.

Figure 1 shows an exploded view of an ultrasonic motor. Traveling rotational waves are created by the two thin piezoelectric ceramic elements and transmitted to the stator. These traveling waves result from the manner in which the two crystals are physically oriented and electrically driven. This phenomenon will be described in greater detail later. The two ceramic elements and the stator are rigidly bonded together and attached to the base to form a stationary unit. An electronic drive circuit (not shown) is designed to drive the stator at or near the desired mechanically resonant frequency. Operating near resonance is necessary to cause a relatively large movement of the tooth-like projections on the vibrating stator. A friction material liner is rigidly bonded to the rotor. The rotor is spring-loaded against the stator by cup washers on the rotor shaft and secured with an E-clip on the shaft end. As the resonant waves travel around the stator, the toothed projections execute an elliptic motion. As they move, these teeth push against the friction liner, resulting in rotary motion. Figure 2 illustrates the driving principle, showing a right traveling wave at two different instances in time.

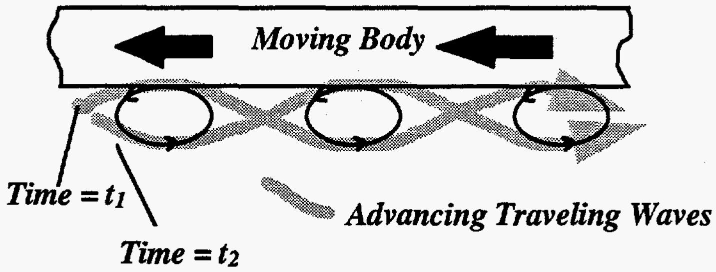

Figure 2. Traveling wave driving principle

As the wave moves through the vibrating body (stator), every point on the surface will execute an elliptic path as shown. Since the moving body (rotor) is pressed firmly against the stator, this elliptic motion transfers torque to the rotor, propelling it in a direction opposite to that of the traveling wave. Figure 3 is an (enormously exaggerated) illustration of the elliptic motion of one of the stator teeth.

The actual movement of the teeth is extremely small. The elliptic path for the 1.5-inch diameter rotary motor is estimated to be approximately circular, with a diameter less than 0.0005 inch. The top surface of each tooth traverses this small circular path at about 70 kilohertz or about once every 14 microseconds. Many people who have touched this vibrating ring-shaped surface report feeling a very slight vibration or a reduced friction as their finger moves across the surface. However, almost any small flat object placed on the circular ring of teeth will rotate.

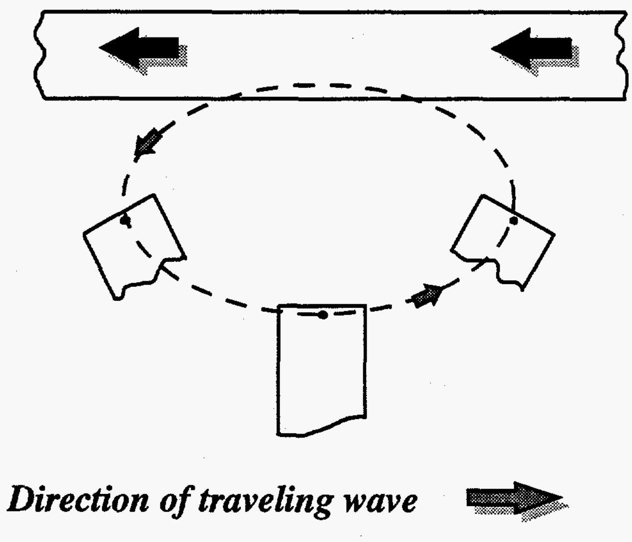

Figure 3. Illustration of elliptic motion of the stator teeth

Generating Waves and Elliptic Motion

Elliptic motion of the stator teeth is produced by resonant frequency traveling waves in the stator. The traveling waves are generated by a specific temporal and spatial combination of two standing waves. Each standing wave is generated by a segmented piezoelectric ceramic element. Although the actual generation of standing and traveling waves by circular piezoelectric ceramic disc elements is fairly complex, the principle in achieving them is best understood by the simplified example of a straight elastic linear body attached to piezoelectric ceramic bars.

Standing Waves

A high-frequency standing wave can be generated in a single piezoelectric bar. The bar is electrically segmented such that adjacent segments are polarized in opposite directions. The segmented piezo bar is attached to an elastic body. The elastic body represents the motor's stator. Once a DC voltage is applied, opposing sides of adjacent segments will contract while expansion occurs at each of the remaining segmented sides. The result is a flexing of the elastic body in the shape of a *(+)SINE* wave. When the polarity of the DC voltage is reversed, flexing of the elastic body in the opposite direction produces a *(-)SINE* wave. A standing wave is generated by the continuous flexing of the elastic body back and forth by the application of an AC signal where polarities are reversed at the signal frequency. A full wavelength is defined by two segments. So if there are four segments, there will be two standing waves that are in phase with each other at every instant of time. (Eight segments producing four wavelengths have been used in the Kansas City Division rotary disc motors.)

Traveling waves.

Standing waves can be combined to produce traveling waves. Two segmented piezoelectric bars, each driven by an AC signal of the same frequency, are arranged such that the segments of one are offset by one-half segment with respect to the other. Since two segments represent a full wavelength, this one-half segment offset causes the standing waves of one element to be translated one-quarter wavelength out of phase with the standing waves of the other. The AC signal driving one bar is a *SINE* wave while that driving the other bar is a *COSINE* wave. These driver signals therefore cause the waves to also be one-quarter wavelength out of phase in time. The combination of these two standing waves of the same frequency which are both spatially and temporally one-quarter wavelength out of phase results in a traveling wave.

This summation of two standing waves, one-quarter wavelength out of phase in both time and space, producing a traveling wave, is easily demonstrated mathematically. The standing wave is represented by Equation (1).

$$
\begin{aligned}
y_1 &= a\sin(2\pi\ x/\lambda)\cos(\omega\ t) \\
&\quad \textit{where} \\
y_1 &= \text{ the amplitude at any time, } t, \\
a &= \text{ the peak amplitude,} \\
x &= \text{ distance along the wave,} \\
\lambda &= \text{ the wavelength and} \\
\omega &= \text{ the circular frequency.}
\end{aligned}
\tag{1}
$$

The first term (*sin*) is the spatial variation and the second term (*cos*) is the variation with time. A standing wave one-quarter wavelength out of phase spatially from Equation (1) is obtained by replacing the *sin* term with a *-cos* term and a similar shift in time can be effected by replacing the second *cos* term with a *sin* term. Therefore, the second standing wave can be represented by Equation (2).

$$y_2 = -a\cos(2\pi\ x/\lambda)\sin(\omega t) \tag{2}$$

Adding Equations (1) and (2)

$$\begin{aligned} y = y_1 + y_2 &= a\sin(2\pi\ x/\lambda)\cos(\omega t) \\ &\quad - a\cos(2\pi\ x/\lambda)\sin(\omega t) \end{aligned} \tag{3}$$

The right side of (3) is recognized as a trigonometric identity, which reduces (3) to the following equation,

$$y = a\sin\left[(2\pi\ x/\lambda) - \omega t\right] \tag{4}$$

which represents a right traveling wave.

Elliptic Motion

The generation of elliptic motion from a traveling wave can be shown mathematically by analyzing the path of a point on a stator tooth as a wave passes through. For a small amplitude wave traveling through the stator, it is reasonably assumed that the tooth remains perpendicular to the wave at all times. This example is illustrated in Figure 4. Vector l represents a stator tooth. A point near the bottom of the tooth (P_0) is fixed at $x = 0$ as the wave moves to the right. Figure 4 depicts the wave and vector at one instant in time. At some other instant in time, point P_0 would remain on the y-axis but be at a different height and l would change slope. While constraining l to remain perpendicular to the wave, a description of the path of the opposite end of l, point P_1, is as follows.

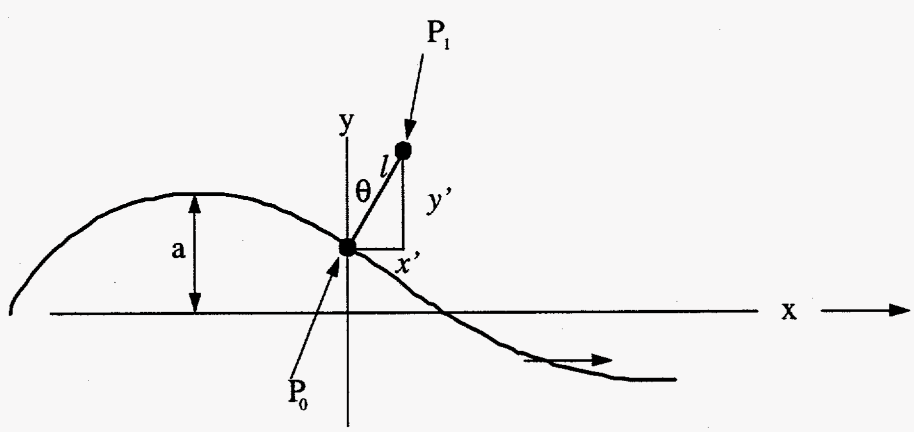

Figure 4. Elliptic Motion Analysis

Since Equation (4) represents the wave at any point in time, the slope can be obtained by differentiation.

$$\frac{dy}{dx}=\frac{2\pi a}{\lambda}\text{Cos}\left(\frac{2\pi x}{\lambda}-\omega t\right) \tag{5}$$

The slope, m, normal to the wave at any position x is given by the negative reciprocal of Equation (5).

$$m=-\frac{\lambda}{2\pi a}\frac{1}{\text{Cos}\left(\frac{2\pi x}{\lambda}-\omega t\right)} \tag{6}$$

Since we have placed the bottom of vector, l, at $x=0$,

$$m=\frac{-\lambda}{2\pi a}\frac{1}{cos\,\omega t} \tag{7}$$

and

$$y=-a\,sin\,\omega t \tag{8}$$

Since x and y define a point on the wave corresponding to P_0, the coordinates of P_1 are given by

$$x'=x+l\,sin\,\theta \tag{9}$$

and since $x=0$,

$$x'=l\,sin\,\theta \tag{10}$$

and

$$y'=y+l\,cos\,\theta \tag{11}$$

Substituting Equation (8) into (11) gives Equation (12).

$$y'=a\sin\omega t+l\cos\theta \tag{12}$$

Whereas the wave shown in Figure 4 is highly exaggerated for analysis, the actual amplitude is very small. The corresponding angle, θ, is estimated to be about 0.36 degrees. For small θ, $sin\theta \cong \theta$, $cos\theta \cong 1$ and $tan\theta \cong \theta$. Then Equations 10 and 12 reduce to

$$x'=l\theta \tag{13}$$

and

$$y'=l-a\,sin\omega\,t \tag{14}$$

From Figure 4, slope m is also given by

$$m = \frac{1}{tan\theta}$$

Equating this to Equation 7,

$$m = \frac{1}{tan\theta} = -\frac{\lambda}{2\pi a}\frac{1}{\cos\omega t}$$

$$tan\theta = -\frac{2\pi a}{\lambda}cos\omega t$$

and since $tan\theta = \theta$ for small angles,

$$\theta = -\frac{2\pi a}{\lambda}cos\omega t \qquad (15)$$

Substituting Equation 15 into Equation 13 gives

$$x' = \frac{2\pi l a}{\lambda}cos\,\omega t \qquad (16)$$

If we translate our origin to a new coordinate system (to center the excursions of P_1) where

$$x'' = x' \text{ and } y'' = y' - 1$$

then

$$x'' = x' = \frac{-2\pi l a}{\lambda}\cos\omega t \qquad (17)$$

and

$$y'' = y' - l = -a\,sin\,\omega t \qquad (18)$$

Substituting Equations 17 and 18 into the trigonometric identity,

$$\sin^2\theta + \cos^2\theta = 1$$

gives

$$\left(\frac{y''}{a}\right)^2 + \left(\frac{x''}{2\pi\, la/\lambda}\right)^2 = 1 \qquad (19)$$

which is clearly the equation of an ellipse centered at $x = 0$ and $y = 1$ with major diameter = $2a$ and minor diameter $= 4\pi l a/\lambda$ as illustrated in Figure 5.

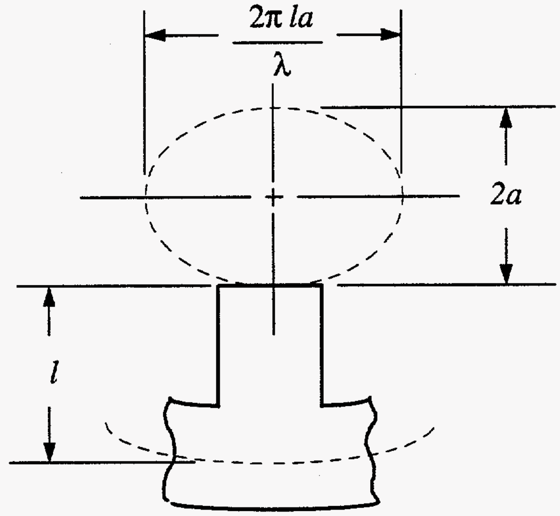

Figure 5. Stator tooth at the lowest point of its elliptic path

Kansas City Division's Continued Development and Commercialization

The Kansas City Division has made great strides in understanding the principles and applications of piezoelectric motors. A full compliment of prototype processes has been developed for complete fabrication of motors from stock materials, including abrasive machining of piezoelectric ceramics and more traditional machining of other motor components, electrode plating and sputtering, electric poling, cleaning, bonding and assembly. Drive circuits have been manufactured and motor controls are being developed. Finite element analysis (FEA) capabilities have been utilized to optimize motor designs. Laboratory facilities have been established for electrical and mechanical testing and evaluation of piezoelectric materials and completed motors.

The Kansas City Division is continuing development of piezoelectric motors for traditional defense-related applications while supporting the commercialization of piezoelectric motors with private industry through various technology transfer and cooperative development efforts. The most recent effort is a technology commercialization initiative with AMMPEC, Inc. (Advance Materials & Manufacturing Processes for Economic Competitiveness). This multiphase initiative is intended to stimulate growth of small, regional businesses by enhancing technologies and defining customers for the ultimate creation of new jobs. The experience gained with piezoelectric motors, coupled with the vast manufacturing knowledge and resources of the Kansas City Division, establishes the solid foundation necessary to step forward with the production of piezoelectric motors. A commitment to piezoelectric material advancement, motor designs optimization, along with manufacturing process improvements are all necessary to ensure piezoelectric motors realize their potential within the United States.

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