PIEZOELECTRIC ACTUATORS

Piezoelectric and electrostrictive devices have become key components in smart actuator/sensor systems such as precision positioners, miniature ultrasonic motors, and adaptive mechanical dampers. This article reviews developments of piezoelectric and related ceramic actuators with particular focus on the improvement of actuator materials, device designs and drive/control techniques of actuators. Developments will be compared among the United States, Japan, and Europe.

TRENDS IN MICRO-MECHATRONICS

Piezoelectric actuators are forming a new field between electronic and structural ceramics (1-4). Application fields are classified into three categories: positioners, motors, and vibration suppressors. The manufacturing precision of optical instruments, such as lasers and cameras, and the positioning accuracy for fabricating semiconductor chips, which must be adjusted using solid-state actuators, is of the order of 0.1 μm. Regarding conventional electromagnetic motors, tiny motors smaller than 1 cm^3 are often required in office or factory automation equipment and are rather difficult to produce with sufficient energy efficiency. Ultrasonic motors whose efficiency is insensitive to size are superior in the mini-motor area. Vibration suppression in space structures and military vehicles using piezoelectric actuators is also a promising technology.

New solid-state displacement transducers controlled by temperature (shape memory alloy) or magnetic field (magnetostrictive alloy) have been proposed but are generally inferior to the piezoelectric/electrostrictive ceramic actuators because of technological trends aimed at reduced driving power and miniaturization (4).

CERAMIC ACTUATOR MATERIALS

Practical Actuator Materials

Actuator materials are classified into three categories: piezoelectric, electrostrictive and phase-change materials. Modified lead zirconate titanate [PZT, $Pb(Zr,Ti)O_3$] ceramics are currently the leading materials for piezoelectric applications. The PLZT [$(Pb, La)(Zr, Ti)O_3$] 7/62/38 compound is one such composition (5). The strain curve is shown in Fig. 1(a) left. When the applied field is small, the induced strain x is nearly proportional to the field E ($x = d\,E$, where d is called the piezoelectric constant). As the field becomes larger (i.e., greater than about 1 kV/cm), however, the strain curve deviates from this linear trend, and significant hysteresis is exhibited due to polarization reorientation. This sometimes limits the usage of such materials in actuator applications that require nonhysteretic response.

An interesting new family of actuators has been fabricated in Germany from a barium stannate titanate system [$Ba(Sn,Ti)O_3$] (6). The useful property of $Ba(Sn_{0.15}Ti_{0.85})O_3$ is its unusual strain curve, in which the domain reorientation occurs only at low fields, and there is then a long linear range at higher fields [Fig. 1(a) right]; that is, the coercive field is unusually small. Moreover, this system is particularly intriguing since it contains no Pb ions, an essential feature as ecological concerns grow in the future.

The second category of actuators is based on electrostriction as in PMN [$Pb(Mg_{1/3}Nb_{2/3})O_3$] based ceramics, developed in USA. Although a second-order phenomenon of electromechanical coupling ($x = M\,E^2$, where M is called electrostrictive constant), it can be extraordinarily large (more than 0.1%) (7). An attractive feature of these materials is the near absence of hysteresis [Fig. 1(b)]. The superiority of PMN to PZT was demonstrated in a Scanning Tunneling Microscope (STM) (8). The PMN actuator could provide extremely small distortion of the image even when the probe was scanned in the opposite direction.

The third category is based on phase-change-related strains, that is, polarization-induced by switching from an antiferro-electric to a ferroelectric state, as systematically investigated by our group (9). Figure 1(c) shows the field-induced strain curves taken for the lead zirconate stannate based system [$Pb_{0.99}Nb_{0.02}((Zr_xSn_{1-x})_{1-y}Ti_y)_{0.98}O_3$]. The longitudi-

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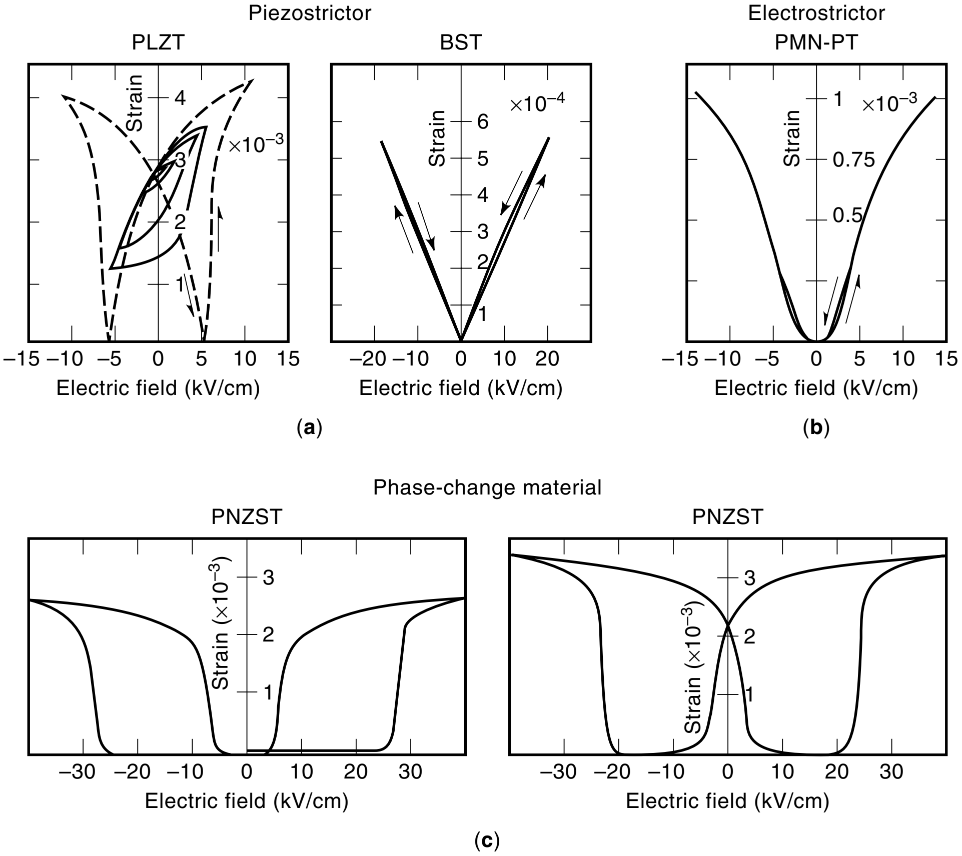

Figure 1. Electric field-induced strains in ceramics: (a) Piezoelectric (Pb,La)(Zr, Ti)O_3 and Ba(Sn,Ti)O_3. (b) Electrostrictive Pb($Mg_{1/3}Nb_{2/3}$,Ti)O_3. (c) Phase-change material Pb(Zr,Sn,Ti)O_3.

nally induced strain reaches more than 0.3%, which is much larger than that expected in normal piezostrictors or electrostrictors. A rectangular-shape hysteresis in Fig. 1(c) left, referred to as a "digital displacement transducer" because of the two on/off strain states, is interesting. Moreover, this field-induced transition exhibits a shape memory effect in appropriate compositions [Fig. 1(c) right]. Once the ferroelectric phase has been induced, the material "memorizes" its ferroelectric state even under zero-field conditions, although it can be erased with the application of a small reverse bias field (10). This shape memory ceramic is used in energy saving actuators. A latching relay in Fig. 2 is composed of a shape memory ceramic unimorph and a mechanical snap action switch, which is driven by a pulse voltage of 4 ms duration. Compared with the conventional electromagnetic relays, the new relay is much simpler and compact in structure with almost the same response time.

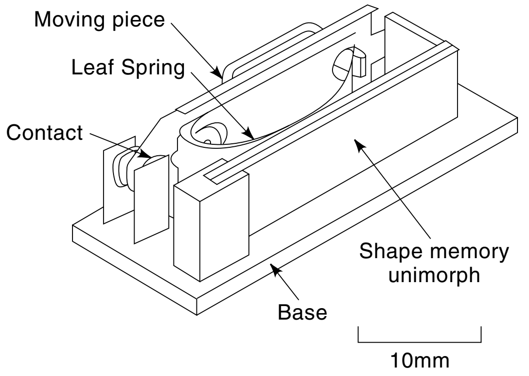

Figure 2. Latching relay using a shape memory ceramic unimorph. The drive requires a 4 ms pulse voltage, not a continuous voltage, which provides a 150 μm tip displacement to the unimorph.

Novel Actuator Materials

A monomorph device with simpler structure and manufacturing process has been developed to replace the conventional bimorphs. The principle is a superposed effect of piezoelectricity and semiconductivity (11). As shown in Fig. 3, the contact between a semiconductor and a metal (Schottky barrier) causes nonuniform distribution of the electric field, even in a compositionally uniform ceramic. When we apply an external voltage to this semiconductor plate, the field is generated only on one side of the plate. Suppose that the ceramic also possesses piezoelectricity; only one side of a ceramic plate tends to contract, leading to a bending deformation in total. A monomorph plate with 30 mm in length and 0.5 mm in thickness can generate 200 μm tip displacement, in equal magnitude of that of the conventional bimorphs (12). The "rainbow" actuator by Aura Ceramics (13) is a modification of the abovementioned semiconductive piezoelectric monomorphs, where half of the piezoelectric plate is reduced, rendering it semiconducting. This leads to bending of a total monomorph ceramic plate.

A photostrictive actuator is a fine example of an intelligent material, incorporating "illumination sensing" and self production of "drive/control voltage" together with final "actua-

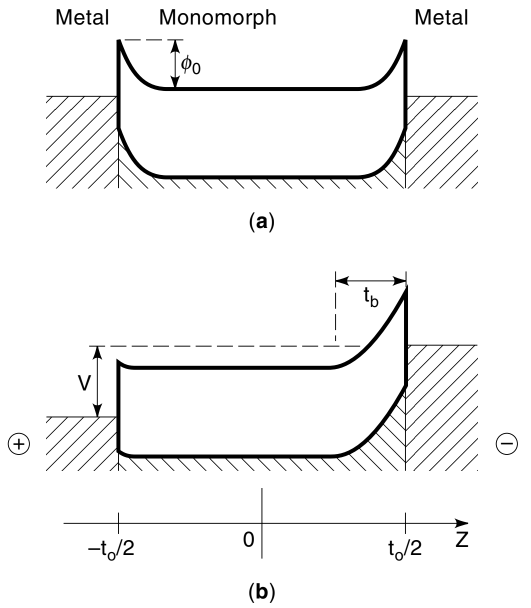

Figure 3. Electron energy band (Schottky barrier) model in monomorph devices (n-type semiconductor). When an external voltage is applied to this semiconductor plate, the field is generated only on one side (cathode) of the plate. Through its piezoelectricity, only the cathode side of a ceramic plate tends to contract, leading to a bending deformation in total.

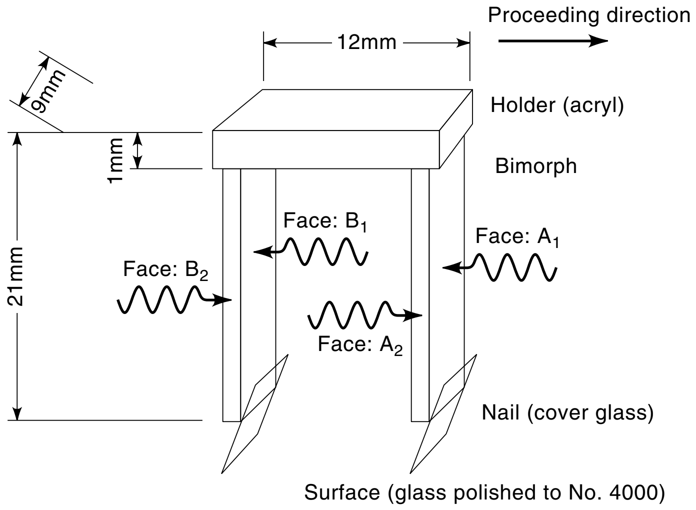

Figure 4. Structure of a photodriven walking device and the illumination directions. Each leg is composed of two photostrictive PLZT plates bonded together, with the remnant polarization of one ceramic layer parallel to the plate and in the direction opposite to that of the other plate.

tion." In certain ferroelectrics, a constant electromotive force is generated with exposure to light, and a photostrictive strain results from the coupling of this bulk photovoltaic effect to inverse piezoelectricity. A bimorph unit has been made from PLZT 3/52/48 ceramic doped with tungsten (14). The remnant polarization of one PLZT layer is parallel to the plate and in the direction opposite to that of the other plate. Upon irradiation with violet light onto one side of the PLZT bimorph, a photovoltage of 1 kV/mm is generated, causing a bending motion. The tip displacement of a 20 mm long bimorph with 0.4 mm in thickness is 150 μm, with a response time of 1 s.

A photo-driven microwalking device has been developed (15). As shown in Fig. 4, it is simple in structure, having neither lead wires nor electric circuitry, with two bimorph legs fixed to a plastic board. When the legs are alternately irradiated with light, the device moves like an inchworm with a speed of 100 μm/min.

PZT: polymer composites play a key role in the design of transducers such as sonars with both actuator and sensor functions (16). In general, two-phase composites can be categorized, according to the connectivity of each phase (1, 2, or 3 dimensionality), into 10 classes. Most popular composites are the 3-0 type, which is fabricated from a polymer matrix mixed with PZT ceramic powder, and the 3-1 composite which is composed of PZT fibers embedded in a polymer matrix. A great enhancement in the effective piezoelectric (sensor) coefficient g^* can be expected in the composites while keeping the effective piezoelectric (actuator) coefficient d^* almost the same as d of the PZT itself. Although the PZT composites are very useful for acoustic transducer applications, care must be taken when using them in actuator applications. Under an applied dc field, the field induced strain exhibits a large hysteresis and creep because of the viscoelastic property of the polymer matrix. More serious problems are found when they are driven under a high ac field, that is, heat generation. The heat generated by the ferroelectric hysteresis in the piezoceramic cannot be dissipated easily due to the very low thermal conduction of the polymer matrix, which results in rapid degradation of piezoelectricity.

Another intriguing application of PZT composites is as a passive mechanical damper, where mechanical noise vibration is radically suppressed by the converted electric energy dissipation through Joule heat when a suitable resistance, equal to an impedance of the piezoelectric element $1/\omega C$, is connected to the piezo-element (17). Piezoceramic:carbon black:polymer composites are promising useful designs for practical application. Figure 5 shows the damping time constant change with volume percentage of the carbon black. The

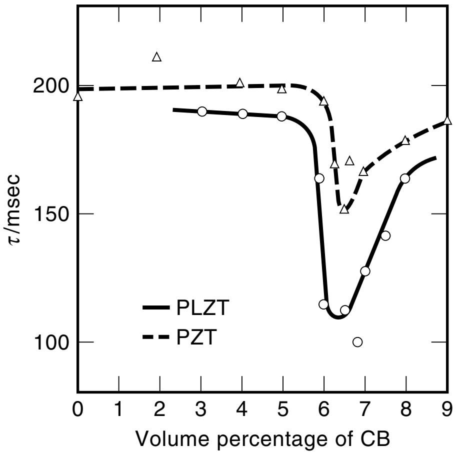

Figure 5. Damping time constant change with volume percentage of carbon black in piezoelectric composite dampers. The minimum time constant (quickest damping) is obtained at the percolation threshold.

minimum time constant (i.e., quickest damping) is obtained at 6% carbon black, where a drastic electric conductivity change is observed (percolation threshold) (18).

ACTUATOR DESIGNS

Two of the most popular actuator designs are multilayers (19) and bimorphs (see Fig. 6). The multilayer, in which roughly 100 thin piezoelectric/electrostrictive ceramic sheets are stacked together, has advantages in low driving voltage (100 V), quick response (10 μs), high generative force (1000 N), and high electromechanical coupling. But the displacement in the range of 10 μm is not sufficient for some applications. This contrasts with the bimorph, consisting of multiple piezoelectric and elastic plates bonded together to generate a large bending displacement of several hundred μm, but the response (1 ms) and the generative force (1 N) are low.

A 3-D positioning actuator with a stacked structure was also proposed by a German company as in Fig. 7, where shear strain was utilized to generate the x and y displacements (20). Polymer-packed PZT bimorphs have been commercialized in the United States, aiming at vibration reduction/control applications in smart structures (21).

A composite actuator structure called the "moonie" (or "cymbal") has been developed at Penn State University to provide characteristics intermediate between the multilayer and bimorph actuators; this transducer exhibits an order of magnitude larger displacement than the multilayer and much larger generative force with quicker response than the bimorph (22). The device consists of a thin multilayer piezoelectric element and two metal plates with narrow moon-shaped cavities bonded together as shown in Fig. 6. The moonie with a size of $5 \times 5 \times 2.5$ mm^3 can generate a 20 μm displacement under 60 V, eight times as large as the generative displacement of the multilayer with the same size (23). This new compact actuator has been applied to make a miniaturized laser beam scanner.

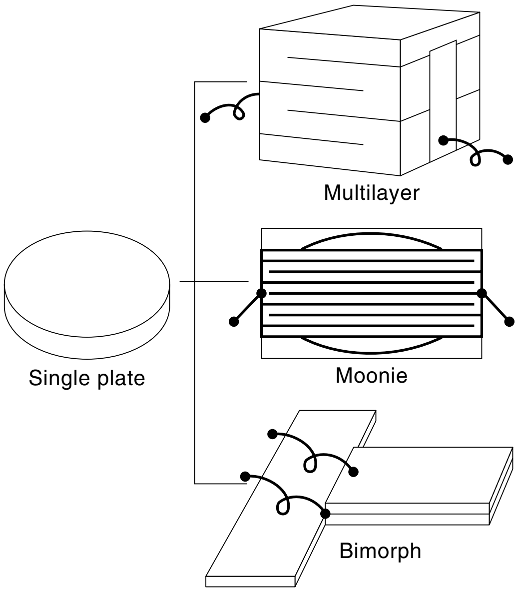

Figure 6. Typical designs for ceramic actuators: multilayer, moonie, and bimorph.

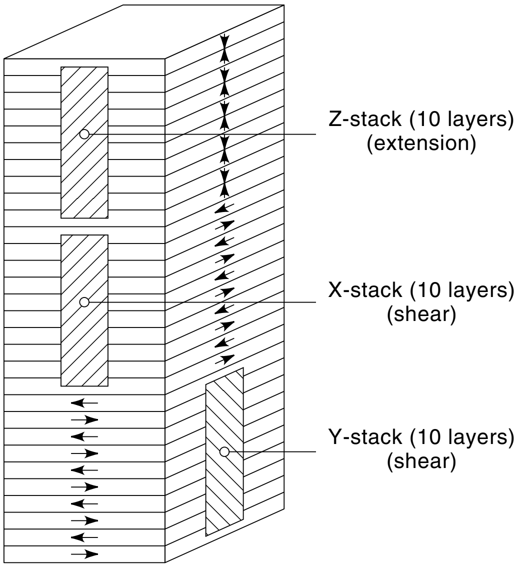

Figure 7. 3-D positioning multilayer actuator. Notice that the x- and y-stacks are using shear mode with the spontaneous polarization perpendicular to the applied electric field direction.

DRIVE/CONTROL TECHNIQUES

Piezoelectric/electrostrictive actuators may be classified into two categories, based on the type of driving voltage applied to the device and the nature of the strain induced by the voltage (Fig. 8): (1) rigid displacement devices for which the strain is induced unidirectionally along an applied dc field, and (2) resonating displacement devices for which the alternating strain is excited by an ac field at the mechanical resonance frequency (ultrasonic motors). The first can be further divided into two types: servo displacement transducers (positioners) controlled by a feedback system through a position-detection signal, and pulse-drive motors operated in a simple on/off switching mode, exemplified by dot-matrix printers.

The materials requirements for these classes of devices are somewhat different, and certain compounds will be better suited to particular applications. The ultrasonic motor, for instance, requires a very hard type piezoelectric with a high mechanical quality factor Q, leading to the suppression of heat generation. Driving the motor at the antiresonant frequency, rather than at the resonant state, is also an intriguing technique to reduce the load on the piezo-ceramic and the power supply (24). The servo-displacement transducer suffers most from strain hysteresis, and therefore, a PMN electrostrictor is used for this purpose. The pulse-drive motor requires a low permittivity material aiming at quick response with a certain power supply rather than a small hysteresis, so that soft PZT piezoelectrics are preferred to the high-permittivity PMN for this application.

Pulse drive techniques for ceramic actuators are very important for improving the response of the device (25,26). Figure 9 shows transient vibrations of a bimorph excited after a pseudo-step voltage is applied. The rise time is varied around the resonance period (n is the time scale with a unit of $T_0/2$, where T_0 stands for the resonance period). It is concluded that the overshoot and ringing of the tip displacement is completely suppressed when the rise time is precisely adjusted to

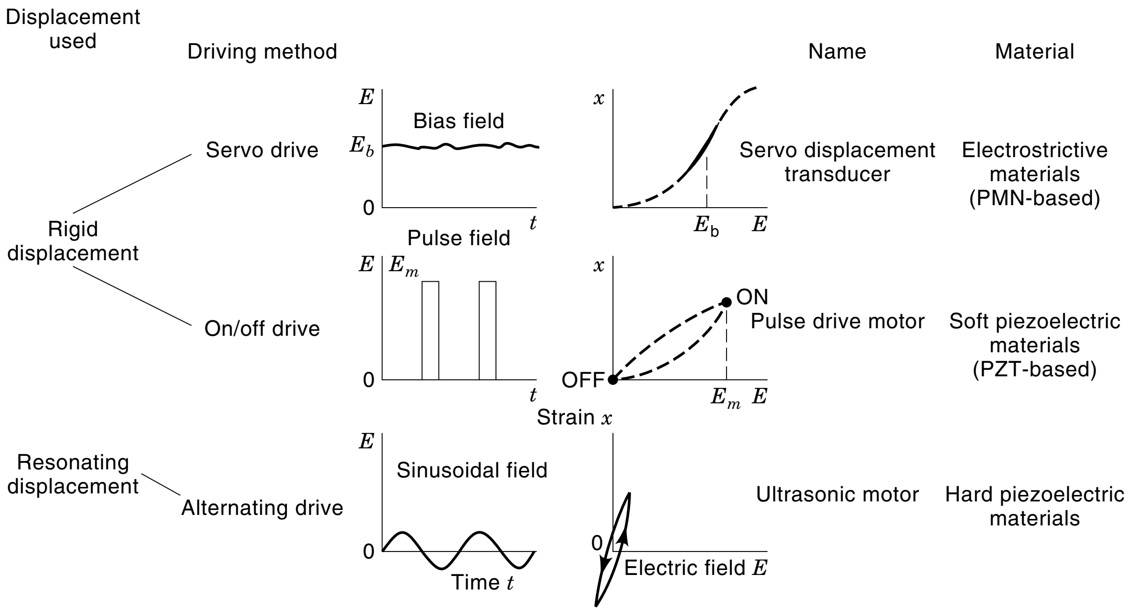

Figure 8. Classification of piezoelectric/electrostrictive actuators.

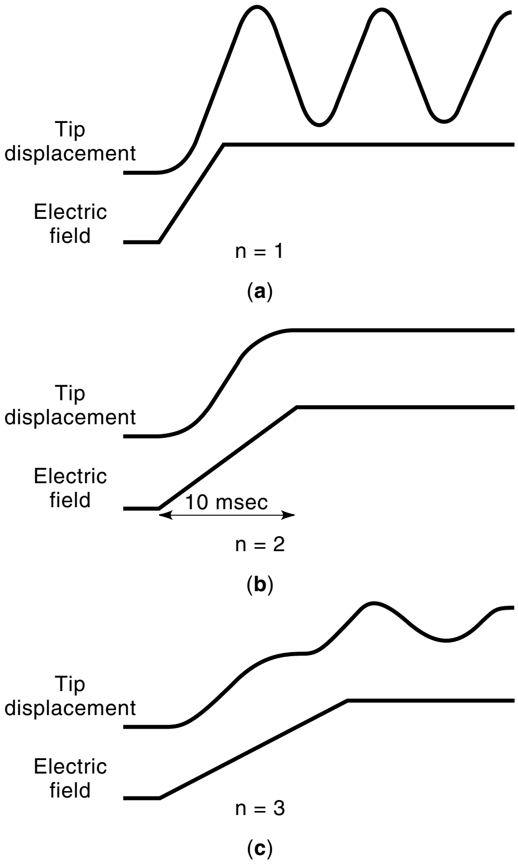

Figure 9. Transient vibration of a bimorph excited after a pseudo-step voltage applied. n is a time scale with a unit of half of the resonance period, that is, $2n$ = resonance period.

the resonance period of the piezo-device (i. e., for $n = 2$) (25). A flight actuator was developed using a pulse-drive piezoelectric element and a steel ball. A 5 μm rapid displacement induced in a multilayer actuator can hit a 2 mm steel ball up to 20 mm in height (25). A dot-matrix printer head has been developed using a flight actuator as shown in Fig. 10 (27). By changing the drive voltage pulse width, the movement of the armature was easily controlled to realize no vibrational ringing or double hitting.

DEVICE APPLICATIONS

Table 1 compares the difference in the ceramic actuator developments among the United States, Japan, and Europe. The details will be described in this section.

The United States

The target of the development is mainly for military-oriented applications such as vibration suppression in space structures

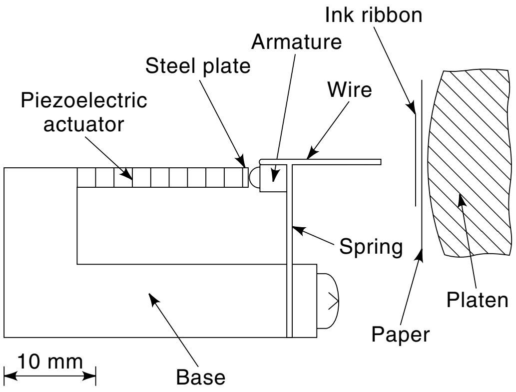

Figure 10. Dot-matrix printer head using a flight actuator mechanism.

Table 1. Difference in the Ceramic Developments Among the United States, Japan, and Europe

	United States	Japan	Europe
Target	Military-oriented product	Mass-consumer product	Lab-equipment product
Category	Vibration suppressor	Mini-motor Positioner	Mini-motor Positioner Vibration suppressor
Application field	Space structure Military vehicle	Office equipment Camera Precision machine Automobile	Lab stage/stepper Airplane Automobile Hydraulic system
Actuator size	Up-sizing (30 cm)	Down-sizing (1 cm)	Intermediate size (10 cm)
Major manufacturer	AVX/Kyocera Morgan Matroc Itek Opt. Systems Burleigh Allied Signal	Tokin Corp. NEC Hitachi Metal Mutsui-Sekka Canon Seiko Instruments	Philips Siemens Hoechst CeramTec Ferroperm Physik Instrumente

and military vehicles. Notice the up-sizing trend of the actuators for these purposes.

A typical example is found in a space truss structure proposed by Jet Propulsion Laboratory (28). A stacked PMN actuator was installed at each truss nodal point and operated so that unnecessary mechanical vibration was suppressed immediately. A "Hubble" telescope has also been proposed using multilayer PMN electrostrictive actuators to control the phase of the incident light wave in the field of optical information processing (Fig. 11) (29). The PMN electrostrictor provided superior adjustment of the telescope image because of negligible strain hysteresis.

The U.S. Army is interested in developing a rotor control system in helicopters. Figure 12 shows a bearingless rotor flexbeam with attached piezoelectric strips (30). Various types of PZT-sandwiched beam structures have been investigated for such a flexbeam application and for active vibration control (31).

Japan

Japanese industries seek to develop mass-consumer products, with the categories limited to mini-motor and positioner areas, with applications to office equipment and cameras/video cameras. In that sense, tiny actuators smaller than 1 cm^3 are the main focus.

A dot matrix printer is the first widely-commercialized product using ceramic actuators. Each character formed by such a printer is composed of a 24 × 24 dot matrix. A printing ribbon is subsequently impacted by a multiwire array. A sketch of the printer head appears in Fig. 13(a) (32). The printing element is composed of a multilayer piezoelectric device, in which 100 thin ceramic sheets 100 μm in thickness are stacked, together with a sophisticated magnification mechanism (Fig. 13(b)). The magnification unit is based on a monolithic hinge lever with a magnification of 30, resulting in an amplified displacement of 0.5 mm and an energy transfer efficiency greater than 50%. A piezoelectric camera shutter is currently the largest production item (Fig. 14). A piece of piezoelectric bimorph can open and close the shutter in a millisecond through a mechanical wing mechanism (33). Piezoelectric gyro-sensors are now widely used to detect the noise motion of a handy video camera. Figure 15 shows a Tokin cylinder type gyroscope (34). Among the 6 electrode strips, two of them are used to excite total vibration, and the other two pairs of electrode are used to detect the Coriolis force or the rotational acceleration caused by the hand motion. By us-

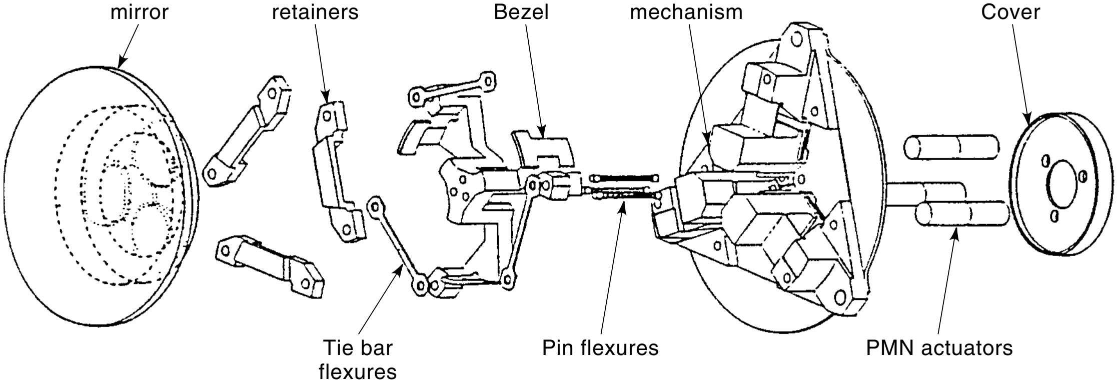

Figure 11. "Hubble" telescope using three PMN electrostrictive actuators for optical image correction.

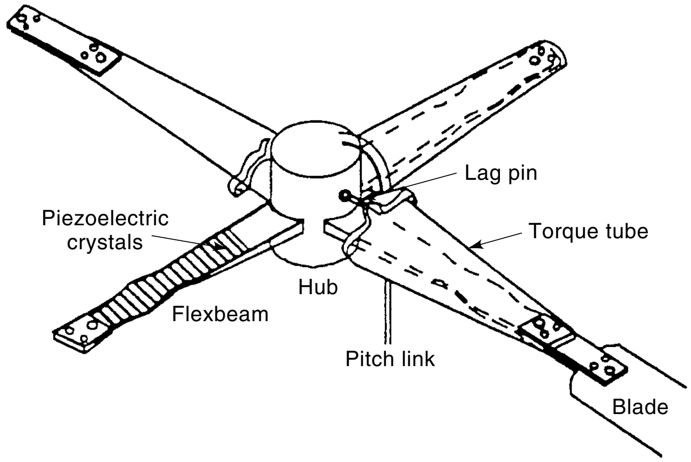

Figure 12. Bearingless rotor flexbeam with attached piezoelectric strips. Slight change of the blade angle provides drastic enhancement of controllability.

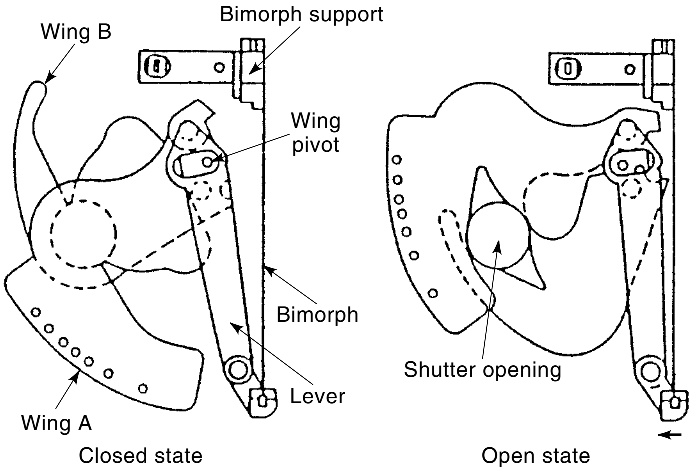

Figure 14. Camera shutter mechanism using a piezoelectric bimorph actuator.

ing the gyro signal, the image vibration can be compensated electrically on a monitor display.

Efforts have been made to develop high-power ultrasonic vibrators as replacements for conventional electromagnetic motors (35). The ultrasonic motor is characterized by low speed and high torque, which is contrasted with high speed and low torque of the electromagnetic motors. Two categories are being investigated in Japan for ultrasonic motors: a standing-wave type and a propagating-wave type.

The standing-wave type is sometimes referred to as a vibratory-coupler type or a "woodpecker" type, where a vibratory piece is connected to a piezoelectric driver, and the tip portion generates flat-elliptical movement. Attached to a rotor or a slider, the vibratory piece provides intermittent rotational torque or thrust. The standing-wave type has, in general, high efficiency, but lack of control in both clockwise and counterclockwise directions is a problem. An ultrasonic linear motor equipped with a multilayer piezoelectric actuator and fork-shaped metallic legs has been developed as shown in Fig. 16 (36). Since there is a slight difference in the mechanical resonance frequency between the two legs, the phase difference between the bending vibrations of both legs can be controlled by changing the drive frequency. The walking slider moves in a way similar to a horse using its fore and hind legs when trotting. A trial motor 20 × 20 × 5 mm^3 in dimension exhibited a maximum speed of 20 cm/s and a maximum thrust of 0.2 kgf with a maximum efficiency of 20% when driven at 98 kHz of 6 V (actual power = 0.7 W). This motor has been employed in a precision X-Y stage.

By comparison, the propagating-wave type (a surface-wave or "surfing" type) combines two standing waves with a 90° phase difference both in time and in space, and is controllable in both rotational directions (Fig. 17) (37). By means of the traveling elastic wave induced by the thin piezoelectric ring, a ring-type slider in contact with the "rippled" surface of the elastic body bonded onto the piezoelectric is driven in both directions by exchanging the sine and cosine voltage inputs. Another advantage is its thin design, which makes it suitable for installation in cameras as an automatic focusing device. 80% of the exchange lenses in the Canon "EOS" camera series have already been replaced by the ultrasonic motor mechanism.

Europe

Ceramic actuator development has begun relatively recently in Europe, and the research topics range widely. The current

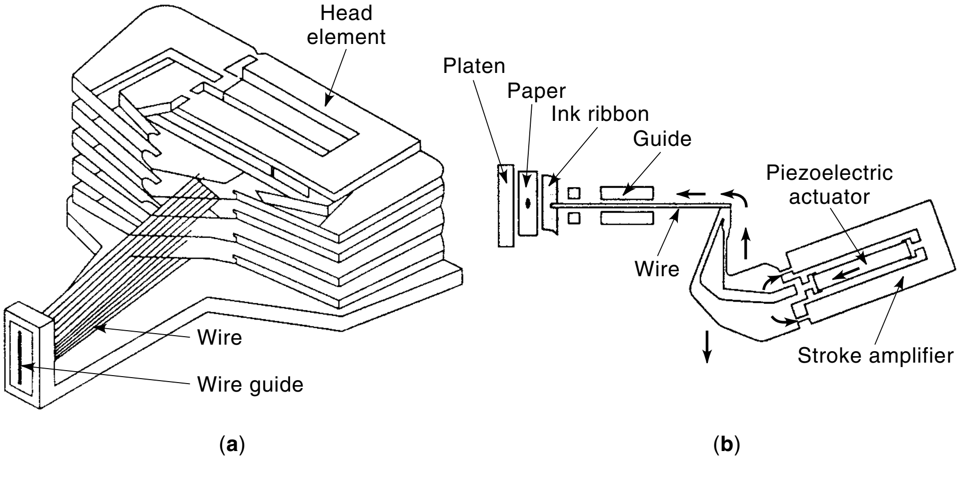

Figure 13. Structure of a printer head (a) and a differential-type piezoelectric printer-head element (b). A sophisticated monolithic hinge lever mechanism amplifies the actuator displacement by 30 times.

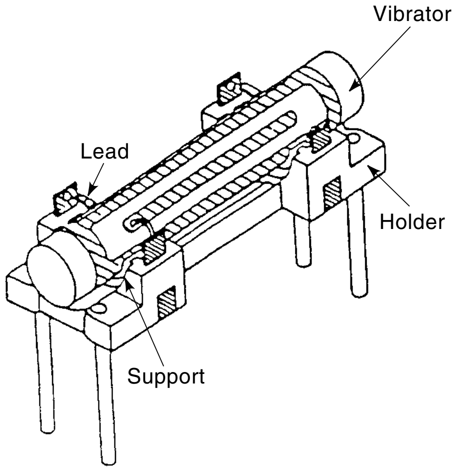

Figure 15. Piezo-ceramic cylinder vibratory gyroscope for detecting rotary acceleration.

focus by major manufacturers is directed toward products such as lab-stages and steppers with sophisticated structures.

Figure 18 shows a walking piezo motor with 4 multilayer actuators (38). The two shorter actuators function as clamps and the longer two provide the movement by an inchworm mechanism.

FUTURE OF CERAMIC ACTUATORS

Twenty years have passed since the intensive development of piezoelectric actuators began in Japan, then spread worldwide. The focus has now shifted to practical device applications.

The markets in the United States are limited to military and defense applications, and it is difficult to estimate the sales amount. The current needs from the Navy are smart submarine skins, hydrophone actuators, propeller noise cancellation, etc.; from the Air Force are smart aircraft skins; while the Army requires helicopter rotor twisting, aeroservoelastic control, and cabin noise/seat vibration cancellation.

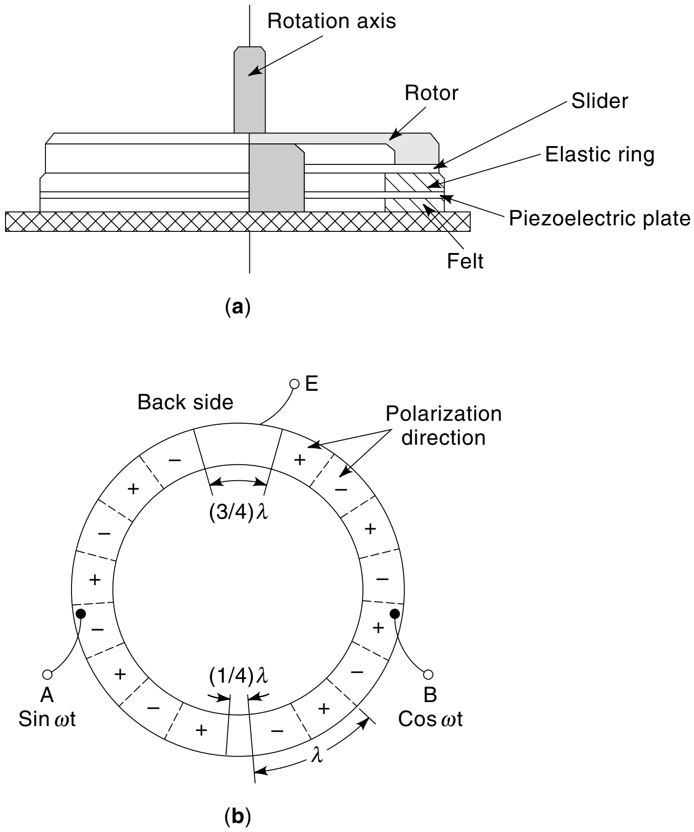

Figure 17. Design of the surface wave type motor (a) and its electrode configuration (b) by Shinsei Industries. Most of the ultrasonic motor researchers are tracing this design.

In Japan, piezoelectric camera shutters (Minolta Camera) and automatic focusing mechanisms in cameras (Canon), dot-matrix printers (NEC) and part-feeders (Sanki) are now being commercialized and mass-produced by tens of thousands of pieces per month. A number of patents have been disclosed particularly by NEC, TOTO Corporation, Matsushita Electric,

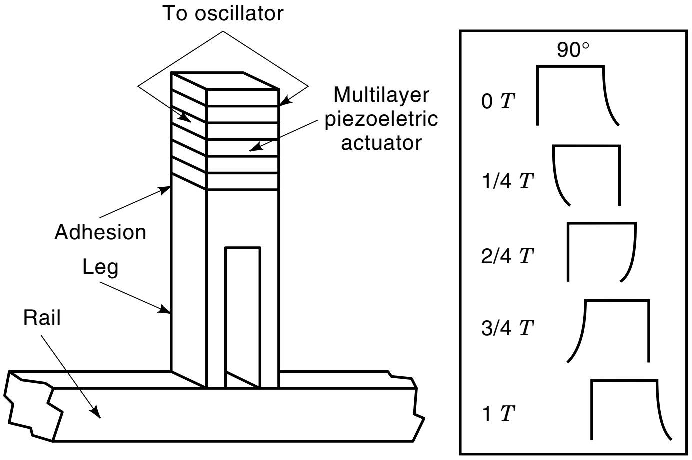

Figure 16. Ultrasonic linear motor of a vibratory coupler type. Choosing slightly different size legs, 90° phase lag of the vibration can be obtained by tuning the drive frequency, which corresponds to "trotting" mode.

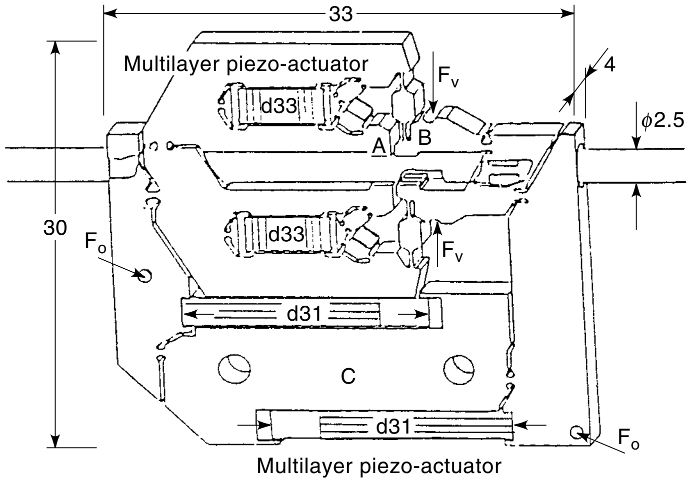

Figure 18. Walking piezo motor using an inchworm mechanism with 4 multilayer piezoelectric actuators by Philips.

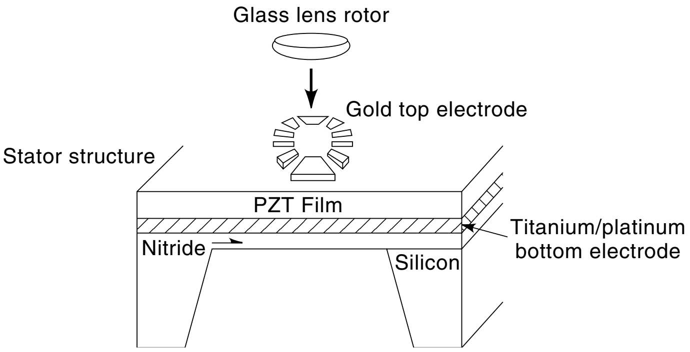

Figure 19. Ultrasonic micro-motor on a silicon diaphragm.

Brother Industry, Toyota Motors, Tokin, Hitachi Metal, and Toshiba.

We estimate the annual sales in 2005, in Japan, of ceramic actuator units, camera-related devices, and ultrasonic motors to reach $500 million, $300 million, and $150 million, respectively (39). These are installed in final actuator-related products, likely reaching $10 billion.

Future research trends will be divided into two ways: upsizing in space structures and down-sizing in office equipment. Further down-sizing will also be required in medical diagnostic applications such as blood test kits and surgical catheters. Penn State University is developing separate component motors with a diameter as small as 3 mm, using a "windmill" shaped torsional vibration coupler, which provides a torque around 0.1 mN.m (40). Piezoelectric thin films compatible with silicon technology will be of much focus in microelectromechanical systems. An ultrasonic rotary motor as tiny as 2 mm in diameter, fabricated on a silicon membrane is a good example (see Fig. 19) (41). However, these thin/thick film actuators cannot separately be used, and the whole device size is relatively large. Photodriven actuators with remote control capability will be developed not only for lightweight flexible space structures but also for microrobot applications.

With expansion of ceramic actuators applications, durability and reliability become more important. The final goal is to develop much tougher actuator ceramics mechanically and electrically. However, the reliability can be improved significantly if the degradation mechanisms can be monitored.

Safety systems or health monitoring systems have been proposed with two feedback mechanisms: position feedback which can compensate position drift and hysteresis, and breakdown detection feedback which can stop the actuator system safely without causing any serious damage onto the work, for example, in a lathe machine (42). Acoustic emission, internal potential measurements, and resistance monitoring of a strain-gauge type internal electrode embedded in a piezo-actuator under a cyclic electric field drive are good predictors of life time (43).

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