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Smart material/actuator needs in extreme environments in space

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ABSTRACT

Future missions to the planets and moons in our Solar System may require new technology. Missions with surface or atmospheric mobility or sample acquisition requirements will need advanced actuation technology to operate in the extreme environments found in the Solar System. Depending on the specific mission this technology may be required to withstand 10's of Kelvin environments or temperatures exceeding that of Venus (460^{o}C). In addition the technology may have to withstand high radiation and corrosive environments and pressures ranging from high vacuum to 100's of MPa. These challenging mission requirements push the limit in performance even under terrestrial conditions. Motors for mobility platforms, deployment devices or actuators for sampling tools are required that can operate reliably and deliver substantial torque and power. These devices must be lightweight, compact and operate effectively under extreme conditions. This paper will focus on a range of actuators based on electromechanical materials used for the applications discussed above and will present some of the challenges of developing these systems for space applications.

Keywords: Actuators, Positioners, Motors, Space exploration, Extreme Temperatures, Pressure

1. INTRODUCTION

Future NASA missions will require a variety of new technologies in order to meet the mass/power/volume envelopes and extreme conditions found on interesting future exploration sites in the Solar System[1]. Examples of the types of environments that may be encountered and typical temperature and pressure ranges are shown in Figure 1. As can be seen from the graph the range in expected pressures is high vacuum to 1000 bar and the temperature range is 460 ^{0}C on Venus to -215 ^{0}C on Pluto. In addition to the thermal and pressure environments experienced at various places in the solar system, spacecraft and instruments also have to be designed to function in gravity fields that can range from μg on comets and asteroids to 2.5g on Jupiter. Another issue is the large radiation dose that can be acquired outside the safety of the Earth's atmosphere and magnetosphere. Generally metals, ceramics and carbon/carbon composite materials may withstand extremely high dosage of the order of 10^{12} Rads without noticeable degradation in mechanical properties[2]. Electronic materials however are generally not as resilient and a large area of research has been dedicated to understanding space environmental effects of an assortment of materials[3,4]. One important technology area is advanced actuators. Technology development for in-situ missions under extreme environmental conditions is required. These actuators need to exert sufficiently high strokes, torques, and forces while operating under relatively harsh conditions. Venus is one of the targets of this program and a mission to this planet has been included in the NASA Decadal Planning effort. The environment on Venus poses a challenge to the existing actuation technology and there are no commercially available motors that can operate at its ambient temperature of 460 ^{o}C. Electromechanical materials (ex. Piezoelectrics, Electrostrictive, etc) have the potential to operate at these temperatures and produce the stroke/velocity and force/torque that is required to operate the needed mechanisms. Ultrasonic drills, corers and rock abrasion tools have be designed, fabricated and tested at JPL which have been tested at -60^{o}C and in simulated Mars environments (6 torr CO_2). Piezoelectric rotary motors have also been developed for composite manipulators[5] for a Mars environment. In order to determine if these materials can be used to build actuators which can operate at or above 460 ^{o}C we have studied an assortment of ceramics to determine the feasibility of these emerging high temperature piezoelectric materials[6] in support of this NASA need.

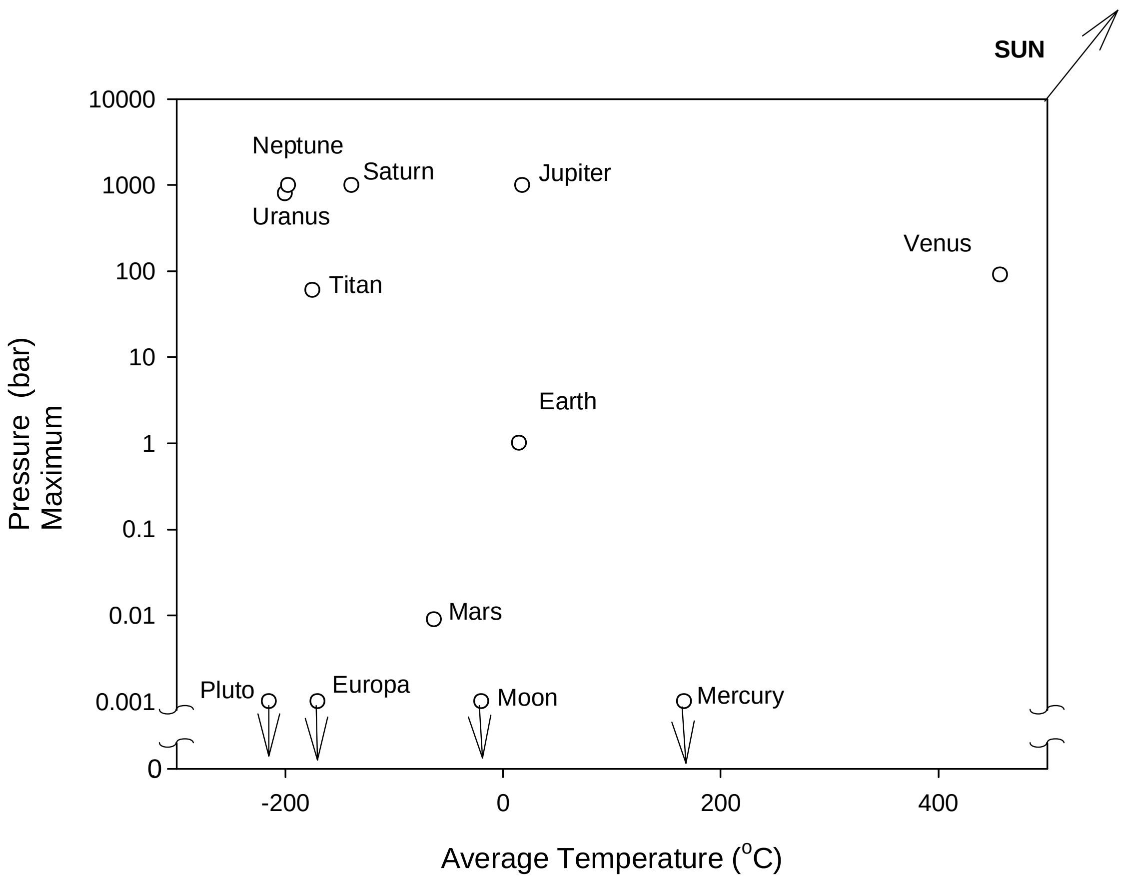


Figure 1. Estimated pressure maximums vs temperature for a selection of proposed mission destinations.[7]

The actuators that are needed for robotic exploration include lander pedal motors, drive/steering motors, manipulator joint motors, latching and deployment motors and sampling tool motors. The requirements on these actuators are very restrictive due to the mass, volume and power envelopes imposed by space applications. A schematic diagram showing some of these actuators which may be used in space exploration missions is shown in Figure 2. Except for the extreme high pressure region, of these restrictions (Pressure, static g, dynamic g, Temperature, Radiation Hardiness) high temperature operation in particular is the most restrictive. Operating at 460 ^{o}C as is found on the surface of Venus is an extreme challenge. Shielding, damping, sealing, heating can be incorporated in designs to account for many of these environmental factors however working in a high temperature environment for extended times is a very difficult technical challenge. Active cooling using one-shot chemical cooling or powered refrigeration techniques can ameliorate the problem for drive electronics and batteries however the actuators, bearings, cabling/insulation, solders, and control sensors may have to be located external to any environmentally controlled space. It is feasible that some of these components may be located intermediate between the high and controlled temperature regions and operated at a temperature below 460 ^{o}C. This paper will discuss the use of high temperature actuation materials and the various actuators that can be made from these materials including piezoelectric motors with substantial torque, fine position actuators with nm position resolution and power ultrasonic tools for sampling.

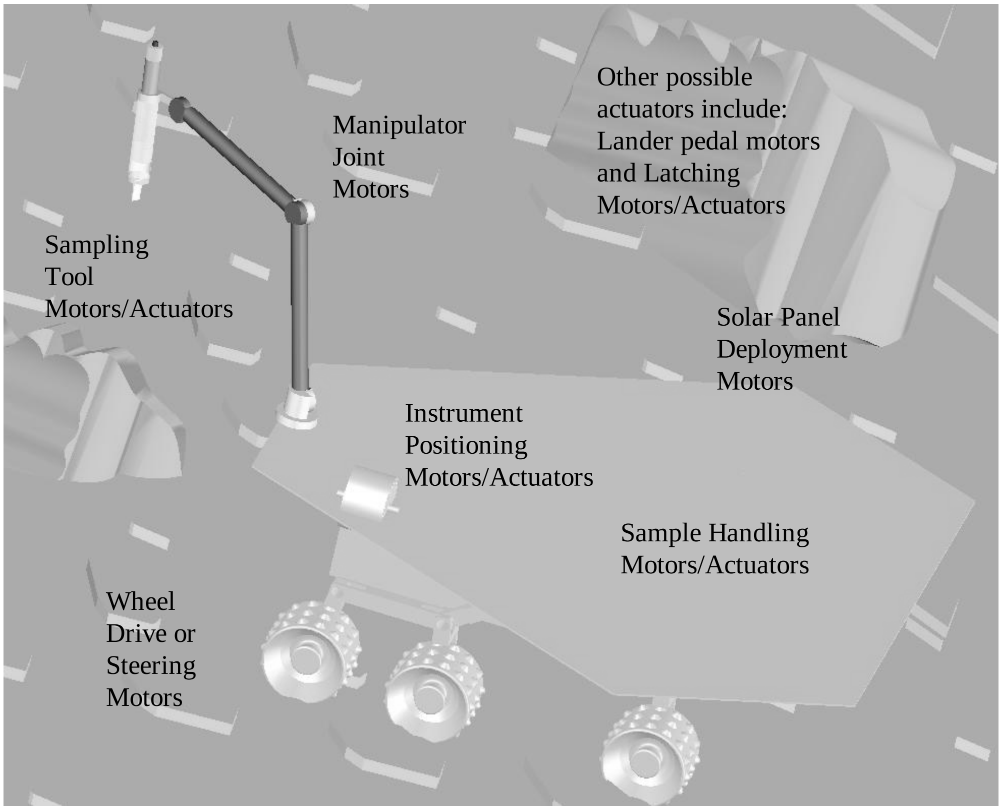


Figure 2. Schematic drawing of the possible actuator/motor locations on a rover.

2. HIGH TEMPERATURE ELECTROCERAMIC ACTUATION MATERIALS

Many issues have to be considered when developing devices for operation at high temperature. Material compatibility, chemical reactions, alloying, annealing, diffusion can effect the chemical and physical nature of components that are being used. In addition thermal expansion mismatch can be catastrophic to a system that requires precision fits. If these issues can be solved using good engineering design the engineer is still left the problem of the innate ability of the material to actuate. The intrinsic problem with high temperatures in standard actuators based on ferromagnetic or ferroelectric materials is the transition temperature (ex. Curie Temperature) where the materials switches from ferro to para and loses its actuation capability. Magnetic actuators such as brush, brushless, stepper motors all require a magnetic material and currently commercial units operate at a maximum temperature of approximately 200 ^{o}C. In these actuators the primary breakdown mechanism is shorting in the windings insulation rather than operation above or near the Curie Temperature. Some motors designed for extraction of smoke and deadly toxic fumes during fire emergencies are available up to the 500 ^{o}C level however these are usually large and have lifetimes of a couple of hours[8]. Since piezoelectric materials do not need windings, can be fixed to a structure and do not require electrical or mechanical commutation we have initiated an investigation into these materials for high temperature actuators. Table 1. lists the Curie Temperature, piezoelectric constants, and other pertinent properties of high temperature materials we have measured in the lab. Many ferroelectric/piezoelectric materials exist that have high Curie temperatures however the piezoelectric response of these materials is generally small. Lithium Niobate ($LiNbO_3$) has a Curie temperature of 1150 ^{o}C however the dielectric constant and piezoelectric constants are a factor of 100 below that of Navy VI PZT compositions. The temperature dependence of the materials listed in Table 1. is shown in Figure 3. The BST-PT and BMT-PT were produced by TRS Technologies Inc. and Bismuth Titanate BT samples were produced by Ferroperm Piezoceramics A/S (Pz46), and Sinoceramics(B8613).

Table 1. Comparison of the room temperature material coefficients of the HT materials with a Navy III material (Channel 5800).

Material Property	Navy III	BS-PT	BMT-PT	Pz46	B8613
Curie Temperature (^{o}C)	300	≈400	≈450	>500	>500
$\mathbf{s}_{11}^{E}$ (10^{-11}m^2/N)	0.94	1.27	1.01	0.84	1.36
$\boldsymbol{\varepsilon}_{33}^{T}/\varepsilon_0$ (#)	1020	1330	860	121	90
$\mathbf{d}_{13}$ (pC/N)	111	136	49	1.3	4.6
$\mathbf{k}_P$ (#)		0.59	0.29		
σ_P (#)		0.27	0.24		
e_{33} (C/m^2)	11.1	12.2	12.8	2.1	2.6
$\mathbf{c}_{33}^{D}$ (10^{11} N/m^2)	1.62	1.46	1.91	1.20	1.28
$\mathbf{k_t}$ (#)	0.39	0.47	0.44	0.19	0.23
$\mathbf{k}_{13}$ (#)	0.38			0.014	0.044
tanδ (at RE or RB mode frequencies)	0.012	0.1	0.12	0.004	0.0024
Mechanical Q (From $\mathbf{s}_{11}^{E}$)	320	14	23	1580*	590*

*Likely decrease from reported values due to damping of resonance by wire contact.

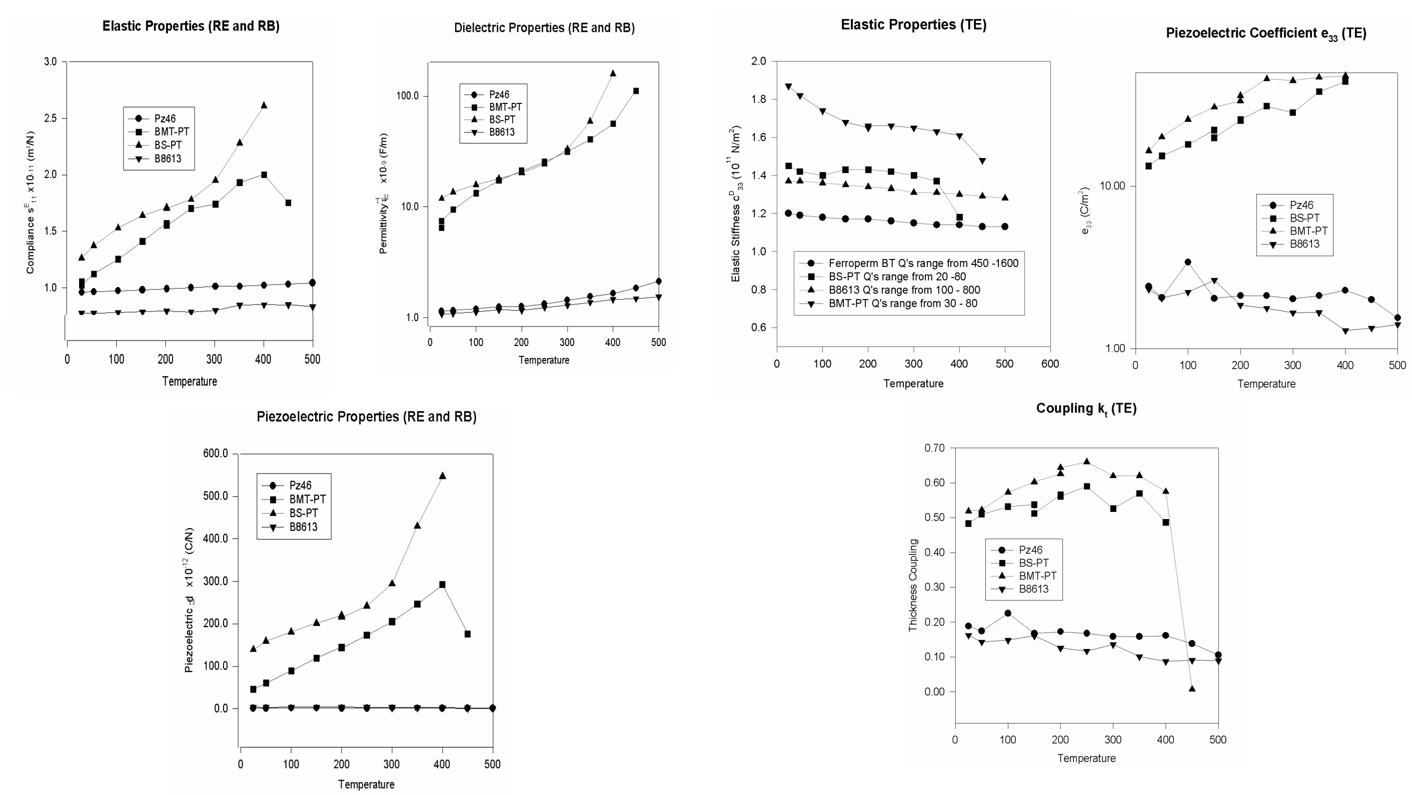


Figure 3. The thickness, radial or ring mode elastics, piezoelectric and coupling coefficients as a function of temperature for four of the materials reported in Table 1.

3. ELECTROCERAMICS ACTUATORS

As was noted in the previous section piezoeelectric materials have the ability to operate over a large temperature range. This makes them atractive as potential materials for high temperature actuators   Piezoelectrics can induce large stress levels, which are essential for many actuation tasks. Unfortunately, the accompanied strain is very small and is far below the levels that can be obtained by electromagnetic devices. To overcome this weakness, a wide assortment of devices and configurations were developed to increase the strain for given levels of applied voltages. Examples of various effective mechanisms are described in this section. One of the most common actuator configurations is the piezoelectric stack, which as the name implies, is a number of thin alternately poled piezoelectric layers connected mechanically in series and electrically in parallel.

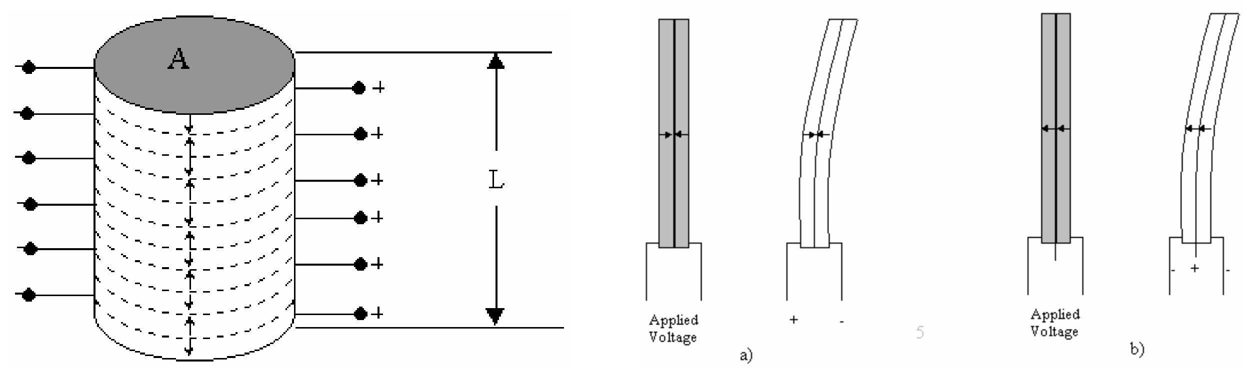


Figure 4: Piezoelectric stack with n layers of length L and electrode area A and schematic view of bimorphs in a) series; and b) parallel.

For the stack configurations shown in Figure 4, assuming zero bond joint thickness, the effective piezoelectric constant and low frequency capacitance C are

$$d_{33}^{eff} = nd_{33} \tag{1}$$

$$C = \frac{n^2 \varepsilon_{33}^{T} A}{L} \tag{2}$$

It should be noted that for a given voltage the displacement is amplified by a factor n over the displacement that would be found on a monolithic ceramic wafer having length L and area A. The displacement as a function of the voltage is then

$$\Delta x = nd_{33}V \tag{3}$$

The total displacement of a stack having a reasonable length without the use of other amplification techniques is limited at room temperature to approximately 100 microns. A recent NASA report by Wise and Hooker[9] provides performance data for several piezoelectric stacks that are manufactured by four different companies.

Piezoelectric bimorphs can be configured in series and parallel and examples are shown in Figure 4. Generally, bimorphs are constructed of two piezoelectric plates that are bonded with their polarity in opposite directions. Under electric field one piezoelectric layer contracts in the thickness direction while the other expands. Due to the contraction and expansion in the thickness direction one layer expands along the length and the other contracts inducing bending of the bonded layers.

For the series-configuration with a free length L, total thickness t and a transverse piezoelectric coefficient d_{31}, the tip displacement is proportional to the voltage V and is expressed as follows.

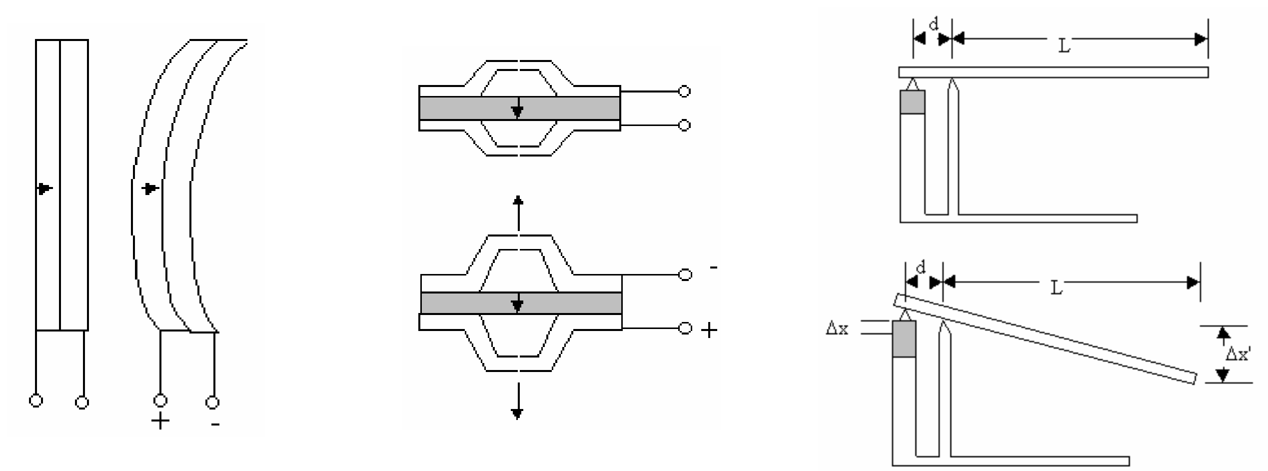
$$\Delta y = \frac{3d_{31}VL^2}{2t^2} \tag{5}$$

The expression for the same parameters with parallel-configuration shows a displacement that is twice the value for the series-configuration when using the same voltage level

$$\Delta y = \frac{3d_{31}VL^2}{t^2} \tag{6}$$

Tip displacements of the order of a centimeter can be induced using bimorph type actuators.

Unimorphs are similar in configuration to bimorphs with the difference that one of the layers in passive. Under expansion in the poling direction the strain in the plane perpendicular to the poling direction undergoes a contraction. As shown in Figure 5. This strain occurs only on the active layer (piezoelectric or electrostrictive material) leading to a bending of the whole device. Such devices can be used to induce relatively large deflections and the amplitude increases with the lateral dimensions. Some of the unimorph configurations that were reported in recent years include the Rainbow or Cerambow - This type of actuators consists of reduced and internally biased oxide wafers or differential electrode thickness. This family of actuators was developed at Clemson by Heartling[10] and Barron, et. al.[11].
Another unimorph is the Thunder actuator. These are thin-layer composite unimorphs were developed by NASA Langley and marketed by Face International[12].



(a) (b) (c)

Figure 5:a) Schematic view of a unimorph actuator, b) Schematic diagram of a Cymbal flextensional design, and c) Example of cantilever design

Flextensional actuators, which are also known as the Moonie and Cymbal[13] use end-caps to convert transverse to longitudinal strain. A schematic diagram of the strain amplification process for this mechanism is shown in Figure 5b. Cantilever designs[14] use a lever configuration to increase the strain. An example is shown in Figure 5c.. A piezoelectric or electrostrictive material is connected mechanically to a lever arm and it is pivoted a distance d from the active element. From the pivot the lever arm extends out to a distance L. For a displacement Δx in the active element the displacement at the other end is Δx' = (L/d) Δx and thus a strain amplification of (L/d) is realized. For example if a piezoelectric stack of maximum displacement of 100-µm is induced and strain amplification factor (L/d=10) then displacements on the order of 1-mm can be achieved. A discussion and comparison of the cantilever, multilayer, flextensional, rainbow and bimorph configuration is given by Near[15]. The devices discussed above have the potential to be used as positioners over a wide temperature range.

Another approach used to increase the strain that can be induced with a piezoelectric material for a given field is to drive the material at its resonance frequency. In general for any mechanical system it can be shown that at resonance the strain in is amplified by a factor called the mechanical Q. The mechanical Q is a measure of the mechanical losses in the material. For a material with high Q, the mechanical losses are small. For PZT the mechanical Q can range from 50 to 1000 and therefore for an ideal system the strain amplification can be as high as 1000 times. However, it should be noted that for materials with large Q it is very easy to drive the active element into a nonlinear regime reducing the overall amplification and/or damaging the element. Another problem with resonance amplification is that the resonance frequency for a piezoelectric material is determined from the velocity of sound and the dimension in which the material is resonating. This means that in practice for most piezoelectric material elements the operating frequency is limited to the range of 100's of kHz and above.

At low frequencies, an effective resonance amplification can be obtained by the configuration of an ultrasonic horn. A schematic diagram of a stepped horn cross section[16] is shown in Figure 6. Due to the conservation of the wave momentum, at resonance, a strain wave induced on the large end creates a displacement at the small end that is amplified by a factor $M=(D_1/D_2)^2$. This amplification is in addition to the amplification due to the material mechanical Q. Other horn configurations include the exponential[17] having amplification of $M=D_1/D_2$ and the linear having amplification factor of M=4.61.

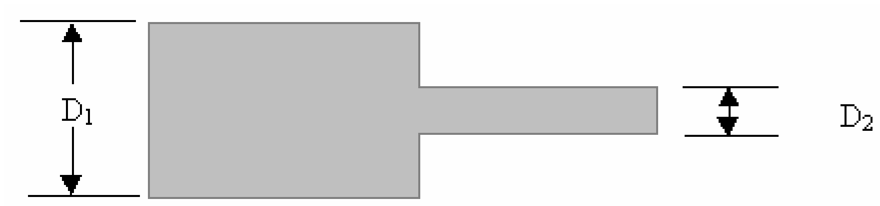


Figure 6. Schematic of a stepped ultrasonic horn. Piezoelectric elements drive the large end to produce an amplified tip displacement

One advantage of ultrasonic horns is the ability to adjust the resonance frequency by changing the relative length of the two sections. The frequency can be adjusted by a factor of 2 without changing the overall length. It should be noted that the amplification is limited in practice by the critical strain of the tip material. This actuator is the critical element of the Ultrasonic/Sonic Driller/Corer which is currently being developed at JPL[18,19,20] .

Motors are an important element of automatic and robotic mechanisms. Most actuators are based on electromagnetic rotary motors, such as DC, AC, brush and brushless, etc. As was previously mention no commercial units are available for operation at high temperatures. In addition these types of motors compromise speed, which can be as high as many thousands of RPM, for torque using speed-reducing gears. The use of gear adds mass, volume and complexity as well as reduces the system reliability due the increase in number of the system components. The miniaturization of conventional electromagnetic motors is also limited by manufacturing constraints and loss of performance efficiency.

Motors that are actuated by piezoelectric ceramics offer an effective alternative to conventional electric motors due to the fact that the actuator material can be fixed and electrical or mechanical commutation is not required This emerging motor technology can provide high torque density at low speed, high holding torque[21], zero-backlash, simple construction, quiet operation and have a fast response time. These motors which are also known as ultrasonic motors (USM) can be made in annular shapes for optical applications, where the electronics and wiring can be packaged in the center. USM's can classified by their mode of operation (quasi static or resonant, traveling), type of motion (rotary or linear) and the shape of actuation element (beam, rod, disk, etc.). Despite these distinctions, the fundamental principle is common to all of these devices. Each of these motor designs uses microscopic material deformations (usually associated with piezoelectric materials) that are amplified through either quasi-static or dynamic/resonant means.

Generally, most quasi-static designed ultrasonic motors are used for micro-positioning applications. One of the first ultrasonic motors was reported by N-Nagy and coworkers[22,23] using two phase-bridge of PZT bimorph to generate rotary motion. Another quasi-static design is based on an inchworm motor[24.25] as shown in Figure 7(a). This inchworm motor is fabricated with a minimum of 3 piezoelectric or electrostrictive actuators. The actuators are excited to mimic the motion of an inchworm and a timed excitation of each of the actuators is required. The actuation cycle is shown in Figure 7(a).

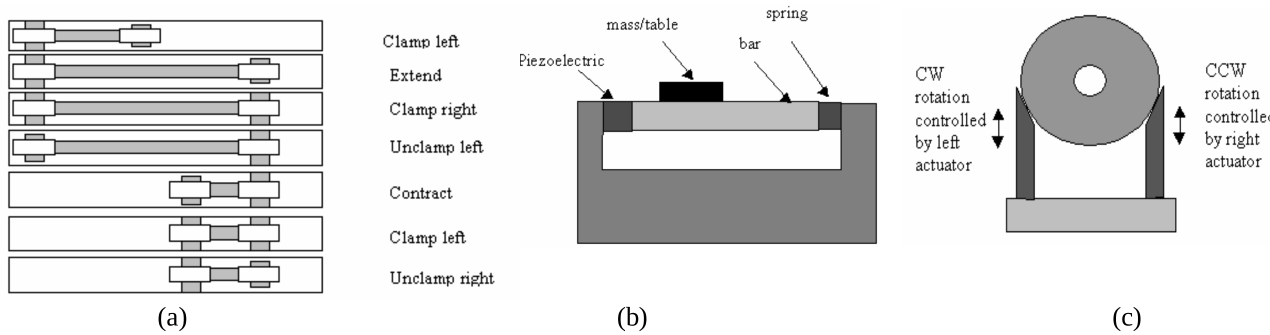


Figure 7. a) Schematic diagram of the movement of an inchworm motor/translator. b) Slider type linear motor. Motion of mass is achieved by activating the stack with a saw-tooth waveform and c) Schematic diagram of the Barth[26] motor

The response time of the actuator *t* and the stroke of the extension actuation Δx limit the speed of the inchworm and the maximum speed is v = Δx/*t*. For a 20 μm stroke and 6 ms actuation time for the actuation cycle the maximum speed is on the order of 3 mm/s[27,28]. One of the disadvantages of these motors is that an electrical power is required to maintain the holding force. Another quasi-static design, which is based on work by Pohl[29], is known as the slider and is shown in Figure 7(b). A piezoelectric stack is used to displace a rod, which is supporting the mass/table to be moved. The stack is excited with a saw-tooth voltage. The initial displacement is gradual and the frictional force between the mass and the rod is sufficient to drag the mass/table along during the displacement. At the point of maximum displacement the stack contracts quickly breaking the friction between the two surfaces and leaving the mass/table in the maximum extension position. This is repeated at a frequency *f* to give a speed $v = f\Delta x$ which is of the order of 5 mm/s. The performance of these types of motors is found to be very dependent on the surface roughness and the friction between the bar and the mass.

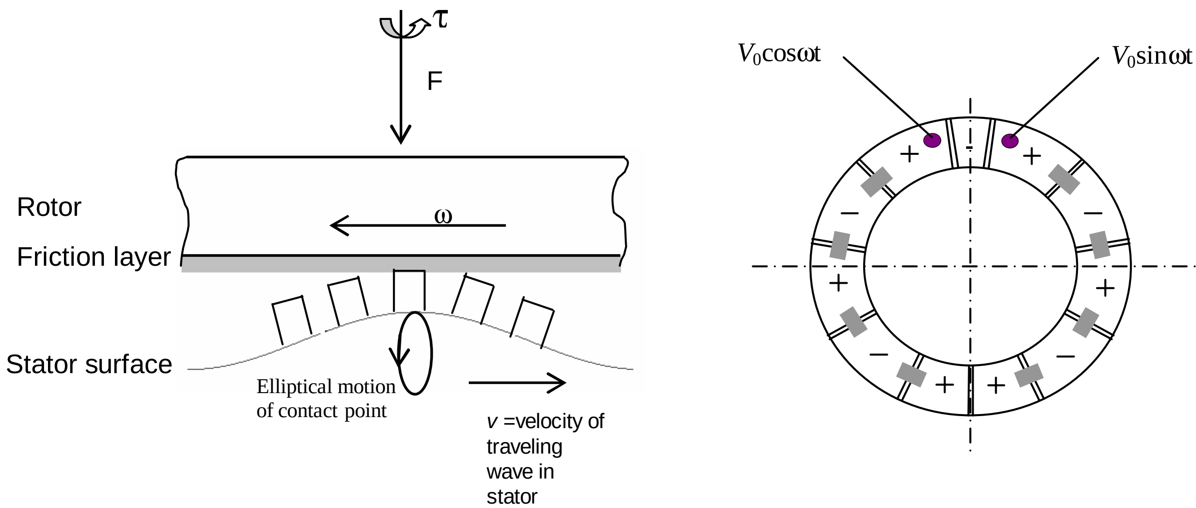
One of the first piezoelectric motor designs with significant rotational speeds was outlined by Barth[26]. This device used extensional piezoelectric elements to produce a time varying force at a distance r from the center of a centrally supported disk as is shown in Figure 7(c). Microsteps are formed at a high frequency and the end result is a macroscopic rotation of the disk. The rotation direction is controlled by the choice of the actuators.

Another group of motors that use standing waves or resonances in the motor elements was develop by Vasiliev and colleagues[30]. They used resonances in an ultrasonic horn to increase the stroke of the actuator and lower the frequency. Sashida and colleagues[31.32] used a wedge type motor based on the Langevin transducer (elliptical motion at contact surface) and improved on the design showing rotational speeds up to 3000 RPM with torques of the order of 0.25 Nm. The efficiency of the motor was found to be in the range of 50-87 percent depending on the diligence of the precision machining and adjustment. The major disadvantage of these types of motors is the high wear rate.

Piezoelectric motors that operate at frequencies above 20 kHz are usually referred to as ultrasonic motors[14 ,33, 34,35,36,37,38,39]. Several USM classes have seen commercial application in areas needing compact, efficient, intermittent motion[40,41]. Such applications include camera auto focus lenses[42,43], watch motors[44] and compact paper handling[34].

The gross motion in these motors is accomplished through the amplification and repetition of the micro-deformations of material. Active materials (mostly piezoelectric) are employed to induce elliptical motion on the surface of a stator at the contact points with a rotor. A frictional interface between the rotor and stator rectifies the micro-motion to produce macro-motion of the rotor. The rotor essentially rides the traveling flexural wave excited within the stator (see Figure 8). Useful work can be done by mechanically connecting a drive shaft to the rotor. Teeth, which amplify the displacements, are used to enhance the speed. The operation of USM depends on friction at the interface between the moving rotor and stator and it is a key design issue, which affects the motor extended lifetime. The torque imparted to the rotor via the stator is obtained by creating a frictional force between the teeth of the stator and the rotor. The frictional force is dependent on the normal forces applied on the rotor/stator interface. This motion transfer operates as a gear and leads to a much lower rotation speed than the wave frequency. The rotation speed can be reduced by a factor of several thousand.

To generate a traveling wave within the stator two orthogonal modes are activated simultaneously. A stator that is constructed with piezoelectric actuators induces these modes. The actuator is bonded to the stator and the flexural waves are induced by poling different sections of the actuator with the opposite polarity and driving with the appropriate voltage excitation. An example of the actuator configuration is shown in Figure 8. Geometrical examination of this pattern shows that driving the two sections using *cos(ωt)* and *sin(ωt)* signals, respectively, will produce a traveling wave with a frequency of $\omega/2\pi$. Also, by changing the sign on one of the drive signals, the



traveling wave would reverses its direction.

Figure 8. Principle of Operation of a Rotary Traveling Wave Motor (Ring type - edge view) and a generic stator design describing the poling sequence on the piezoelectric disk for a 5-wavelength motor.

A generic description of the stator is shown in Figure 8. The stator can be driven by a piezoelectric wafer that is placed either on one surface[43] or sandwiched between two wafers[45]. To generate traveling wave, the piezoelectric ceramic materials internal poling is structured such that quarter wavelength out-of-phase is formed. This poling pattern is also intended to eliminate extension in the stator and maximize bending. The teeth on the stator are arranged in a ring at the radial position. In Figure 8, the solid lines indicate electrode segments that are used to pole the ring in alternating polarities. After poling each half of the ring is electrically connected (shown as grey tabs) to its neighbor segment. The two halves are driven 90 degrees out of phase by the application of a cos(ωt) and sin(ωt) driving signals. The area not activated can be used as a sensor to gauge the condition of the resonance. Five wavelengths are allowed for the design shown in Figure 8.

Two factors dominate the optimization of the motor performance: the tooth height and the applied axial loading. Analysis of the motor performance has shown that an increase of the teeth height increases the speed of the motor with relatively small effect on the stall torque. Further, the effect of the teeth height on the motor efficiency requires optimization since there is an increase at small values reaching a maximum at certain ratios of the teeth height to the stator thickness. The two most important characteristics of the motor are speed-torque and efficiency-torque. Typical graphs for low axial loading of a traveling wave USM yields a low stall torque and a relatively fast no-load speed. As the axial loading increases, a steady state progression is observed from high no-load speeds and low stall-torque to lower no-load speeds and high torque. This rotor speed decrease is due to the normal forcing on the stator, as the axial load increases, more energy is taken out of the stator vibration and thus the stator surface velocity decreases which in turn affects the rotor velocity. Examination of the efficiency-torque curves shows that maximizing the output power does not maximize the efficiency. The cause of this behavior is the clamping effect that is associated with the increased load and reduced capability of the stator to resonate.

The analysis of the nonlinear, coupled rotor-stator dynamic model discussed above has demonstrated the potential to predicting motor steady state and transient performance as a function of critical design parameters such as interface normal force, tooth height, and stator radial cross section. These models can account for the shape of the stator, the piezoelectric poling pattern, and the teeth parameters. Electronic speckle pattern interferometry[46] has been used to corroborate the predicted modal response and the agreement was found to be very good. The predicted resonance and measured resonance frequency for a 4.34-cn diameter steel stator were in excellent agreement between the calculated and measured data. Another advantage of USM's is their ability to handle extreme environments. The effect of low temperatures and vacuum, on a 2.8-cm USM on the speed and the torque was measured down to -150^{o}C and at a vacuum level of 1.6x10^{-2} Torr. The motor showed a remarkably stable performance under these harsh conditions. Other work has shown that these motors work for up to 300 hrs at -150^{o}C in vacuum[47]. These results are very encouraging for potential application of these motors to space mechanisms. Since the piezoelectric motors do not require commutation and are generally fixed to structures, high temperature piezoelectrics appear to be a viable approach to building high temperature motors for use in space.

5. CONCLUDING REMARKS

Future missions to the planets and moons in our Solar System require advanced actuation technologies. The most difficult challenge is to find actuators that will operate at high temperatures as is found on Venus (460^{o}C). In order to develop actuators that can work at these temperatures we have investigated high temperatures piezoelectric materials. Materials were tested up to the temperature of Venus (460^{o}C). Bismuth Titanate samples (Pz 46 supplied by Ferroperm, B8613 supplied by Noliac) were found to be stable up to 500^{o}C whereas the BMT-PT and the BS-PT samples depoled between 450^{o}C and 500^{o}C, and 400^{o}C and 450^{o}C, respectively. Although the BMT-PT and BS-PT materials have piezoelectric activity of the same order as in the PZT type Navy III material, the mechanical and electrical losses are about an order of magnitude higher. The Bismuth Titanate samples (Pz46 and B8613) have piezoelectric activity that is considerably lower than the Navy III material however their losses are generally lower. Ideally, high piezoelectric activity and low losses are required to produce high power actuation mechanisms (Horns, stacks, motors, etc). A review of many of the actuation mechanisms that could be used in Space which use piezoelectrics was reported. Since piezoelectrics do not require commutation and are generally fixed to structures, high temperature piezoelectrics appear to be a viable approach to building high temperature actuators or motors for use in space.

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REFERENCES

[1] R. Gershman, R.A Wallace, "Technology Needs of Future Planetary Missions, Acta Astronautica, **45**, Nos. 4-9, pp. 329-335, 1999

[2] B.P. Dolgin, "Radiation Effects on Non-Electronic Materials Handbook", JPL Document D5312, Oct 1991

[3] R.C. Haymes, Introduction to Space Science, New York, NY, John Wiley and Sons Inc., 1971

[4] D. Hastings, H.B. Garrett, "Spacecraft-Environment Interactions", <u>Atmospheric and Space Science Series</u>, Ed. A.J. Dessler, Cambridge University Press, Cambridge, England, 1996

[5] Paul S. Schenker, Eric T. Baumgartner, Sukhan Lee, Hrand Aghazarian, Michael S. Garrett, Randall A. Lindemann, D. K. Brown, Yoseph Bar-Cohen, Shyh-Shiuh Lih, Benjamin Joffe, Soon S. Kim, B. D. Hoffman, Terrance L. Huntsberger "Dexterous robotic sampling for Mars in-situ science," Proc. SPIE Vol. 3208, p. 170-185, Intelligent Robots and Computer Vision XVI: Algorithms, Techniques, Active Vision, and Materials Handling; David P. Casasent; Ed., Sept 1997

[6] S. Sherrit, X. Bao, Y. Bar-Cohen, and Z. Chang, "Resonance Analysis of High Temperature Piezoelectric Materials for Actuation and Sensing," SPIE Smart Structures and Materials Symposium, Paper #5388-34, San Diego, CA, March 15-18, 2004

[7]see–http://en.wikipedia.org/wiki/Planets#Accepted_planets,or http://www.jpl.nasa.gov/solar_system/ or http://www.nineplanets.org/.
[8]See - http://www.teco.com.sg/2hightmp.htm, or http://www.loher.de/en/news/articles/news-Fire%20damp%20exhaust%20motor.htm.
[9] Wise S.A., Hooker M.W.(1997): "Characterization of Multilayer Piezoelectric Actuators for Use in Active Isolation Mounts", NASA Technical Memorandum 4742
[10] Haertling G. , "Rainbow Acuators and Sensors: A New Smart Technology, Proceeding of the SPIE conference on Smart Materials, In Smart Material Technologies, vol. 3040, pp. 81-92, 1997
[11] Barron B.W., Li G., Haertling G.H, "Temperature Dependent Characteristics of CERAMBOW Actuators, Proceedings of the 10th IEEE International Symposium on the Application of Ferroelectrics, East Brunswick, N.J., vol. 1, pp. 305-308, August, 1996
[12] Face International, THUNDER Technical Specifications, Face International Corp. 427 35th St. Norfolk, VA, 23508, 1999
[13] Dogin A., Uchino K., Newnham R.E, (1997):"Composite Piezoelectric Transducer with Truncated Conical Endcaps 'Cymbals'", IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, **44**, pp.597-605
[14] Burleigh Instruments Product Catalogue, Burleigh Instruments, Inc. Fishers, New York., Burleigh Instruments Micro-positioning Systems, 1991, Burleigh Instruments, Inc. Fishers, New York.
[15] Near, C. , "Piezoelectric Actuator Technology", Proceeding of the SPIE Smart Structures and Materials Conference, Vol.2717, pp. 246-258, San Diego, CA , 1996
[16] Belford J.F. ,"The Stepped Horn", Proceedings of the National Electronics Conference, pp. 814-822, Chicago, 1960
[17] Mason W.P., Physical Acoustics and the Properties of Solids, D. Van Nostrand Co Inc., Princeton, NJ, 1958
[18]S. Sherrit, B.P. Dolgin, Y. Bar-Cohen, D. Pal, J. Kroh, T. Peterson "Modeling of Horns for Sonic/Ultrasonic Applications," Proceedings of the IEEE International Ultrasonics Symposium, Lake Tahoe, CA, October 1999, pp. 647-651
[19] Bao X., Y. Bar-Cohen, Z. Chang, B. P. Dolgin, S. Sherrit, D. S. Pal, S. Du, and T. Peterson, "Modeling and Computer Simulation of Ultrasonic/Sonic Driller.Corer (USDC)", *IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control (UFFC)*, Vol. 50, No. 9, (Sept. 2003), pp. 1147-1160.
[20] Bar-Cohen, Y., Sherrit, S., Dolgin, B., Bao, X., Chang, Z., Krahe, R., Kroh, J., Pal, D., Du, S., and Peterson, T., "Ultrasonic/Sonic Driller/Corer(USDC) for planetary application," *Proc. SPIE Smart Structure and Materials 2001*, pp. 529-551, 2001.
[21] Flynn, A. ,"The Scoop on Ultrasonic Motors in Japan," Office of Naval Research Asian Office Scientific Information Bulletin, NAVSO P-3580, Vol. 17, No. 2, April-June, pp. 99-102., 1992
[22] N-Nagy F.L., Calderwood J.H., Abstract in IEEE Trans. Electron Devices, **16**, 6, pp.603, 1969
[23] N-Nagy F.L., Joyce G.C , Solid State Control Elements Operating of Piezoelectric Principals, Physical Acoustics, **9**, pp. 129-165, 1972
[24] Shimizu N., Kimura T., Nakamura T., Umebu I, "An Ultrahigh Vacuum Scanning Tunneling Microscope with a new Inchworm Mechanism, J. Vac. Sci. Technol. , A8, pp. 333-335, 1990
[25] Wallace J.L., Espinoza-Faller F.J (1995):., "A Vibrating Reed Magnetometer Based on an inchworm Motor and a Tunelling Tip Sensor", Meas. Sci. Technol., 6, pp. 1221-1224, 1995
[26] Barth H.V, Ultrasonic Driven Motor, IBM Technical Disclosure Bulletin, **16**, pp. 2263, 1973
[27] Galante, T., Frank, J., Bernard, J., Chen, W., Lesieutre, G., Koopman, G.H., "Design Modeling and Performance of a High Force Piezoelectric Inchworm Motor", Proceeding of the SPIE Smart Structures and Materials Conference, Vol.3329, pp. 756-767, San Diego, CA, 1998
[28] Chen, Q. Yao, D., Kim, C.J. , Carman, G.P., "Frequency Response of an inchworm motor fabricated with micro machined interlocking surface Mesoscale Actuator Device (MAD)", Proceeding of the SPIE Smart Structures and Materials Conference, Vol.3329, pp. 768-776, San Diego, CA, 1998
[29] Pohl D.W., "Dynamic Piezoelectric Translation Device", Rev. Sci. Instrum., **58**, pp.54-57, 1987
[30]Vasiliev P.E. et al. , UK Patent Application GB 2020857 A , 1979
[31] Sashida T., Oyo Butsuri, **51**, pp.713-720, 1982
[32] Sashida T., Kenjo T, An Introduction to Ultrasonic Motors, Claredon Press , Oxford, 1993

[33]Uchino K., Kato K. Tohda M., "Ultrasonic Linear Motors Using a Multilayered Piezoelectric Actuator," Ferroelectrics, Vol. 87, pp. 331-334, 1988
[34]Inoue T., Takahashi S. Suga M., "Application of Ultrasonics to Paper Transport Mechanisms," Techno, pp. 4749, in Japanese, 1989
[35]Zemella R. J., "Design and Development of a Linear Traveling Wave Motor," MIT Master's Thesis in Aeronautics and Astronautics., 1990
[36] Kumada, A., "A Piezoelectric Ultrasonic Motor," Japanese Journal of Applied Physics, Vol. 24, Supplement 24-2, pp. 739-741, 1985
[37] Minoru K., Ueha S., Moru E.,"Excitation Conditions of Flexural Traveling Waves for a Reversible Ultrasonic Linear Motor," Journal of the Acoustic Society of Japan, Vol, 77, No.4, 1983
[38] Inaba R., Tokushima A., Kawasaki O., Ise Y., And Yoneno H., "Piezoelectric Ultrasonic Motor," Proceedings of the IEEE Ultrasonics Symposium, pp. 747-756, 1981
[39]Ueha S., Tomikawa Y., Ultrasonic Motors, Claredon Press, Oxford, 1993
[40]Panasonic "Ultrasonic Motor", Panasonic Technical Reference. Panasonic Industrial Co., Division of Matsushita Electric Corp. of America, 1 Panasonic Way, Secaucus, NJ,1987.
[41]Masaki Y., (1991):"Vibrator and Ultrasonic Motor Employing the Same," U.S. Patent 4,983,874, January 8, 1991
[42]Hosoe J , "An Ultrasonic Motor for Use in Autofocus Lens Assemblies," Techno. pp. 36-41, , in Japanese., 1989
[43]Cannon"Cannon Develops an 11x25-mm Miniature Ultrasonic Motor," Cannon, Nikkei Mechanical, June 1992.
[44]Seiko, "Ultrasonic Micromotor Data Sheets", Seiko Instruments Inc., Precision Instruments Department, Consumer Products Div., 1-9-1 Miyakubo, Ichikawa-shi, Chiba 272, Japan, 1992
[45]Hagood N. W., Mcfarland A., "Modeling of a Piezoelectric Rotary Ultrasonic Motor," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,.**42**, No. 2, pp. 210-224, 1995
[46]Lih S.-S., Bar-Cohen Y. , Grandia W., "Rotary Piezoelectric Motors Actuated By Traveling Waves," Proceedings of SPIE, Vol. SPIE 3041, Smart Structures And Materials Symposium, Enabling Technologies: Smart Structures and Integrated Systems, Marc E. Regelbrugge (Ed.), ISBN 0-8194-2454-4, SPIE, Bellingham, WA (June 1997), p. 912-917, 1997
[47] Bar-Cohen Y., Bao X., Grandia W, "Rotary Ultrasonic Motors Actuated by Traveling Flexural Wave", Proceedings of the SPIE International Smart Materials and Structures Conference, SPIE paper 3329-82, San Diego, CA, 1998