II ECCOMAS THEMATIC CONFERENCE ON SMART STRUCTURES AND MATERIALS
C.A. Mota Soares *et al.* (Eds.)
Lisbon, Portugal, July 18-21, 2005

APPLICATION OF PIEZOELECTRICS TO SMART STRUCTURES

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Keywords: Smart Structures, Smart Materials, Piezoelectric

Abstract. *This paper describes piezoelectric materials, actuators and their use in smart structures. The paper provides criteria for the evaluation and selection of piezoelectric materials and actuator configurations. Typical applications using piezoelectrics in smart structures are also presented, with particular emphasis on shape and vibration control.*

1 INTRODUCTION

There is an increasing awareness of the benefits to be derived from the development and exploitation of smart materials and structures in applications ranging from hydrospace to aerospace. With the ability to respond autonomously to changes in their environment, smart systems can offer a simplified approach to the control of various material and system characteristics such as noise, shape and vibration, etc., depending on the smart materials used.

The benefits that can be derived from the use of smart materials and composites are discussed. With the ability to develop high strains and to act with small or suitably modeled hysteresis, these materials offer engineers the opportunity to micomanipulate optical devices, small robots, and other system components[1,2]. Examples of material properties that can be engineered into smart structures are presented based on recent developments in the field.

This paper starts with a discussion of the piezoelectric effect and piezoelectric materials. Focus will be on ceramic materials that offer efficient, reliable, and low-cost sensor and actuator configurations. This will include some materials that have been used for may years, and others that were recently developed[3,4]. Criteria for the selection of a piezoelectric material will be discussed.

Sensor and actuator configurations will play an important role in smart structures. The operating principles of such devices will be discussed and selection criteria based on sensitivity, displacement, force, frequency response and bandwidth will be presented. Trade-off considerations for such devices will also be discussed.

Application of piezoelectrics in smart structures will be reviewed. The paper will identify four broad areas of application involving active control of vibration, shape, noise as well as active health monitoring. Several case studies involving these applications will be presented with a discussion of problems and issues. For example, vibration can cause damage or compromise precision instruments and/or human health, especially for operators of heavy equipment. Stray vibration may cause misreading and reduce sensitivity in navigational gyroscopes; in precision machining devices chatter vibrations present in a machine tool structure can severely reduce machining tolerances and mar surface finishes. Active control techniques using embedded piezoelectric actuators can substantially reduce the vibration amplitude and settling time[5]. Active control of shape can be used in receiver filters in satellites to provided optimum response at all times[6].

2.1 The Piezoelectric Effect

Piezoelectricity is a property exhibited by materials that become electrically charged when subjected to mechanical stress. The converse effect, in which a mechanical deformation is induced by an applied electric field, also occurs. Experimental measurement of the piezoelectric effect was first reported by Pierre and Jacques Curie in 1880[7]. The Curies studied naturally occurring crystals such as quartz, Rochelle salt and tourmaline. They later observed the converse effect[8], which was predicted from thermodynamic principles by Lippmann in 1881[9]. The direct effect may be used in sensing applications, while the indirect effect may be used in actuation and acoustic transduction.

The piezoelectric effect is caused by an asymmetry in the unit cell and the resulting relationship between mechanical distortion and electric dipole separation. The effect may be quantified through the use of suitable piezoelectric coefficients, the measurement of which has been described in various standards on piezoelectricity[10,11]. The piezoelectric charge coefficient is the ratio of the electric charge to the applied force that induced the charge. It is expressed in Coulomb/Newton (C/N) and may be written as

$$\mathrm{d} = \frac{\text{Generated Charge Density (open circuit)}}{\text{Applied Stress}} \tag{1}$$

In the converse effect, the same constant has the alternate expression

$$\mathrm{d} = \frac{\text{Strain Developed (open circuit)}}{\text{Applied Field}} \tag{2}$$

The coupling coefficient is defined by the ratio of the mechanical energy accumulated in response to an electrical input or vice versa. The square of the coupling coefficient is given by

$$\mathrm{k}^2 = \frac{\text{Electrical Energy Stored}}{\text{Mechanical Energy Applied}} \tag{3}$$

Conversely,

$$\mathrm{k}^2 = \frac{\text{Mechanical Energy Stored}}{\text{Electrical Energy Applied}} \tag{4}$$

The d and k constants above are usually represented as matrix quantities d_{ij} and k_{ij}, where the subscript i refers to the direction of the applied or induced electric field and j to the direction of stress or strain. By convention $i,j = 3$ corresponds to the poling direction of the material, and the 1, 2 and 3-directions are mutually orthogonal. The subscripts $j = 4$, 5 and 6 are used for shear stresses about the 1, 2 and 3-axes respectively.

Lettered subscripts, as in d_h and k_p, are used to handle special cases[2]. Here, h is used for hydrostatic stress that is equal in all directions with applied electric field in the 3-direction. The letter p is used for stress or strain that is equal in all directions perpendicular to the 3-axis with applied field in the 3-direction.

Finally, complex components are sometimes used, particularly for materials with high dielectric loss, to represent the lag between electrical or mechanical stimulus and response[12,13]. These imaginary components are often neglected, unless otherwise stated.

2.2 Currently Available Materials

Single crystal materials like α-quartz are still used in applications such as precision frequency control and surface-acoustic-wave (SAW) devices[14,15]. However their use in other applications rapidly declined following the development of polycrystalline ceramics such as barium titanate in the 1940's[16] and lead zirconate titanate (PZT) in the 1950's[17]. Since the 1950s PZT has largely replaced barium titanate because of its larger Curie temperature and higher efficiency. The polycrystalline ceramics are less expensive and easier to machine in a wide range of shapes and sizes than single crystals. In this section we review the properties of lead zirconate titanate, which has become the most commonly used material composition in sonar transducers, actuators and smart structures. Lead titanate (PT) and Lead Magnesium Niobate – Lead Titanate (PMN-PT) compositions are also discussed.

Lead Zirconate Titanate (PZT)

PZT materials are available in a wide variety of compositions that are optimized for different applications. PZT is a mixture of lead zirconate ($PbZrO_3$) and lead titanate ($PbTiO_3$) and has the perovskite structure[16]. Various additives and Ti/Zr ratios may be used to yield material that has one or more desired properties such as high piezoelectric activity, low loss or temperature and time stability. Trade-offs are generally required to obtain the best values of the most important properties at the expense of some degradation of others.

PZT ceramics are often classified as "hard" or "soft", according to the characteristics shown in table 1. Those impurities that cause a hardening effect are acceptors while those that cause softening are donors[18]. Charge imbalances induced by donors or acceptors are made up for by vacancies at Pb or Zr-Ti sites in the case of donors and at oxygen sites in the case of acceptors.

Harder ⇔ PZT ⇔ Softer		
⇓	piezoelectric d constants	⇑
⇓	dielectric constant	⇑
⇓	dielectric loss	⇑
⇓	hysteresis	⇑
⇑	mechanical Q	⇓
⇓	coupling factor	⇑
⇓	resistivity	⇑
⇑	coercive field	⇓
⇓	elastic compliance	⇑
⇑	aging effects	⇓

Table 1: Comparison of hard and soft PZT ceramic properties

The high coercive field of hard PZT is due in part to the presence of an internal bias field. The internal field allows higher externally applied electric field amplitude to be used without depolarization-induced losses. In field-limited devices, such as high-power sonar transducers, this can offset the disadvantage of lower piezoelectric d constants. A new internally biased PZT composition (b-PZT) has recently been developed that has a high internal bias field but with less degradation of the piezoelectric d constants than occurs in other hard PZT compositions[4].

Lead Titanate

Lead titanate compositions have been developed to achieve very high anisotropy in piezoelectric properties. These compositions are most often used in applications where it is necessary to eliminate interference from radial modes. While pure lead titanate has the highest Curie temperature (T_C) known for perovskite feroelectrics (490^oC)[19], the impurity additions used in most commercial high anisotropy compositions lower T_C to values comparable to soft PZT.

Lead Magnesium Niobate – Lead Titanate (PMN-PT)

PMN-PT is a relaxor perovskite that exhibits low hysteresis and high strain near a diffuse ferroelectric to paraelectric transition[3]. In the most commonly used composition, PMN-0.1PT, it is an electrostrictive material that has a square-law dependence between strain and applied electric field.

3 CRITERIA FOR SELECTING PIEZOELECTRIC MATERIALS

In this section we first review the main actuator configurations that may be realized using piezoelectric materials, with emphasis on the force and displacement ranges that can be achieved. This is followed by a discussion of piezoelectric material properties and the material selection criterion for the actuation devices.

It is worth noting that while piezoelectric materials can be used for sensing as well as actuation, it is more common at the present time to use alternative sensing technologies such as strain gages, capacitive sensors or optical sensors in smart structure systems. This is due to mechanical loading, nonlinearity and other considerations that currently favor the latter technologies. However this situation may change in the future by implementing self-sensing techniques in which the sensing signal is extracted from the piezoelectric actuation signal using a suitable nonlinear model[20]. But for the purposes of this paper, we focus on the actuation component of smart structure technology and merely assume that a feedback signal for control purposes will be available by the most appropriate means.

3.1 Actuator Configurations

Piezoelectric actuators may be implemented in a wide range of configurations depending on the force and displacement requirements. In this section we focus first on two actuator types—multi-layer stack actuators and bending-mode actuators—that bracket extreme ends of the force-displacement range that is attainable with single-stroke piezoelectric actuators. We then discuss other actuator types that provide intermediate force and displacement capabilities. Finally, we discuss compound devices that use step-and-repeat or traveling-wave motions to achieve long-range displacement.

For multi-layer stack actuators the zero-load displacement and blocked force at frequencies substantially below resonance may be expressed by the relations[21]
and

$$\Delta L = N d_{33} V \tag{5}$$

$$F = N d_{33} V Y \ \frac{A}{h}, \tag{6}$$

where N is the number of layers in the stack, d_{33} is the piezoelectric charge constant, V is the applied voltage, Y is average Young's modulus of the stack, A is the stack area, and h is the stack height. Maximum displacements are typically in the range of tens of microns, while blocked-force values of thousands of Newtons can be readily achieved.

It can be seen from the above equations that displacement of multi-layer actuators increases with number of layers, while the blocked force is independent of the number of layers because of the N/h dependence (h=N*layer thickness). Increasing the stack area is the primary means to increase the blocked force of a multi-layer stack. When estimating the blocked force using eq. 6, the Young's modulus, Y^{E}_{33}, of the piezoelectric ceramic can be used to provide an upper bound. However when epoxy or other intermediate layers are used in the stack construction, the Young's modulus of these materials may lower the average Young's modulus of the overall stack, resulting in a reduced blocked force. Nevertheless, it is possible to come reasonably close to the theoretical blocked force, appropriate to the ceramic modulus, by using sufficient pre-stress to compress any epoxy layers used in the stack construction.

Bending mode actuators typically consist of two piezoelectric plates that are bonded together, with one plate biased to expand and the other biased to contract. If one end of the plate is fixed in a cantilever configuration and the other is free to deflect, the zero load displacement and blocked force at frequencies well below resonance may be expressed as[21]

$$\delta = \frac{3}{2} d_{31} \frac{L^2}{t} E \tag{7}$$

and

$$F = \frac{3}{8} d_{31} Y \frac{wt^2}{L} E, \tag{8}$$

where δ is the cantilever deflection, d_{31} is the piezoelectric d constant, L is the cantilever length, w is the actuator width, t is the total ceramic thickness and Y is the effective Young's modulus of the structure, approximately equal to $Y^E{}_{11}$ of the ceramic. E is the electric field, which is equal to V/t for series-connected plates and 2V/t for parallel-connected plates.

Bending-mode actuators provide larger displacement, up to the mm range, but have smaller force capability than multi-layer actuators, typically no more than 1 or 2N. Length and width scaling according to equations 7 and 8 can be used to arrive at suitable geometry for given displacement and force requirements.

Bending mode actuators can also be realized by bonding a single piezoelectric plate to a thin metal foil. Rainbow (Reduced and Internally Biased Oxide Wafer) actuators are a variation of this design that have somewhat higher displacement and force capability. In these devices a reduction process forms an integral electrode with internal compressive stress and yields a bowed shape suitable for point loading[22].

Flextensional devices can be used to amplify the displacement of piezoelectric actuators, but typically achieve a strain amplification of no more than five times. This amplification level, however, is usually accompanied by a decrease in load carrying capability by up to 1000 times[21]. Lever systems can provide similar or greater displacement amplification with relatively less degradation of the force capability[21], but both lever and flextensional systems have limited temperature ranges due to thermal mismatch between components.

Tubular actuators are a versatile technology that can provide either linear extension or multi-directional bending motion in a simple compact device. When a piezoelectric tube has uniform metal on the inside and outside surfaces, an applied voltage causes the length to increase or decrease, depending on polarity. Displacements of up to several microns can be achieved[21]. On the other hand, if the contact electrodes are segmented with segment boundaries parallel to the tube axis, it is possible to achieve a bending motion by biasing opposing segments in opposite directions. By using a four-segment tube, two-dimensional x-y bending can be achieved. By further adding an unsegmented section on top of the four-segment portion, full x-y-z control can be obtained. Devices of this type are ideally suited for probe control in scanning tunneling microscopes[23].

High displacement actuators can be achieved by using a step-and-repeat approach in Inchworm® actuators. These devices typically use two clamps and an extender section, which are activated in a properly timed sequence, to achieve long range motion. A fine-positioning mode can also be realized by activating the extender section only while one clamp is on and the other is released. It has recently been shown that by using a complementary design, where one clamp releases with low voltage and the other with high voltage, the fine-positioning mode can be realized with both clamps unpowered. Also in this case, the two clamps can share a common drive signal in the coarse-positioning mode[24,25]. Step-and-repeat motors can achieve high stiffness, with up to 200N restraining force and nanometer resolution[26]. With optimal clamp timing, speeds as high as 50cm/s may be achieved[27].

Ultrasonic motors are another piezoelectric technology that can achieve long-range motion. These devices use an elliptical motion that results from waves that are produced by a piezoelectric actuator attached to a vibrator[28]. The motion is transmitted by friction to the moving part. These motors can be very compact but are not suitable for low-speed positioning.

Fig. 1 shows the force versus displacement characteristics of various piezoelectric actuators. Single-stroke actuators are limited to no more about a millimeter displacement and the force becomes small near the higher end of the displacement range. Nevertheless, the force-displacement range for single-stroke devices is useful for many smart structure applications such as those described in section 4. The linear-motor portion of the figure includes the inchworm and ultrasonic-type motors discussed above.

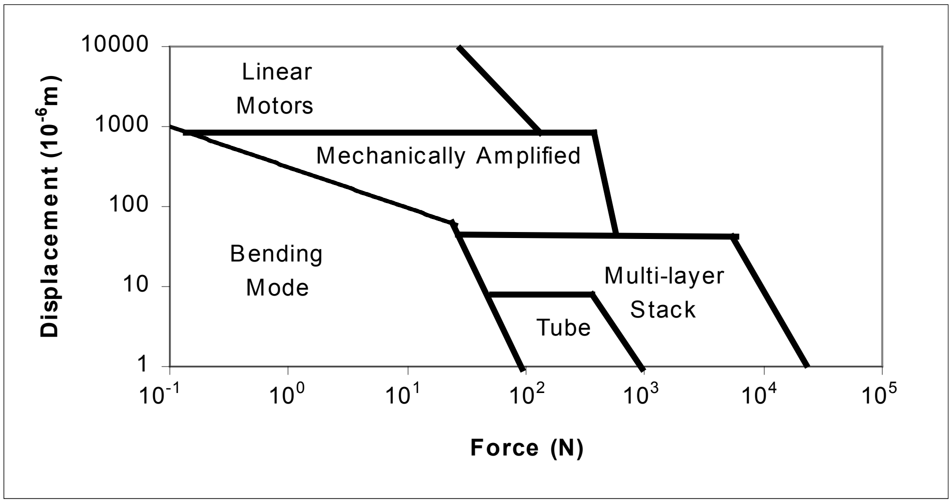

Figure 1: Force and displacement ranges for piezoelectric actuators

3.2 Material Selection

Table 2 summarizes key properties of selected piezoelectric ceramics. For low-frequency operation, equations 5-8 suggest that ceramics having large piezoelectric d constants, such as Navy Type VI, are preferred for actuator applications in smart structures. However, when temperature stability is also required, Navy Type II, with its larger Curie temperature, is a better choice.

Electrostrictive PMN-0.1PT may also be considered for low-frequency applications. Properties of this material are not shown in Table 2, because the quadratic strain versus field characteristic of electrostrictive materials makes it possible to define only differential properties at specified fields. The apparent d_{33} obtained by differentiating the strain versus field curve is small at low fields but reaches a peak as high as 1800pC/N at a field of

0.4MV/m[3]. However, this material is also temperature-sensitive, even more so than Navy Type VI.

For higher frequencies, the higher dielectric constant of softer PZT ceramics may pose difficulties for current-limited power supplies. This is also true for PMN-0.1PT, which has a temperature-dependent relative dielectric constant that can exceed 30,000[3]. Harder PZT ceramics can be driven with higher frequency and electric field amplitude, both from the point of view of power supply limitations and from the point of view of dielectric loss tangent and internal heating[4].

The smaller dielectric loss tangent of hard PZT ceramics is connected with smaller hysteresis in the polarization vs. field loops. This is in turn is reflected in smaller hysteresis in strain versus field loops which is beneficial for high positioning accuracy, under both open-loop and closed-loop control[29]. However, hysteresis modeling can be integrated into a closed-loop controller to achieve high positioning accuracy even with soft PZT ceramics[30].

		LT	b-PZT	Navy Type I	Navy Type II	Navy Type III	Navy Type V	Navy Type VI
		Lead Titanate	"hard" biased PZT	"hard" PZT	"soft" PZT	"hard" PZT	"soft" PZT	"soft" PZT
K^T_{33}	---	200	1080	1350	1750	100	2750	3250
Tan δ	%	2.0	0.3	0.4	1.6	0.3	2.0	2.0
Q_M	---	800	1000	500	80	1000	70	70
k_{31}	---	0.03	0.31	0.35	0.37	0.3	0.37	0.39
k_{33}	---	0.51	0.64	0.7	0.72	0.64	0.72	0.75
d_{31}	10^{-12}C/N	-3.0	-100	-125	-175	-60	-215	-270
d_{33}	10^{-12}C/N	70	250	300	365	225	500	590
Y^E_{11}	10^{10}N/m^2	14	9.3	8.0	6.5	9.1	6.9	7.1
Y^E_{33}	10^{10}N/m^2	11	6.5	6.7	5.3	7.4	5.1	5.0
T_C	^{o}C	225	320	350	360	325	225	210

Table 2: Comparison of key properties of piezoelectric ceramics[31]

4 APPLICATIONS TO SMART STRUCTURES

4.1 Active Vibration Control

Smart structures that use discrete piezoelectric patches to control the vibration of thin plates have been of considerable interest in recent years. The development of finite element codes, such as ANSYS^{TM}, makes it possible to fully model coupled thermo-mechanical-electrical systems of one or more dimensions and obtain reciprocal relations between piezoelectric actuator voltages and system response. By integrating such models into a closed-loop control system, very effective active vibration suppression can be achieved. Active vibration control strategies such as H_∞ have been applied to one-dimensional beams[32] as well as two-dimensional plates[33] and a fin that emulates an aircraft tail[32,5]. These studies used multiple Navy Type II piezoelectric patches of area

25mmx25mm and thickness 0.5mm, bonded to the aluminum structure whose vibration is to be controlled. In the case of the two-dimensional fin, shown in Fig. 2, it was found that a single sensor as control input was inadequate and it is believed that a multi-input multi-output system model is needed to suppress multiple vibrational modes[5].

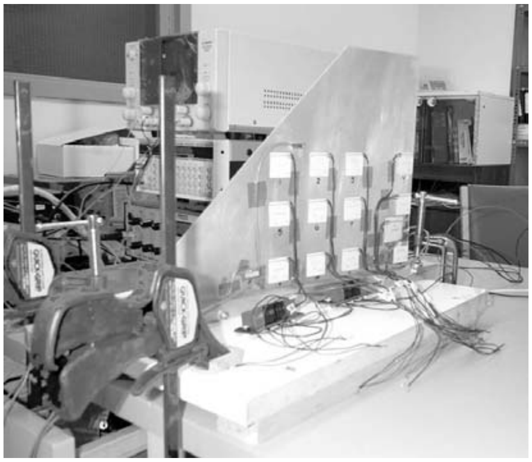

Figure 2: Smart fin with attached piezoelectric patch actuators.

4.2 Active Noise Control

The sources for noise are numerous. For example, noise can radiated from engines, exhaust systems, fans, and blowers. Active noise control (ANC) was developed as a way to reduce if not eliminate some of these different types of noise. Noise is usually defined as a sound due to irregular vibration or any sound that causes discomfort. The importance of active noise control in the workplace is becoming increasingly important primarily due to hearing loss resulting from long term exposure to workplace noise[34].

Active control of sound is very similar in nature to ANC and is often described in the same terms. ANC works on the basic principle of destructive interference, where the undesirable sound wave is countered with a sound wave of equal amplitude, but 180 degrees out of phase. The result is that the sound waves cancel each other, and the undesirable sound is reduced or eliminated. This principle is implemented in smart structures, including noise cancellation headsets, transformer quieting systems, and interior noise reduction in automobiles and aircraft[35,36].

Such a smart system will consist of a sensor(s), electronics and a projector or transmitter of sound. This system may be configured differently depending on the acoustic objectives of the system. Control system strategies applied to active noise or sound control are similar to those employed in active vibration control. The control strategy involves the noise source being measured in the primary sound field and electronically conditioned before creating and passing the conditioned signal through a transmitter. In this system no prior knowledge of the noise is necessary.

Piezoelectrics are used extensively to monitor the noise associated with panel vibrations such as those present in transformers. In underwater acoustics, piezoelectrics generally far outperform other types of sensors and actuators for the generation and reception of sound. It is generally very difficult to produce broadband sound sources for underwater due to difficulties associated with the design and manufacture of acoustic transducers. Active control of sound principles can be used to create such a source. The Broadband Acoustic Transmission System[37] uses such technology. A hydrophone is generally used as a sensor for these applications. It is relatively simple to build a broadband hydrophone with standard piezoelectric ceramic materials. However, broadband high-power acoustic projectors are difficult to build. Fig. 3 shows the response characteristics of such a transducer (SX01 from Sensor Technology) and also shows the radiating characteristics of the same transducer after conditioning the signal. Such broadband systems have a number of applications including the study of marine mammals, sonar communication, underwater pagers, diver recall systems and seismic surveys.

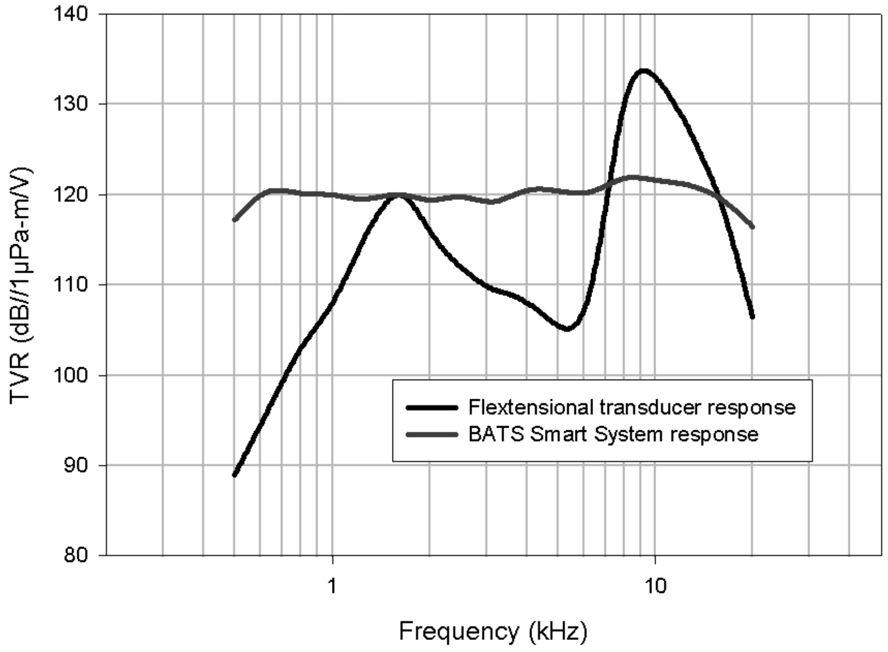

Figure 3: Response characteristics of the BATS smart system

4.3 Active Shape Control

Active shape control is of substantial interest for reflectors and antennas that must maintain precise dimensions for optimal performance. This is of particular importance for structures in space that are made of lightweight materials and are exposed to thermal distortion. Instruments such as millimeter-wave and sub-millimeter-wave passive instruments and those operating up to the infrared spectrum for space radio astronomy need to maintain micrometer accuracy, with overall dimensions of up to a few meters[38]. Yet thermal distortions of space structures of this size—even those using low co-efficient of thermal expansion materials such as carbon fiber reinforced plastic—can result in RMS surface errors on the order of 0.8mm[39]. For these applications, smart structures involving attached piezoelectric actuators have been proposed[38].

Active shape control has also been proposed for use in RF filters for communications satellites. A typical filter design uses cascaded resonators that have adjustable posts for frequency tuning. The posts are adjusted prior to launch but exhibit thermal expansion in space, resulting in frequency shifts. By integrating piezoelectric stack actuators into the posts and applying active control, a three-times reduction in frequency shifting with temperature has been reported[6].

4.4 Active Health Monitoring

Civil, industrial and aerospace structures can benefit from the smart structure approach as the basis for active health monitoring. Structural panels embedded with a series of sensors and actuators can be used in civil, industrial and aerospace structures. These panels can actively monitor the structural integrity and detect faults at early stages, thereby providing precise information on structural failure and life expectancy. This will be very useful for the aerospace sector[40] where in the absence of active health monitoring, expensive aircraft or their systems are prematurely taken out of service or allowed to operate when 'unsafe', which could result in loss of life in addition to the aircraft. If the health of these structures is known with good reliability, considerable cost savings could be realized by extending the useful life of these aircraft or their systems. Other promising applications of health monitoring are in heavy machinery (such as turbines) applications, early and accurate detection of earthquakes in seismic regions , and a smart bridges with the ability to monitor and readjust its structure to decrease stress levels in the bridge[41].

Acoustic emissions from dislocation movements, phase transformations, friction mechanisms, and crack formation and extension was proposed as a method of monitoring the health of structures for several decades. Piezoelectrics are by far the most widely used device materials for the monitoring of such acoustic emissions. However, since these emissions are usually surface waves, special measuring techniques need to be applied. Once a surface wave has been detected, the structure can process that information in order to take an appropriate action, which may involve grounding an aircraft, suggesting maintenance, or the activation of mechanical stress relief in the specific part of the structure[40].

Sun et al.[42] used piezoelectric sensor/actuator patches on a truss structure to monitor the integrity of the truss. The technique used the impedance-signature technique to assess the structural integrity of the truss, as any damage to the structure would effect the mechanical impedance of the structure. Piezoelectric ceramics have also been bonded to the outside of structures to monitor delaminations[43,44] and damage[45] in composites. In both cases, piezoelectrics monitor the natural vibration frequencies of the composite. If the composite begins to delaminate, its vibrational frequency will be effected and the piezoelectric sensor will be able to detect those changes. By exciting and monitoring the frequency response of the composite and being able to monitor the structure's integrity, more cost effective maintenance could be completed before the structural element failed during operation.

In acoustic emission techniques, it is important that the area of contact with the structure is small and the sensor itself should have a broadband response. Fig. 4 shows such a sensor manufactured by SensorTech and its frequency response transfer function characteristic.

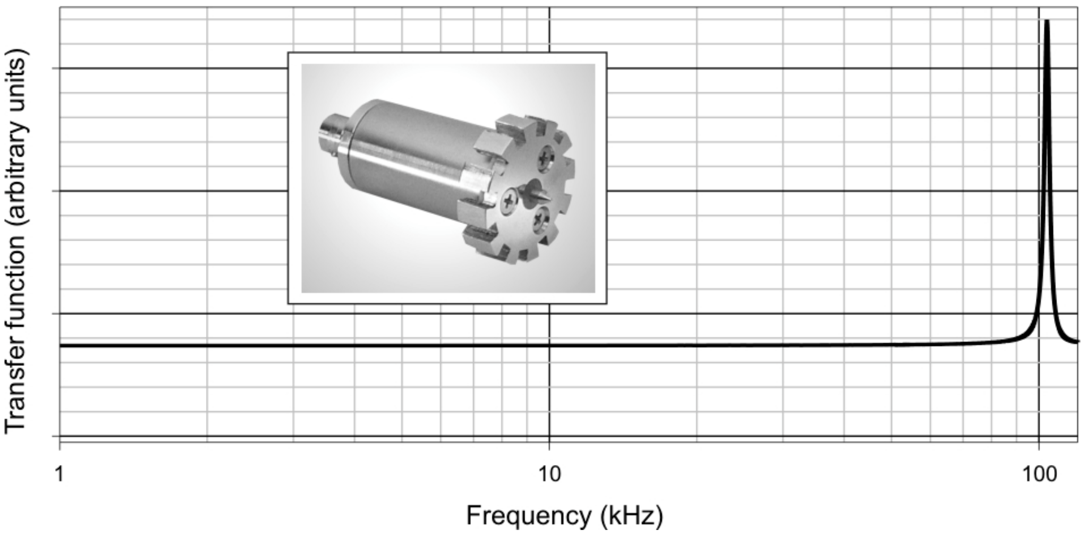

Figure 4: Acoustic sensor response transfer function

5 REFERENCES

[1] S.E. Prasad, D.F. Waechter, R.G. Blacow, *"Application of Piezoelectrics to Smart Structures*", NATO-RTA Workshop on Smart Structures, Middle East technical Univerity, Ankara, Turkey, March 2002. A series of four lectures.

[2] D.F. Jones, S. E. Prasad and J.B. Wallace, "Piezoelectric Materials and Their Applications*",* In *Advanced Ceramic Materials: Applications of Advanced Materials in a High Technology Society I,* Trans Tech Publications, Switzerland, 71-144 (1996).

[3] D.F. Waechter, D. Liufu, M. Camirand, R. Blacow and S.E. Prasad, "Development of high-strain low-hysteresis actuators using electrostrictive lead magnesium niobate (PMN)", *Proc. 3rd CanSmart Workshop on Smart Materials and Structures*", Montreal, 31-36 (2000).

[4] D.F. Waechter, S.E. Prasad and R. Blacow, "Biased PZT materials for acoustic transducers, sensors & Systems*", ICONS-2002*, Cochin, India, 665-672 (2002).

[5] Y. Yaman, F.D. Ulker, V. Nalbantoglu, T. Caliskan, E. Prasad, D. Waechter and B. Yan, "Application of μ-synthesis active vibration control technique to a smart fin", *Proc. 6th CanSmart Meeting, International Workshop on Smart Materials & Structures*, Montreal, Canada, 109-118 (2003).

[6] E. Charbonneau, S. Caron, D. Waechter, and E. Prasad, "Active stabilization of bandpass filter with multilayer piezoelectric actuators*", 2nd Canada-US CanSmart Workshop on Smart Materials and Structures*, Montreal, 83-93 (2002).

[7] J. Curie and P. Curie, "Développement par compression de l'électricité polaire dans les cristaux hémièdres à faces inclinées," *Bulletin de la Société Minéralogique de France,* **3**, 90-93 (1880); also in *Compt. Rend.* **91**, 294-295 & 383-386 (1880).

[8] J. Curie and P. Curie, "Contractions et dilations produites par des tensions électriques dans les cristaux hémièdres à faces inclinées," *Compt. Rend.* **93**, 1137-1140 (1881); also *in Oeuvres de Pierre Curie*, Gauthier-Villars, Paris (1908)

[9] G. Lippmann, "Sur le principe de la conservation de l'électricité", *Compt. Rend.* **92**, 1049-1051 & 1149-1152 (1881).; also in *Journal de Physique* **10**, 381-394 (1881); and *Ann. Chim. et Phys.* **24**, 145-178 (1881).

[10] "IEEE Standard on Piezoelectricity", IEEE Standard #176-1978. Institute of Electrical and Electronics Engineers Inc., 345 East 47th St., New York, NY 10017.

[11] "Measurements of Piezoelectric Ceramics", *IRE Standards on Piezoelectric Ceramics; 1961, Proc. IRE,* 1161-1169 (1961).

[12] A. Alemany, L. Pardo, B. Jimenez, F. Carmona, J. Mendiola and A.M. Gonzalez, "Automatic iterative evaluation of complex material constants in piezoelectric ceramics" *J. Phys. D; Appl. Phys*. **27**, 148-155 (1994).

[13] S. Sherrit, H.D. Wiederick and B.K. Mukherjee, "Non iterative evaluation of the real and imaginary material constants of piezoelectric resonators" *Ferroelectrics*, **134**, 111-119 (1992).

[14] L.E. Halliburton, J.J. Martin, and D.R. Koehler, "Properties of piezoelectric materials", in *Precision Frequency Control: Volume 1, Acoustic Resonators and Filters*, edited by E.A.

Gerber and A. Ballato, Academic, Orlando, FL, 1-45 (1985).

[15] S.A. Fedulov, Z.I. Shapiro, and P.B. Ladyzhinskii, "The growth of crystals of $LiNbO_3$, $LiTaO_3$ and $NaNbO_3$ by the Czochralski method," *Sov. Phys. Crystallogr.* **10**, 218-220 (1965).

[16] B. Jaffe, W.R. Cook, and H. Jaffe, *Piezoelectric Ceramics*, Academic Press, London, (1971).

[17] B. Jaffe, R.S. Roth, and S. Marzullo, "Piezoelectric properties of lead zirconate-lead titanate solid-solution ceramic ware," *J. Appl. Phys.* **25**, 809-810 (1954).

[18] Q.M. Zhang and J. Zhao, "Electromechanical properties of lead zirconate titanate piezoceramics under the influence of mechanical stress", *IEEE Trans. UFFC,* **46**,1518(1999).

[19] F. Jona and G. Shirane, *Ferroelectric Crystals*, Diver Publications Inc. New York (1993).

[20] H.M. Saoulli and R. Ben Mrad, "Modeling of piezoceramic actuators for smart applications", in Preprints *2nd IFAC Conf. Mechatronic Systems*, Berkley, CA, 169-174 (2002).

[21] C.D. Near, "Piezoelectric actuator technology", *Proc. SPIE Smart Structures and Integrated Systems*, **2717**, 246-258 (1996).

[22] G.H. Haertling, "Ultra-high-displacement actuator", A. Cer. Soc. Bull. **73**, 93-96 (1994).

[23] G. Binnig, and D. P. E. Smith, "Single-tube three-dimensional scanner for scanning tunneling microscopy," Rev. Sci. Instrum. v57, pp. 1688-1689, (1986).

[24] D.F. Waechter, S. E. Prasad, R.G. Blacow, B. Yan, S. Salisbury and R. Ben Mrad "Complementary inchworm® actuator for high-force high-precision applications", Proc. SPIE Smart Structures and Materials Conf., 5390 San Diego, Ca, March 14-19 (2004) pp.13-23.

[25] S.P. Salisbury, D.F. Waechter, R. Ben Mrad, S.E. Prasad, R.G. Blacow and B. Yan, "Design considerations for complementary inchworm® actuators", to be published, *IEEE/ASME Transactions on Mechatronics*.

[26] B. Zhang and Z. Zhu, "Developing a linear piezomotor with nanometer resolution and high stiffness", *IEEE/ASME Trans. Mechatron.* **2**, 22-29 (1997).

[27] R. Ben Mrad, A. Abhari and J. Zu, "A control methodology for an inchworm piezomotor", *J. of Mechanical Systems and Signal Processing*, **17**, 457-471 (2003).

[28] K. Uchino, *Piezoelectric actuators and ultrasonic motors*, Kluwer Academic Publishers (1997).

[29] R. Ben Mrad and H. Hu, "A model for voltage-to-displacement dynamics in piezoceramic actuators subject to dynamic-voltage excitations", *IEEE/ASME Trans. Mechatronics,* **7**, 479-489 (2002).

[30] B. Yan, D. Waechter, R. Blacow, S. E. Prasad, H. Hu, N. Somayajula and R. Ben Mrad "A configurable control system for smart structure research", *2nd Canada-US CanSmart Workshop on Smart Materials and Structures*, 285 (2002).

[31] See material property dats sheets @ www.sensortech.ca.

[32] Y. Yaman, F.D. Ulker, V. Nalbantoglu, T. Caliskan, E. Prasad, D. Waechter and B. Yan,

"Application of H∞ active vibration control strategy in smart beam structures", Third Int. Conf. Advanced Engineering Design (AED 2003) 1-4 June, 2003, Prague, Czech Republic.
[33]Y. Yaman, T. Caliskan, V. Nalbantoglu, E. Prasad and D. Waechter, "Active vibration control of a smart plate", *ICAS2002*, Toronto, Canada (2002).
[34] J.R. Gyorki, "Putting a Lid on Factory Noise", Machine Design 106-112 March (1994).
[35] S.J. Elliot and P.A. Nelson, "Active Noise Control", IEEE Signal Processing Magazine 12-35 Oct. (1993).
[36] H.F. Olson and E.G. May, "Electronic Sound Absorber", Journal of the Acoustical Society of America 25(6) 1130-1136 (1953).
[37] See Broadband Acoustic transmission System, Sensor Technology Limited, www.sensortech.ca.
[38] A.G. Roederer, N.E. Jensen and G.A.E. Crone, "Some european satellite-antenna developments and trends", *IEEE Antennas and Propagation Magazine*, 38, No. 2, 20 (1996).
[39] A. Meguro, A. Tsujihata, N. Hamamoto and M. Homma, "Technology Status of the 13m aperture deployment antenna reflectors for engineering test satellite VIII", *Acta Astronautics*, **47**, 147-152 (2000).
[40] C. Boller, "Monitoring the integrity of Aircraft Structures - Current Procedures and smart sensing Options". Proceedings of International Conference on Smart materials and Systems, p31, Bangalore, 1999.
[41] C. Abdunur, "Stress Monitoring and Re-Adjustment in Concrete Structures", 1st European Conf. on Smart Structures and Materials (Glasgow) 263-266 (1992).
[42] F.P. Sun, Z. Chaudhry, C. Liang and C.A. Rogers, "Truss Structure Integrity Identification Using PZT Sensor-Actuator", Journal of Intelligent Material Systems and Structures 6 134-139 (1995).
[43] C.H. Keilers, Jr. and F.-K. Chang, "Identifying Delaminatin in Composite Beams Using Built-In Piezoelectrics: Part I - Experiments and Analysis", Journal of Intelligent Material Systems and Structures 6 649-663 (1995).
[44] C.H. Keilers, Jr. and F.-K. Chang, "Identifying Delamination in Composite Beams Using Built-In Piezoelectrics: Part II - An Identification Method", Journal of Intelligent Material Systems and Structures 6 664-672 (1995).
[45] Y.-S. Roh and F.-K. Chang, "Effect of Impact Damage on Lamb Wave Propagation in Laminated Composites", Dynamic Response and Behaviour of Composites, AD-Vol. 46, 127-138 (1995).

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