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Ceramic Sensors and Actuators for Smart Structures

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Abstract

The role of ceramic sensors and actuators in smart structures is presented. The benefits derived from the use of newer piezoelectric and electrostrictive materials and composites is discussed. With the ability to develop high strains and to act with little hysteresis, these materials offer systems engineers the opportunity to micro-manipulate optical devices such as mirrors, phase, shifters etc., within fractions of a wavelength, thereby directly linking electronics and photonics. The most well-known example of such applications was the recent repair to the Hubble telescope. Examples of the material properties that can be engineered into smart structures are presented based on recent developments in the field.

Introduction

Although the field of “smart materials” and “smart systems” is of increasing importance to many sectors of society, there is still no internationally acceptable definition of what is meant by the term “smart” when used in this context. As a result the field is evolving somewhat differently in different parts of the world. For example, Japanese scientists have a rather anthropomorphic viewpoint with regards to smart/intelligent materials. Their goal is to design intelligent materials that have human-like intelligence or characteristics. They define intelligent materials as those which respond to environmental changes at the most optimum condition and manifest their own functions depending on the changes. A detailed description of this concept can be found in the report entitled "The Concept of Intelligent Materials and Guidelines on R&D promotion", published by the Science and Technology Agency, Japan [1]. As a result, Dr. Takagi [2] has classified intelligent materials into three categories:

i) **Intelligence at the most primitive levels in materials:** such materials have primitive functions such as a sensor function, an actuator function and a processor function including a memory function. These functions arise from their inherent properties that result from their electronic and atomic structure.

ii) **Intelligence inherent in materials:** This category includes materials into which intelligence is built through a process of systematization and accumulation, a process that incorporates both hardware and software systems into materials. These materials/systems possess characteristics such as self-diagnosis, self-repair, self-degradation, self-learning, ability to recognize or discriminate etc. Time responsiveness is the most basic intelligence in this category.

iii) **Intelligence from the human view point:** Materials in this category will have characteristics such as human friendliness, environment friendliness, reliability, analytical judgement, rationality and all-round harmony.

On the other hand, Professor Newnham of the Pennsylvania State University defines "Smart Materials" as materials that have both sensing and actuating abilities [3]. He further categorizes them as being:

i) **Passively smart**,
ii) **Actively smart** or
iii) **Very smart materials**.

Passively smart materials respond to a stimulus in a useful manner without assistance. An example is a ZnO-based varistor which displays dramatic changes in electrical conductivity above a threshold high voltage. They are exploited widely to protect electrical systems from voltage “spikes” which occur when an inductive load or lightening is coupled to a power line. Placed between a high voltage line and ground, a varistor normally exhibits a very high resistance and so draws essentially no current. However, during brief periods of overload, it has the ability to switch to a highly conductive state in milliseconds thereby shorting a voltage pulse to ground. Once the voltage drops below a characteristic value, the varistor “switches off” by reverting to its high resistance state. In this way, damage is avoided to computers and power-line transformers etc.

Actively smart materials posses a feedback loop which allows them to both recognize the change and initiate an appropriate response through an actuator circuit. Examples of the actively smart materials include vibration-damping systems for outer-space platforms and electrically controlled automobile suspension systems using piezoelectric ceramic sensors and actuators. These systems are described in a later section.

By including a learning function into smart materials, the degree of smartness is enhanced to a high level of intelligence. A very smart material senses a change in the environment and responds by changing one or more of its property coefficients. Such a system can "tune" its sensor and actuator functions along with memory and feedback systems to optimize future behaviour. These systems exploit the non-linear properties of intelligent materials to acquire a tunable capability. Electrostrictive ceramics fall into this category. These materials display a non-linear relationship between strain and electric field that can be used to tune the strain response for a given electric field.

From the above it can be appreciated that no single definition exists to describe intelligent or smart materials. However, it is apparent that the term intelligent or smart materials has been used to describe materials that have intrinsic or extrinsic capabilities to respond in a useful manner to external stimuli such as light, temperature, pressure or environment, i.e., they have the ability to change properties, such as size, shape, colour, structure, composition etc., in response to a change in their environment or operating conditions. Using sophisticated hardware (control devices e.g., actuators) and software these materials can be incorporated into a smart/intelligent system, that possesses a higher level of intelligence such as self-diagnosis, self-repair, learning ability, ability to discriminate shapes and forms, ability to judge etc. A block diagram illustrating a conceptual design of a smart system is shown in Fig. 1. The basic components of a smart system may include embedded sensor(s), an information processing (software) system for data analysis, logic and decision making and system hardware (e.g., multiplexers, actuators etc) interfaced to a computer for control, actuation and feedback .

Figure 2 shows a block diagram of a simple yet smart/intelligent system commissioned in our laboratories for automated electrical data acquisition at controlled temperatures. Although the system does not have sensors and actuators that are embedded in the test sample and thus is classified as a low level intelligence system, it clearly demonstrates the basic operating principles of a smart/intelligent system. The system is routinely used to measure dielectric and piezoelectric properties of ceramics and composite materials under development. With the advent of fast, low-cost desktop computers with a large memory and the widespread adoption of the IEEE-488 standard for the general purpose interface bus (GPIB) in virtually all current scientific equipment, it is possible to assemble highly sophisticated data acquisition and control systems that perform these measurements quickly and unattended [4].

The heart of the system is a PC interfaced to an HP3497A data acquisition and control system and an HP4192 impedance analyser via an IEEE-488 bus. The sample is electrically connected to the analyser and placed in a furnace for temperature-controlled impedance data measurement. The sample temperature is monitored by a thermocouple (a passively smart system that produces a voltage as a function of temperature) placed adjacent to the sample. A second thermocouple is used to control the furnace via a temperature controller equipped with a power package. The power to the furnace is computer controlled via the data acquisition and control system.

To characterize a sample, the temperature range over which electrical data is to be acquired is first entered by the operator. The computer then instructs the control system to apply appropriate power to the furnace (actuator function) while the sample temperature is continuously monitored (sensor function). When the temperature reaches the first set-point (logic and decision making function), the computer instructs the controller to regulate the power to the furnace to keep the temperature at this set-point (control function). After the temperature has been constant for a specified period, the computer then triggers (actuation function) the impedance analyser to record the electrical data over a specified frequency range. The data are then printed out in both tabular and graphical form and also stored on disc. The computer then instructs the controller to adjust the power to the furnace for the next set-point temperature. This cycle is repeated until the electrical data are recorded at all temperatures. Software routines are also included to turn the power off in case of a malfunction (e.g., thermocouple breakage) and at the completion of the experiments. The system, in fact, has intelligence built-in, as it performs sophisticated functions such as a sensing, actuating, feedback and controlling, information processing, logic/decision making, etc. rendering the system fully self-controlling.

A number of smart systems similar in function but much more complex are used today in the modern automobile. Driven by an on-board computer taking data up to 30 times a second from a variety of embedded sensors monitoring, e.g., the manifold air pressure, throttle position, coolant temperature, exhaust-gas oxygen concentration, engine-block knock etc., the system strives to provide an optimum performance by matching the operating environment (engine load, wheel traction, outside temperature, etc.) with responses dictated by a look-up table held in memory.

Smart Materials and Systems

In this section, the basic properties of some selected intelligent/smart materials and their potential applications in intelligent systems will be discussed. The aim is to relate the above basic concepts to the material characteristics and illustrate their potential as smart materials/systems. Typically a smart system/structure consists of a host structural material having a network of embedded sensors/actuators interfaced to a micro-processor based data acquisition/manipulation and control unit. Some of the most promising smart materials known today include, piezoelectrics, electrostrictors, shape memory alloys, electro-rheological fluids, fibre optics, conducting polymers, composites, bio-materials etc.

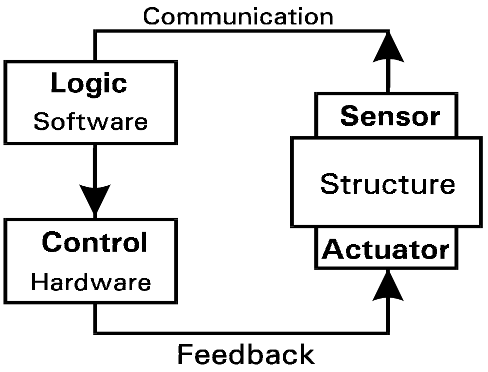

Figure 2 *- The elements of a smart system*

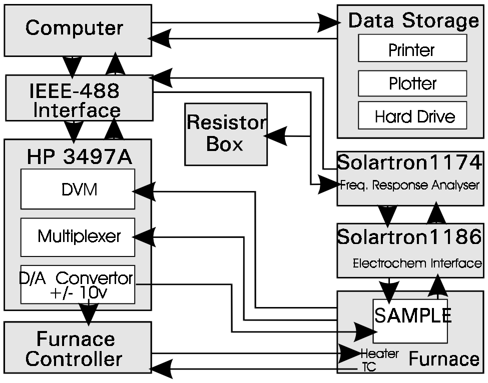

Figure 1*: Schematic of electrical-electrochemical data acquisition system*

The smart system used in the modern automobile has been referred to above. However, the materials that comprise the sensors are themselves smart in that they can respond to their environment with a change in their properties which can be used to generate or modify a voltage signal used by the central computer. For example, the exhaust gas sensor is based on either a doped ZrO_2 (GM, Chrysler, Volvo etc.) acting as a solid electrolyte or on a doped TiO_2 acting as a semiconductor (Ford). Both these materials show electrical changes when subjected to an atmosphere of varying oxygen content. In the case of TiO_2, the conductivity changes sharply whereas ZrO_2, which is used as the solid electrolyte in an oxygen concentration cell operating with air in one half-cell (pO_2 ~0.21 atm) and exhaust gas (pO_2 ~ 10^{-6} atm) in the other, gives a linear voltage output with the logarithm of the oxygen gradient that follows the Nernst equation in the same manner as a pH electrode and other specific-ion electrodes. Because the oxygen content of the exhaust changes dramatically with minor changes in the air:fuel ratio, the voltage output also changes significantly, Fig. 3. By having the computer rapidly cycle the air:fuel ratio from rich to lean and back again, switching direction as the sensor output exceeds a pre-set operating window of ~0.3-0.8 volts, the ratio is held exactly on the 14.7:1 required of a gas engine for the successful operation of the catalytic convertor and good fuel economy [5]. In this case, the air:fuel management system is actively smart and the ZrO_2 sensor is passively smart. However, when appropriately doped, ZrO_2 itself is also a very smart material in its own right.

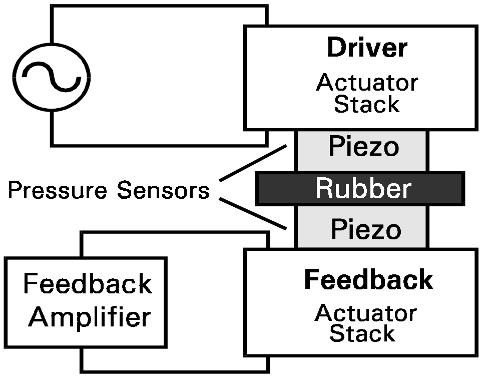

***Figure 4**: Schematic of an active vibration damping system.*

Zirconia can exist in four crystallographic forms (tetragonal, monoclinic, cubic and orthorhombic) depending on the temperature and the concentration of aliovalent dopants such as CaO, MgO and Y_2O_3 and, as a result, it has a number of other interesting properties in addition to being an excellent oxygen ion conductor above about 500°C. For example, by controlled doping it is possible to generate the tetragonal/monoclinic form as a precipitate in a cubic matrix. In this state, the partially stabilized material exhibits excellent mechanical wear properties: any propagating crack is impeded by the inversion of the tetragonal phase to the monoclinic form with a corresponding removal of energy from the crack tip, i.e., the material is very smart from a mechanical point of view - under stress, it undergoes a phase change that dramatically improves its resistant to wear and impact. Unfortunately, the process is not reversible: removal of the stress does not reform the original microstructure. In this manner, its behaviour is analogous to that of a shape memory material.

Other smart ceramic materials exploited by the automotive industry include the doped $BaTiO_3$ positive temperature coefficient of resistance materials used as self regulating air-intake heaters - if the air flow is restricted temporarily, the temperature does not rise uncontrollably. Instead, the resistance of the ceramic heater rises rapidly with a minor temperature increase to restrict the current and thereby essentially eliminate any minor temperature excursion. However, much more dramatic and of relevance to their use in smart structures is the increasing use of smart piezoelectric and electrostrictive materials.

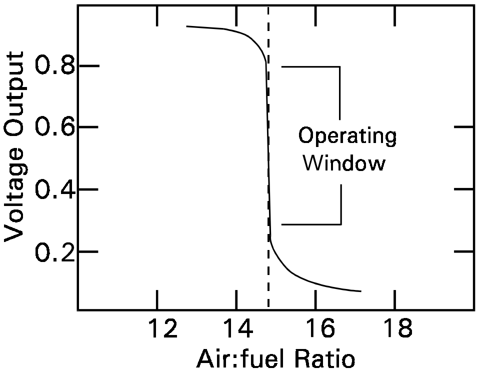

***Figure 3**: Characteristics of ZrO_2 sensor*

From the mid 1980's to the present, the onset of pre-ignition in an engine has been detected by a piezoelectric washer of lead zirconate titanate (PZT) bolted to the engine block and responding to 10kHz frequency. If pre-ignition is detected, the computer retards the timing until the condition is corrected. One of the features of PZT and related piezoelectrics that renders them smart is that they can act as both sensors and actuators constantly responding to their changing environment. For example, the piezoelectrics can not only detect motion and generate a voltage but they can also move in response to an impressed voltage. This capability has been exploited for many years in underwater, medical and non-destructive testing transducers which can emit a short tone burst to interrogate a body and then become quiescent while listening for any echo.

The combination of sensing and actuating functions in the same material are attractive in a number of applications. For example, it is possible to sense a change in the environment and to nullify or minimize that change. This has been shown by Newnham et al. [6] in their demonstration of a controlled compliance or vibration damping system based on PZT piezoelectric stack actuators and sensors arranged as shown in Fig. 4. in which a thin rubber sheet separates the two stacks. The driver actuator is triggered using an ac voltage. The pressure waves so generated (monitored through the upper sensor) impinge upon the lower sensor. This signal is amplified using a low noise amplifier and fed back through a phase shifter to the lower actuator to control the compliance. When the phase of the feedback voltage is adjusted to cause the responder to contract rather than expand in length the material mimics a very soft compliant substance. This reduces the force on the sensors and partially eliminates the reflected signal. The reduction in output signal of the upper signal is a measure of the effectiveness of the feedback system. Alternatively the system can be made to mimic a very stiff solid.

This concept has already been exploited in the automotive industry by both Toyota and Cadillac in their active suspension systems, Fig. 5. First introduced by Toyota in 1991 as their piezoTEMS (Toyota Electronic Modulated suspension), these systems have been developed to improve the driveability and stability of the automobile and enhance passenger comfort [7]. The system uses a closed loop of piezoelectric ceramic sensors and actuators to continually monitor the suspension vibration arising from road roughness. The sensor produces a voltage which is amplified, altered in phase, and applied to the 88-element piezoelectric actuator. The actuator produces ≈50μm displacement which is hydraulically amplified to 2mm and which is sufficient to adjust the damping force in the shock absorber system from firm to soft within ≈20 milliseconds.

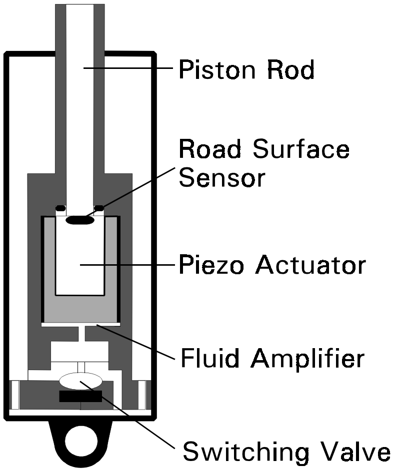

Figure 5: Schematic of active vibration damping shock absorber based on piezoelectric sensors and actuators.

One of the variations in developing a micropositioning system is based on the construction of a so-called piezoelectric bimorph in which two thin wafers of ceramic of opposite polarity are bonded together and driven with a dc signal in such a way that as one side expands, the other contracts resulting in the beam bending, Fig. 6A. When this configuration is modified as in Fig. 6B, then the bending can be more complex as shown [3]. This geometry is now used in video tape equipment for the precise positioning of the recording head. Because the head position during read-back of the tape is dictated by a feedback loop that monitors the signal from the tape, the head can be micro-positioned to ensure that a maximum signal:noise ratio is achieved. A variation of this assembly has been available for some time in which an ac signal forces the beam to `wag' thereby acting as an effective compact cooling fan for instrumentation.

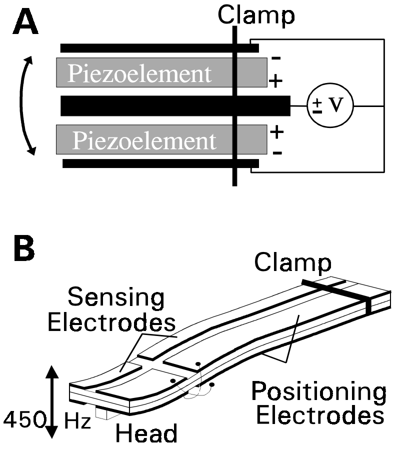

Figure 6 - Schematic of a ceramic bimorph assembly used for micropositioning.

In the United States, NASA space missions have been the major motivator of the design and development of intelligent/smart systems. The space based systems requiring large (20-100 metres) precision structures such as reflectors , antennas, interferometers, etc., pose serious vibration problems due to the absence of gravity in space. For stable operations these structures require accuracy in micron to submicron dimensions. The Jet Propulsion Laboratory at the California Institute of Technology, has developed [8] precision composite truss structures that can be actively damped using piezoelectric sensor/actuator systems attached or embedded in structural members. Severe vibrations in a horizontal truss have been shown to disappear within three oscillations by activating the smart systems.

Piezoelectric sensor/actuator systems have also been used for precise shape control over a range of +70 to -130 µm with a resolution of a few µm. Professor Inderjit Chopra at the University of Maryland has recently demonstrated [9] that directionally attached piezoelectric (DAP) sensors and actuators embedded in helicopter blade structures can be used to effectively combat vibrations. Here the vibrational forces detected by the piezo sensors are turned into aerodynamic advantage by the actuators. The technique, called aeroelastic optimization, seeks to suppress the vibration and optimize the twist of the blade at the same time facilitating increased speed, range, and maneuverability. Investigations show that one degree of wing twist, induced by the DAP actuators, equals 10 degrees of inboard aileron deflection and 5 degrees of outboard deflection. Nitzche [10] and co-workers at the DLR, the German air and space research centre have also been investigating the scope for embedding piezoelectric materials in helicopter blades to control undesirable vibrations as the helicopter flies forwards. The piezoelectric sensors generate voltages in response to vibrations or air pressures on the blades, reflecting the degree to which they were being squeezed or compressed. Based upon this information a signal is then sent to piezoelectric actuators that produce vibrations 180 degrees out-of-phase, thus damping the undesirable vibrations.

The sidewinder missiles used by the allied forces in the 1991 Gulf war follow a preset path with the help of sets of rigid fins at the front and back that alter position in accordance with instruction from an on-board computer. Defence contractors in the US now plan to use embedded piezoelectric materials in order to reduce aerodynamic drag on the fins by more than 90%. The piezoelectric elements are attached in parallel strips to the fibreglass plates. When actuated these plates bend and twist accordingly to reduce aerodynamic drag. Researchers at Pennsylvania State University have developed systems for defence applications that would help submarines avoid sonar detection. This is achieved by coating two layers of an acoustically active smart polymeric material on the submarine surface. The coating senses incoming sonar waves and transmits this information to an electronic feedback controller which determines the phase and direction of the arriving waves by noting the slight time delay between reception of the waves at the two polymer layers. This information is used to activate a piezoelectric cell to generate waves 180^{o} out-of-phase with the arriving sonar beam resulting in submarine disappearance. Similar technology has been used in the F-117A stealth fighter to avoid detection by ground based radar. For civilian applications, the same technology can be used to cut down the noise from car engines to benefit people inside and outside the vehicle, or to reduce or eliminate echoes in concert halls, lecture theatres or air conditioning ducts.

Another important application of the smart material/system that is being developed in the US is for the health monitoring (i.e., damage detection/control/life time prediction etc) of dynamic structures such as military or civilian aircraft, submarines, space based vehicles etc. Such a system may incorporate sensors, actuators, artificial intelligence (neural network), and advanced analytical techniques to provide real-time and continual health assessment. For example the aircraft assessment can begin during the manufacturing process. When the aircraft leaves the factory, it will have detailed engineering data stored in its computer memory. As a preflight check-up the integrality of the aeroplane can be judged against the engineering data stored in the memory. Thus the pilot as well as the maintenance staff can be provided with the visual display of the health of all systems prior to take-off. Any in-flight changes will be displayed with recommended action. The life history of the aircraft will be continually and automatically updated for accurate structural integrity assessments. This will lead to improved safety, reduced and simpler maintenance, and reduced life-cycle costs [11].

Researchers at the Virginia Polytechnic Institute and State University have recently shown that piezoelectric ceramics can be used for active fatigue or damage control [12]. The technique, mimicking the self-repairing function of biological beings, can greatly increase the lifespan and reliability of structures in the future. The basic concept in active damage control is to redirect the energy flow in the structure, resulting in less high-energy concentration, or high stress- concentration in the structure. The energy flow direction can also be altered by inputting energy from outside. The total energy of the system may increase, but the energy that is deteriorating the structure can be decreased. In a simple experiment, a composite beam was bonded to an aluminum bracket and subjected to a fatigue loading from a motor. Two PZT actuators mounted on the roof of the beam operated at the same frequency as the fatigue loading, but the induced stress from the actuators in the bonding area was 180 degrees out-of-phase with the fatigue loading. By reducing the fatigue stress amplitude, the lifetime of the bonded joint was increased significantly from 52,000 cycles to 500,000 cycles. At the same time, the vibration amplitude of the beam was also greatly reduced.

Actuator Materials

It has been tacitly assumed to this point that all actuator materials behave similarly, however, that is not the case. In broad terms, some actuators are developed using piezoelectric materials whereas others exploit electrostrictive materials based on relaxor ferroelectrics. In addition, within the piezoelectric materials there is considerable variation in how each material responds to an applied voltage which is a reflection of both their composition and microstructure. Some examples of this variation are shown in Fig. 7 in which PMN refers to lead magnesium niobate, BST refers to barium tin titanate, and PZST refers to lead zirconium tin titanate having the composition $Pb_{0.99}Nb_{0.02}(Zr_xSn_{1-x})_{1-y}Ti_y)_{0.98}O_3$ where x=0.70, y=0.045 for (a) and x=0.60, y=0.055 for (b) [13].

It can be seen that the strain developed as a function of applied voltage varies considerably. In the case of piezoelectric BST, the response is nominally linear with voltage, showing moderate hysteresis. This situation is improved in electrostrictive PMN with gives a larger strain and a much lower hysteresis but now with a decidedly non-linear response. However, PMN has an exceptionally high dielectric constant (K>20,000) and is unsuitable for applications requiring very rapid response - in such cases, a more commonly used material would be Ba-doped PZT in which K is ~3000. Both these materials exhibit limited strains (between 0.007 and 0.01%), for even larger displacements, actuators are often based on PZT. However, the various doped piezoelectric PZT's also exhibit considerable hysteresis which can range over 80% (ratio of the displacement hysteresis at half voltage as a ratio of the displacement at full voltage).

The existence of a sometimes considerable hysteresis in an actuator material may or may not be a concern depending on the application. For example, the hysteresis shown by the PZT-based materials may be of little consequence in pulse-drive motor actuators where a quick response is important. However, it would be a major concern in applications in which the fine manipulation of optical components to fractions of a wavelength is required. In such cases, PMN-based materials are being developed as they offer a small but adequate strain coupled with a low hysteresis to minimize "lash" in the system.

In some cases, the hysteresis can be extreme such as exhibited by PNZST during the antiferroelectric-to-ferroelectric phase transition which gives a longitudinal strain of over 0.3% which is greater than that expected of a piezoelectric. In those cases where a sufficiently large hysteresis occurs during voltage cycling [PNZST(b)] a digital displacement actuator can be built for applications requiring precise micropositioning with a constant distance change such as for optical diffraction gratings and photolithography. On the other hand, with a modified composition [PNZST(a)] which retains a considerable displacement at zero field it is possible to fabricate latching relays which can hold their "on" state without requiring a constant power supply.

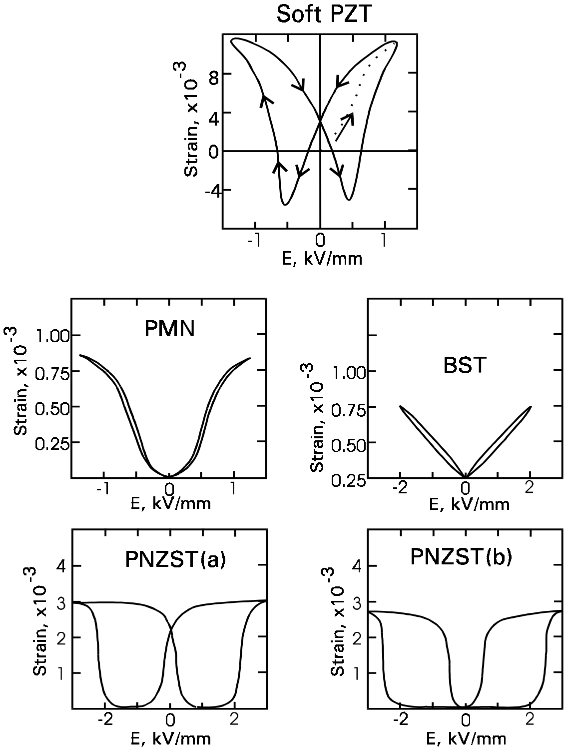

Figure 7: Longitudinal strain vs field for various actuator materials.

At present, the authors are involved in a development program to produce electrostrictive and piezoelectric actuator materials for various applications. The materials are based on selected composites derived from the ternary system PMN-PT-PZT (PT - lead titanate) with various added dopants and processed under a variety of conditions to control the microstructure and grain and grain boundary compositions. Figure 8 shows the extremes of hysteresis that can be generated in this system by varying the PZT content. Details on these materials and their other properties have been published elsewhere [14].

With the addition of PZT to PMN, the material changes from an electrostrictor to a piezoelectric. In general this is accompanied by an increase in strain developed at a given field. However, the penalty is that the hysteresis also increases which is undesirable for fine micro-positioning applications. This ability to transform from a piezoelectric to an electrostrictor imparts other attractive characteristics. Like piezoelectric ceramics, electrostrictive ceramics show a dimensional change when an electric field is applied. However, in piezoelectric materials induced strain is directly proportional to applied field, resulting in a positive or negative displacement, depending on polarity. Whereas, in electrostrictive materials, the induced strain is proportional to the square of the applied field, creating unidirectional displacement regardless of polarity. Since electrostrictive ceramics always give positive displacement, they are always in compression when doing work. This avoids the typical weakness of ceramics in tension, which can be experienced with the piezoelectric ceramic actuators.

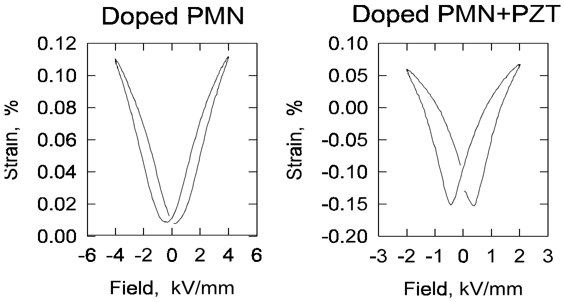

Figure 8: Comparison of strain-field behaviour for electrostrictive (left) and piezoelectric materials.

Electrostrictive materials offer important advantages over piezoelectric ceramics in actuator applications: they do not contain domains and so return to their original dimensions immediately after the field is removed; they show microsecond recovery time upon withdrawal of the electric field, compared to millisecond for piezoceramics. The metastability of the poled state and availability of many alternative domain arrangements in piezoelectric materials can provide stress relief leading to dielectric aging and associated dimensional drift associated with domain rearrangement. This occurs particularly when the piezoceramic is driven hard by high electric fields, as required in many actuator applications. When the electric field is removed piezoceramics exhibit significant hysteresis, and require negative voltage to return to original size or shape. Electrostrictive ceramics on the other hand exhibit little remnant displacement, making them suitable for extremely accurate (micron-level) displacement control device applications.

An additional advantage of electrostrictive PMN is that the micropolar regions that form due to compositional heterogeneity give rise to very high nonlinear polarization over a range of temperatures near the mean Curie point (-15° to ~50°C depending on composition) without a stable remnant polar state. This nonlinear behaviour imparts tuneable characteristics to PMN-based electrostrictors, i.e., they are very smart materials [3]. Electromechanical strains comparable to PZT can be induced in PMN through the application of high dc fields (3-4 kV/mm) without experiencing the severe hysteresis shown by PZT. For example, PMN based ceramics can exhibit a d_{33} value of 1300 pC/N, about 3 times larger than PZT under a bias field of 3.7 kV/cm).

Some of the potential applications of electrostrictive actuators include micron-level manipulation of deformable mirror-surface contours to create correct optical effects at rates up to 1000 times a second. These actuators are also used for space-communication-system optical mirrors or lasers, micro-machining and tool controls, fuel injection valves for precision control of gas/air mixtures in automobiles, linear and rotational micromotors, automatic pattern recognition, vibrational control and management, micropositioning devices, high precision ac interferometric dilatometers, etc.

Summary

In the past, the stimulus for the development of smart materials/systems has been their value in military applications, however, there are many opportunities for the application of this technology such as the control of vibration and noise using the principles of `stealth' signal damping in which the incoming signal is analysed for phase and direction and countered with a similar amplitude but out-of-phase response. The appearance of smart suspensions in automobiles is an indication that this technology will enjoy widespread application as the benefits of vibration control become not only an engineering issue but a feature demanded by the consumer. Irrespective of the specific application, there is an inherent appeal in the applications of these materials and systems - particularly, when they can offer potentially low-cost, high sensitivity and rapid response. The future is undoubtedly very bright for these materials.

References

1. "The concept of intelligent materials and guidelines for their promotion", *Japanese Science and Tech. Agency*, 1990.
2. T. Tagaki, "A concept of intelligent materials and the current activities of intelligent materials in Japan", *Proc.1st European Conf. on Smart Structures and Materials, Glasgow*, Eds. B. Culshaw, P.T. Gardiner and A. McDonach, pp. 13-18, 1992.
3. R.E. Newnham and G.R. Ruschau, "Smart Electroceramics", *Jour. Amer. Ceram. Soc.*, vol. 74, no. 3, pp. 463-480, 1991.
4. A. Ahmad, J.D. Canaday, T.A. Wheat and A.K. Kuriakose, "A computer-controlled data acquisition system for electrical/electrochemical characterization of ceramic materials", *Jour. Can. Ceram. Soc.*, vol. 53, pp. 8-14, 1984.
5. T.A. Wheat, "Superionics - today and tomorrow", *Jour. Can. Cer. Soc.,* vol. 48, pp. 27-37, 1979.
6. R.E. Newnham, Q.C. Xu, S. Kumar and L.E. Cross, "Smart ceramics", *Jour. Wave-Material Interaction*, vol. 4, pp. 3-10, 1989.
7. H. Tsuka, J. Nakomo and Y. Yokoya, "A new electronic controlled suspension using piezoelectric ceramics", paper presented at IEEE Workshop on Electronic Applications in Transportation, 1990.
8. B.K. Wada, J.L. Fanson, G.S. Chen and C.P. Kuo, "Adaptive structures in space", *U.S.-Japan Workshop on Smart/Intelligent Materials and Systems, Honolulu, HA*, pub. by Technomics, Lancaster, PA, U.S.A., pp. 59-81, 1990.
9. R.N. Boggs, "Smart materials bolster helicopter blade design", *Design News*, vol. 47, no. 8, p.28, 22 April 1991.
10. F. Nitzche and E. Breitback, The smart structures technology in the vibration control of helicopter blades in forward flight", *Proc. 1st European Conf. on Smart Structures and Materials, Glasgow*, Eds. B. Culshaw, P.T. Gardiner and A. McDonach, pp. 321-324, 1992.
11. T.G. Gerardi, "Health monitoring aircraft", *U.S.-Japan Workshop on Smart/Intelligent Materials and Systems, Honolulu, HA* pub. by Technomics, Lancaster, PA, U.S.A., pp. 82-91, 1990.
12. C.A. Rogers, C. Liang and S. Li, *AIAA/ASM/ASCE/AHS/ASC 32 Structures, Structural Dynamics and Materials Conference - Part III* , AIAA Inc., Washington DC, pp. 1190-1203, 1991.
13. K. Uchino, "Advances in ceramic actuator materials", *Mat. Letters*, vol. 22, pp. 1-4, 1995.
14. S.E. Prasad, S. Varma, T. Hoang, T.A. Wheat and A. Ahmad, "The role of statistical design in the development of electrostrictive materials", *Proc. 9th IEEE Intl. Symp. on Applications of Ferroelectrics*, Edited by R.K. Pandey, M. Lui and A. Safari, pp. 762-765, 1994.