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Introduction

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1.1 What are 'Smart Materials'?

Smart materials represent one of the technological marvels of the 20th century which continue to make sizeable impact in the 21st century. Many of the so-called smart materials were discovered earlier but it is only during the last fifty years or so that they have ventured into mainstream application areas in engineering and technology. These materials are termed 'smart' owing to their ability of fairly quick 'response' to certain external stimuli, including mechanical stresses and environmental variables. The definition of the term 'smart material' was formally agreed upon by the scientific community in 1988 at the United States Army Research Office Workshop. At this workshop, Rogers *et al*. (1988) defined smart materials as those materials which possess the ability to change their physical properties in a specific manner in response to specific stimulus input. The words 'stimulus' and 'response' are central to the idea of smart materials. The nature and the quantum of the response can be tailored in the laboratory. Earlier, the term 'intelligent' was also used to describe these materials. However, experts at the 1988 workshop specifically agreed to discontinue this term since 'intelligence' is associated with higher cognitive capabilities which are at the moment lacking in these materials. 'Smartness', on the other hand, implies exhibiting prior learned behavior, a much lower trait than 'intelligence', which befits to describe the response of these materials.

The wide range of stimuli could be pressure, temperature, electric and magnetic fields, moisture, pH, specific chemicals or nuclear radiation. The associated changeable physical properties could be strain, color, shape, stiffness, viscosity, damping or any other physical aspect. The present day smart materials include piezoelectric ceramics and polymers, optical fibres, electro-rheological (ER) fluids, magneto-strictive materials, shape memory alloys (SMAs) and many more. Table 1.1 summarizes some of the prominent modern day smart materials, the associated stimulus-response pairs and the key application areas. The list of smart materials invented/ discovered till today is somewhat exhaustive and several newer smart materials are at developmental stage.

Table 1.1: Prominent modern day smart materials, associated stimuli and responses and key application areas

Smart Material	Stimulus	Response	Applications
Piezoelectric	(a) Stress (b) Electric field	(a) Electric charges (b) Strain field	(a) Sensors (b) Actuators
Shape memory alloy/polymer	Temperature change	Martensitic phase change (recovery to memorized shape)	Bio-engineering (opening blocked arteries), fire protection systems
Optical fiber	Temperature, pressure, strain	Change in opto-electronic signals	Sensors
Electro-rheological fluid	Electric field	Change in viscosity	Hydraulic valves, clutches, shock/ vibration absorption
Magneto-strictive	(a) Magnetic field (b) Stress	(a) Strain (b) Change in magnetization	(a) Actuators (b) Sensors
pH sensitive polymer	pH	Volume change	Drug delivery systems, biomimetics
Photochemical	Light exposure	Shape change	Bioreactors
Thermoelectric	Temperature change	Electric field	Thermal sensors
Photochromic	Light exposure	Color change	Sunglasses
Halochromic	pH	Color change	Paints, corrosion detection

1.2 'Smartness' of Piezoelectric Materials

The piezoelectric materials enjoy a very special status among the smart materials covered in Table 1.1. They stand among the most fascinating and the earliest discovered smart materials. The word "piezo" is derived from a Greek word synonymous with term "pressure". The phenomenon of

piezoelectricity was discovered in 1880 by Pierre and Paul-Jacques Curie. It occurs in several non-centrosymmetric crystals, such as quartz (SiO_2), in which electric dipoles (and hence surface charges) are generated when the crystals undergo mechanical deformations. The same crystals also exhibit the converse effect, that is, they undergo mechanical deformations when subjected to electric fields.

Commercial piezoelectric materials are now available as ceramics and polymers, which can be manufactured into a variety of convenient shapes and sizes. Lead (Pb) zirconate titanate (PZT), a stiff and brittle variant, is the most widely used piezoceramic today. Piezopolymers, on the other hand, are very flexible in nature. The most common commercial piezopolymer is the polyvinvylidene fluoride (PVDF). Traditionally, the piezoelectric materials find their use in accelerometers, strain sensors, emitters and receptors of stress waves, vibration sensors, actuators and pressure transducers. During the last two decades or so, they have been increasingly deployed in turbo-machinery actuators, vibration dampers and for active vibration control of stationary/moving structures. In the field of structural health monitoring (SHM), they are used as dynamic strain sensors and as impedance sensors. A detailed description concerning these applications has been covered in Chapter 2 of the book.

1.3 Structural Health Monitoring and Non-Destructive Evaluation

Optimal performance of civil, mechanical, aerospace and other structures or machines is very crucial for smooth functioning of any modern nation's industry. It is desirable that occurrence of any damage/deterioration be timely detected, so that breakdown scenarios could be reduced to minimum possible. It is in this context that SHM has become a necessity for critical civil, mechanical and aerospace structures. It is today recognized as one of the forefront areas which carry the potential of driving global economy in terms of huge market potential.

In a broad sense, SHM is defined as the measurement of the operating environment and critical responses of a structure to track and evaluate the symptoms of operational incidents, anomalies, and deterioration or damage indicators that may affect the operation, serviceability, safety or reliability (Aktan *et al*., 2000). SHM implies continuous monitoring, acquisition, validation and analysis of the technical data to facilitate life-cycle management decisions (Kessler *et al*., 2002). A subset of SHM is *condition*

assessment, which is defined as the periodic or one-time establishment of the current conditions, specifically aimed at assessing fitness for purpose. SHM, on the contrary, implies continuous monitoring of the concerned infrastructure.

Non-destructive evaluation (NDE) is another term associated with SHM. NDE specifically refers to the wide group of experimental analysis techniques used in laboratories and industry to evaluate the properties of a material, component or system or for detection of surface or internal flaws or metallurgical conditions, without interfering in any way with the integrity of the material/ system or its suitability for service. These techniques by themselves do not qualify for SHM but may invariably aid in SHM. Some SHM experts refer to these techniques as 'local' techniques owing to the localized interrogation, which is the key feature of these techniques. Ultrasonic interrogation, acoustic emission, eddy currents, impact echo testing, magnetic field analysis, penetrant dye testing and X-ray analysis are some of the popular NDE techniques. In practice, these techniques are often applied at selected probable damage locations, primarily based on preliminary visual inspection coupled with past experience.

Piezoelectric materials, specifically PZT, have found widespread interest of researchers for SHM and NDE owing to their striking sensing and actuation capabilities and highly competitive performance. In this book, Chapters 2, 5, 6 and 7 cover specific details of SHM and NDE with the aid of PZT based sensor patches.

1.4 Piezoelectric Energy Harvesting

The process of extracting energy from the environment or from a surrounding system and converting it to useable electrical power for direct use or storage for future use is known as *energy harvesting*. Energy harvesting eliminates the requirement of running wires for operating electronics and the need of frequent replacement of batteries is also taken care of. Due to miniaturization of sensors, tremendous increase in their demand and the development of the low power consuming electronics, energy harvesting has attracted the researchers and application engineers worldwide. Numerous product prototypes and the rising number of publications in the field clearly indicate the importance of the area. Piezoelectric energy harvesting (PEH) utilizes the direct effect of piezoelectricity, in which a piezoelectric material produces electricity when deformed, thus acting as a generator.

The piezoelectric energy harvesters possess various advantages over conventional renewable sources of energy such as wind and solar energy. The easy installation and low maintenance required by the piezoelectric harvesters renders them cost effective and appropriate for end product in the market. Another advantage is that they do not require vast area of public space for their operation and at the same time are not restricted to any specific climate, weather, time of the day or geographic locations. Specifically configured piezoelectric energy harvesters provide the additional advantage of converting the host structure into a "smart" structure by providing the real-time data assessment of the structure. Above all, the most striking feature of PEH is the low embodied energy as compared to photovoltaic cells. Needless to say, like SHM, PEH also carries a big potential and technology market share worldwide. Chapters 8 and 9 of the book are specifically dedicated to PEH.

1.5 Extension of SHM Technologies to Bio-mechanics and Bio-medical Engineering

Bio-mechanics is the study of structure, function or operation of biological systems by means of the techniques of mechanics. It is closely related to bio-medical engineering, which entails the application of the engineering principles and technologies to medicine and biology for healthcare and related diagnostics. SHM technologies, which have matured during the last two to three decades, carry enormous potential of extension in the bio-mechanics and the bio-medical fields. Piezo based materials, acting as sensors and actuators, offer new solutions to the bio-medical community to augment their conventional set of sensors, tools and equipment. In essence, there is a whole new gamut of possibilities for SHM technologies making their foray into the bi-medical sector. Towards this end, Chapter 10 of the book covers plantar (foot) pressure measurement using PZT patches and other case studies such as condition monitoring of bones.

1.6 Concluding Remarks

This chapter has introduced the concept of smart materials, SHM, NDE and PEH. It has also specifically highlighted piezoelectric materials, which form the main substance of this book in the forthcoming chapters. Rest of the chapters of the book shall cover the theoretical and application oriented aspects of the piezo-materials in the specific areas.

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