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Introduction

This book outlines the properties and applications of piezoelectric materials for sensor, actuator and energy harvesting applications. Piezoelectric materials are of significant interest since they exhibit both active and sensory responses, and can form the basis of *smart* or *multifunctional* devices, systems or structures. We will begin here with the basic definition of a smart system.

1.1 Active and Sensory Materials for Smart Systems

Before examining the properties and applications of piezoelectric materials, it is first of interest to define the terminology used to describe materials that are used as *actuators*, *sensors* or *energy harvesters* and how they are combined to create a *smart system*. We will describe an *active material* as a material that exhibits a specific response (which can be considered as an 'output') when some form of stimulus is applied (which can be considered as an 'input'). Specific examples of the potential stimuli/inputs include the application of force, an induced strain, vibrations, a change in temperature or the application of an electric or magnetic field [1]. Examples of the resulting responses/outputs to any stimulus by an *active material* can include a dimensional or shape change of the material, a change in its stiffness, the generation of electrical charge or even a change in colour. 'Classical' active materials, such as piezoelectric, shape memory alloys, dielectric elastomers or magnetostrictive materials [2–4], are widely employed as actuators in a smart system since they are able to produce a deflection, strain or force in response to an applied field (electrical, magnetic or thermal).

In addition to their use as an active element in an actuator, piezoelectric materials are attractive since they can also be employed as sensory elements, whereby any applied force or strain is converted into an electric charge, current or voltage. The generated signal can be used to measure the applied force or strain and provide a sensory function to a smart system. We will see later in this book that many piezoelectric materials are also pyroelectric, where a change in temperature also produces an electric charge, so these materials can often be employed as thermal sensors or even provide a combination of functions simultaneously. Piezoelectric materials are therefore particularly attractive since they can act as both an

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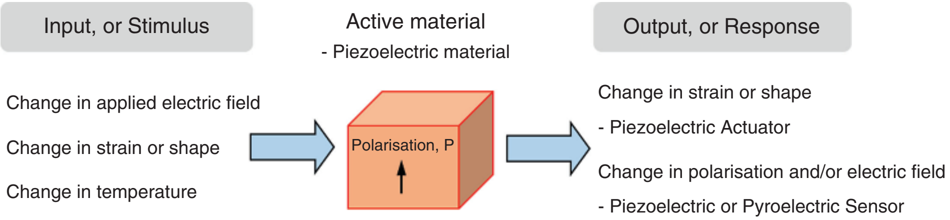

Figure 1.1 Schematic of a piezoelectric element employed as an *active material*, behaving as either a sensor or an actuator; the function depends on the nature of the stimulus and the resulting response. *Source:* Adapted from Nelson [1].

actuator and a sensor of mechanical and thermal stimuli, thereby providing a high degree of *multifunctionality*.

The concept of an active material that reacts to an applied stimulus (or an 'input') giving a resulting response (or an 'output') is outlined in Figure 1.1 for piezoelectric and pyroelectric elements.

In order to be able to react to any changes in its surroundings, a truly *smart system* should provide the following functions [1]:

i) the smart system must be able to receive sensory information from the active material in order to provide some form of 'sensing' function,
ii) the smart system must be able to process the sensory data and then provide an 'analysis and decision' function, and
iii) in response to the outcome of the 'analysis and decision' function, it must be able to act on that decision; for example, in a vibration control system, this can include the actuation of an engineering structure to reduce the level of vibration.

This hierarchy of a potential smart system is outlined in Figure 1.2 [1], which shows engineering structures exhibiting only an *actuated* or *sensory* function, along with *controlled*,

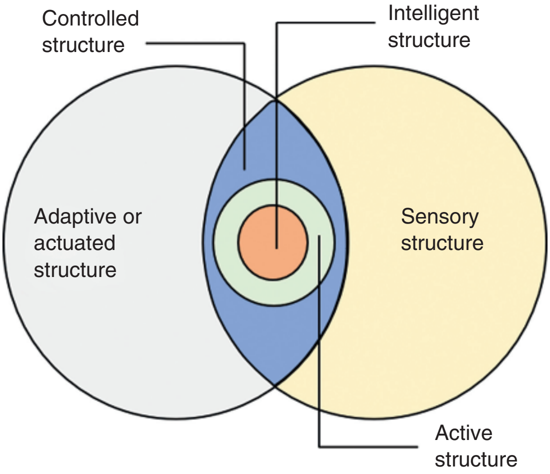

Figure 1.2 Representation of actuated, sensory, controlled, active and intelligent structures. A smart structure is typically a controlled, active or intelligent structure. *Source:* Adapted from [1–3].

active and intelligent *structures* that provide additional functionalities to the system. Potential applications for such smart systems include civil and transport structures [5–7], robotics [8] and wearables [9]. Based on Figure 1.2, engineering structures, which contain *only* sensors can be described as *sensory*. Structures that contain *only* actuators can be defined as *adaptive* or *actuated* structures. Engineering structures that have both sensing and actuation functionalities can be described as *controlled* structures if the ability to sense and then actuate is linked by some form of closed-loop control, for example, controlled passive vibration damping. Additional definitions of smart structures, such as *active* and *intelligent* structures, are indicative of a higher level of functionality; this can encompass a greater degree of integration, utilising external energy input (such as active vibration damping), the inclusion of additional power electronics or even exploiting energy harvesting [1–3].

1.2 Energy Harvesting Materials

In addition to sensing and actuation, there has been growing interest in the topic of energy harvesting in an effort to produce autonomous self-powered systems, for instance, self-powered structural health monitoring. This interest has been motivated by the reduction in the necessary power levels for wireless sensing and the continued growth in the Internet of Things (IoT), where large numbers of distributed sensors are to be deployed. A potential application for energy harvesting is to provide power for wireless sensor networks that consequently do not require any external power sources or any battery replacement; such networks often need only small levels of power in the μW–mW range [10–12]. The concept of ‘energy harvesting’ is therefore typically associated with scavenging local energy sources (vibrations, heat, airflow, etc.) to produce low levels of power and is therefore different from ‘energy generation’, which is associated with harnessing our primary sources of power on a large scale. Energy harvesting is of particular interest in the deployment of sensing elements or sensor networks in highly remote or hostile locations, or if many sensors are required [10]. The use of piezoelectric materials to transform vibrations, strains or dynamic forces into usable electrical energy, rather than simply acting as a sensing signal, is therefore a promising approach [10].

1.3 Multifunctional Materials, Devices, Systems and Structures

The research and development area of smart systems and structures is highly interdisciplinary, encompassing advanced materials, composites, electronics, mechanics, dynamics, physics and chemistry.

It is of interest to define here the terms *material*, *device*, *system* and *structure* since they are often used interchangeably in the literature. The active *material* can be considered as the simplest element, which can be a bulk material that simply reacts to a stimulus, as shown in Figure 1.1. At a higher level of complexity, *devices* that provide a sensing, actuating or harvesting functionality are then constructed from an active material. Complete engineering *systems* or *structures* are then designed that contain a combination of active, sensing and harvesting devices, along with some form of 'analysis and decision' function, usually in the form of a control system.

The concept of *multifunctionality* is also used, where the material or system can perform multiple tasks through the appropriate combination of different functional capabilities. This can be achieved using piezoelectric materials as they provide sensing, actuation, harvesting and even energy storage capability since they can also be used as simple capacitors [13, 14].

From our discussions above, it can be considered that it is difficult for a single material on its own to be truly smart, controlled or intelligent; it usually acts as an *active* material. As a result, the concept of a '*smart material*' is often used to describe a material that exhibits some form of *activity,* as shown in Figure 1.1, that allows it to be employed as an active element (sensor, actuator or harvester) in a smart system or structure.

Note 1.1

Smart systems or structures often combine a sensing capability with an analysis and decision function that leads to an active response, such as actuation.

Note 1.2

Multifunctional materials or systems have the ability to combine a range of functional capabilities such as sensing (force or temperature), actuation or energy harvesting.

Note 1.3

Smart systems have the potential to be self-powered by means of energy harvesting.

1.4 Piezoelectric, Pyroelectric and Ferroelectric Materials

We have seen that a piezoelectric material generates an electrical charge when subjected to a mechanical stress/strain, which can produce an electric field under open-circuit conditions or a current under short-circuit conditions. This type of response is termed the *direct* piezoelectric effect and forms the basis of the use of piezoelectric materials as an active material in a sensor device or an energy harvesting device. In addition, piezoelectric materials produce a strain (or displacement) when they are subjected to an applied electric field; this is termed the *converse* piezoelectric effect, which enables them to be used as an active material in an actuator device.

We will see in this book that *ferroelectric* materials represent an important subgroup of piezoelectric materials. The term *ferroelectric* is used to describe materials that exhibit a spontaneous polarisation, where the direction of polarisation can be reoriented (or 'switched') by the application of an externally applied electric field, and on the removal of that applied electric field there is a remnant polarisation that results in the material exhibiting piezoelectric behaviour. Ferroelectrics are piezoelectric materials that have the widest practical usage in engineering since they can be formed in a variety of geometries, and the polarisation direction can be selected and tailored by the application of an electric field after manufacture. We will see later that all ferroelectric materials are also *pyroelectric*, which means they can act as thermal sensors since they develop electrical charge when subjected to a change in temperature [15]. As an example, lead zirconate titanate (PZT) is a commonly used piezoelectric material that is also both ferroelectric and pyroelectric. This wide-ranging functionality makes these materials of particular interest for the range of structures in Figure 1.2.

This book is devoted to piezoelectric materials and their use in sensors, actuators and energy harvesters, either as discrete devices or as part of controlled, active or intelligent systems or structures with multiple functions. The properties of the materials will be discussed together with detailed examples of use in a wide variety of applications. The book attempts to cross the boundary between fundamental materials physics and applied engineering to ultimately provide engineers with a key understanding to help create either discrete sensors, actuators or energy harvesters or lead to the formation of more advanced smart systems. The book deliberately provides some of the underlying science to help those interested in using piezoelectric materials in engineering applications. It is important to examine these concepts since the underlying science in Chapters 2 and 3 will help the reader understand the limits and appropriate operating conditions for piezoelectric, ferroelectric and pyroelectric materials for use in the sensing, actuator and harvesting applications that are discussed in Chapters 4–8.

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