

# 1

## Introduction to Smart Structures

This chapter introduces the concept of smart structures, with reference to the traditional concept of structure and to the enhanced capabilities, such as sensitivity, actuation, and a logic that includes feedback control, that a smart structure can produce. The concept of active material is then proposed as a material that reacts to a nonmechanical stimulus (such as an electric or magnetic action) with a structural response (e.g. by producing an induced strain field), or that reacts to a mechanical action (such as an applied force) with a nonmechanical response (e.g. by producing an electric charge). The physics that rules these responses, that couples the structural mechanics field with others such as electromagnetism, is then illustrated in a basic fashion for piezoelectric and electrostrictive materials, for magnetostrictive materials and for shape memory alloys. The physical formulations for the mathematical models described in Chapter 2 for piezoelectric material are illustrated by introducing the physical meaning and typical values of the constants that characterize the most common active material.

The advantages of using a smart structure in real practice are highlighted and some of the major areas of application such as structural health monitoring, shape morphing, vibration control and energy harvesting, are briefly introduced.

### 1.1 Smart Structures and Traditional Structures: Definition and Main Constituents

Smart structures can probably be considered the major innovation in the field of structural mechanics since the introduction of composite structures in engineering practice in the 1970s. As the practical use of composites well shows, the process by which an innovation pervades a market is rather complicated but reflects at least three phases: a slow but steadily increasing initial phase; a rapid and sudden

growth; and finally a stable phase, once the market has reached its capacity. The first phase could take a long time (it took decades for the application composites) and usually still requires major research developments at the highest technological level possible.

Before the second phase can start, the innovative technology should have demonstrated not only its effectiveness in real practice but also its value in terms of the ratio between costs and benefits. It could well be that an innovation never enters the second phase, thus their market impact is minimal. At the beginning of the new millennium, and even earlier, composite structures were at the second stage of their development, as their large-scale introduction in commercial airliners demonstrates.

Smart structures could well follow the success of composites. The very extensive research and development programme conducted in the past 20 years and the presence in the market of several products with their main functionality based on the working principle of smart structures, indicate very good premises for real progress in the application of this technology and its market development.

With this aim in mind the time has come to better describe what a smart structure can do compared with a traditional structure and what are the basic working principles on which a smart structure operates. Before doing that it is necessary to return to the basics of structural mechanics and, more precisely, to structural engineering.

Mechanical engineering can be viewed as the conceptual definition, design, construction and operation of a mechanical system that is able to perform a target mission, or a specific function, in the context of legal and commercial requirements. In the framework of a mechanical (or engineering) system, the structure is the part or assembly of the system that is able to provide support or containment to all the other parts. At the same time the structure has to have sufficient robustness (strength) and stiffness to avoid failures or excessive deformation occurring during the operational life of the system. With such a definition the primary structure of an engineering system plays a major role both for very complicated systems, such as a car, an airplane, a spacecraft, a bridge or a nuclear plant, and for very simple devices.

For larger systems it is usually the case that the structure is a system in itself, made up of distinct elements connected together. Each structural element, and the structural system as a whole, has to withstand the loads and all the other physical demands that are generated during the life cycle of the system. Structural systems perform to their capabilities as a result of the material from which they are made and the geometry of their design. In fact a good structure not only is made from a material with high structural characteristics (especially stiffness and strength) but also has a geometry suited to withstand and transfer the loads in an optimal way. This means that, especially if the mass has an influence on the cost of the system, geometry is chosen in such a way that all the structural mass performs at the highest level possible, with no parts of the structural volume being stressed at low levels. In other words, stiffness and strength are the most important features of a traditional structure, and are realized by using the lowest density materials possible with the best stiffness properties and least propensity to fail when arranged in a suitable geometry.

Returning to the case of composite structures, the greatest innovative technology recently introduced in structural engineering, what are the main technical reasons for their success? The very good specific properties of stiffness and strength of reinforcement materials and the possibility of ‘using’ their intrinsic anisotropy, owing to the presence of reinforcement fibres, for constructing optimal structural geometries have made structures comprising these materials very attractive from the perspective of the structural components market. In recent years it has been demonstrated that users were willing to pay the extra costs related to the production of a multiphase fibrous material in order to benefit from advantages in structural performance.

## 1.2 Smart Structures and Active Materials

The introduction of composite structures, although revolutionary from many aspects, was achieved within the framework of the traditional idea of a structure. As will be clarified in the following, the case of smart structures is completely different and much more revolutionary. The concept of smart structures started with research activities showing that a particular material known for its application in areas of engineering other than mechanical engineering, could withstand a significant range of mechanical environments with no failures and acceptable stiffness. At the same time these materials, because of the behaviour of their constituents, are able to perform other functions such as, for example, the sensing of their strain and stress state or the variation of their shape resulting from stimulus by nonmechanical means. This kind of behaviour has been very well known for many years. One could also mention that for the majority of structural materials it is well known that an increase in temperature induces a thermally induced strain state that might induce significant stress level (thermoelastic effect).

The novelty introduced in the field of engineering by smart structures was twofold: first of all the existence of materials that can perform a nonstructural function and at the same time can withstand a significant stress state; second their capability of performing functions, such as stress sensing and shape changing, by means of a physical coupling between the structural mechanics and other fields of physics, such as electromagnetism.

Being able to withstand loads, these materials can be considered as ‘structural’ materials, but at the same time they are able to function in other ways. The properties of these materials have been known for some time, but never considered in the context of a structural material. Piezoelectric and electrostrictive materials, magnetostrictive materials and shape memory alloys are structural materials that do not just passively undergo a state of stress depending upon external loads and experience deformation in proportion to their use, but they also actively produce additional functions. Early research work showed how these materials can be properly sized and arranged, in combination with other classic engineering material, in order to realize a structural system that can incorporate at the structural level the functions of these quite special materials, and also perform additional functions.

The use of the adjectives ‘smart’ and, although less properly, ‘intelligent’, to characterize the behaviour of structures that incorporate and expand the capability of materials such as piezoelectric or shape memory alloys, highlights the very special behaviour of these structural systems. Different to composite structures, smart structures produce an innovation in the concept itself of a structural system. In fact, although the classic functions of a structure are maintained, smart structures usually perform several functions, or if you wish possess additional engineering capabilities that are not typical of the structural systems as they are traditionally described, as recalled in preceding parts of this section.

The rigorous definition of a smart (or intelligent) structure has attracted the interest of many research groups. Wada, Fanson and Crawley [1] gave a general framework for the definition of what an intelligent structure is. They first define *sensory* structures as those possessing sensors that enable the determination or monitoring of the system’s states or characteristics, and *adaptive* structures as those possessing actuators that enable the alteration of a system’s states or characteristics in a controlled manner. *Intelligent* structures are those where sensors and actuators are contained in a feedback architecture that is highly integrated into a structure that also includes control logic and electronics.

Rogers [2] defined ‘intelligent material systems’ as those possessing ‘intelligent and life features integrated in the microstructure of the material system to reduce mass and energy and produce adaptive functionalities’. It should be emphasized that in this definition inspiration can be sought from nature, where real smart structures do exist, such as in the sensor functionality of the nerves that monitor the state or stress of muscles, or in the adaptive wings of a bird (or more in general the adaptation of the skeleton and muscular system of any living creature). Moreover in Roger’s definition a critical role is devoted to energy and mass as quantities to be optimized in an optimal material system. Other attempts to define smart structures are discussed in several review articles [3–6].

One critical element of smart structures is the role played by active materials. By such a term one can define a large class of materials possessing quite different properties (such as piezoelectric materials, magnetostrictives and shape memory alloys) that are capable of producing either a mechanical effect (such as a strain or a stress) subsequent to a nonmechanical stimulus (such as an electric or magnetic field), i.e. *materials for actuation*, or are capable of producing a nonmechanical effect (such as an electric charge or current) by means of a mechanical stimulus (such as a stress), i.e. *materials for sensing*. These materials are of course supposed to be structural, that is of sufficient stiffness and strength to be able to withstand certain loads. In some cases active materials can be for both actuation and sensing, and piezoelectric materials can be considered the typical materials of this kind.

The coupling of the structural response behaviour of active materials with other fields in physics, such as electromagnetism, is the physical basis for developing a sensing or actuation capability of a smart structure. In the following section considerable attention is given to active materials and their physical behaviour. In fact it is the knowledge of the behaviour of these materials and the capability of modelling their behaviour that provides the opportunity to conceive, design,

implement and operate a real smart structural system. From the modelling and simulation viewpoint the analysis of the behaviour of a smart structure is very challenging because of the need to address coupled problems in a multiphysics perspective. The behaviour of active materials, including active composites, also requires analysis of the problem at smaller scales or at different scales, from the assumption of continuity to the atomic level.

## 1.3 The Physical Behaviour of Active Materials for Actuation and Sensing

### 1.3.1 Piezoelectric Materials

The direct piezoelectric effect was discovered in 1880 by the brothers Pierre and Jacque Curie, who were able to prove that by applying a mechanical pressure on the surface of certain crystalline materials, such as quartz, an electric charge proportional to the applied pressure is generated [7]. In ancient Greek the word piezo means pressure, consequently piezoelectricity means pressure electricity. Soon after, the converse piezoelectric effect, that is the property of certain crystals to produce a geometric strain when electrically charged, was experimentally verified by the Curie brothers [8], after being theoretically predicted by Lippmann in 1881 [9]. Also for the converse effect the strain produced was proportional to the electric charge.

Piezoelectricity is known to occur in dielectric materials, for which the constituent atoms are either positively or negatively charged. For displaying the piezoelectric effects the crystal cannot have a centre of symmetry. Namely, when considering a unit cell of the crystal, that is an elemental volume representative of the distribution of the atoms in the material, the centre of the positive charges of the unit has to be different from that of the negative charges. The material then is said to be polarized and the line connecting the centres of negative and positive charges is the direction of polarization. Only 20 out of the 32 crystal classes can be piezoelectric, i.e. characterized by the presence of a spontaneous polarization that is due to the arrangement of the atoms in the crystal pattern.

In most cases piezoelectric materials are also ferroelectric, whereby at higher temperatures a transformation occurs from the piezoelectric phase to a higher symmetry nonpiezoelectric phase. The temperature below which the piezoelectric phase is present is known as the Curie temperature  $T_c$ .

Piezoelectricity is not present only in single-crystal materials. In polycrystalline piezoelectric materials a randomly oriented polarization of each elemental crystal results in the absence of a global spontaneous polarization. Nonetheless in the 1940s it was discovered that polycrystalline ceramics can acquire induced polarization when subjected to a poling process, at high temperatures and electric fields, that is able to reorient the polarization of the constituent crystals in one main direction [10]. This process has opened the way for the largest category of piezoelectric materials in terms of volume of production, that is piezoelectric ceramics.

### 1.3.1.1 Direct and Converse Piezoelectric Effect

The experimental evidence shows that an electrical charge is developed on a material surface upon the application of a mechanical stress and that the effect is proportional to the pressure applied (direct piezoelectric effect). By calling  $P$  the charge produced per unit surface and  $\sigma$  the mechanical stress applied, a piezoelectric coupling coefficient  $d$  can be defined

$$P = d\sigma. \quad (1.1)$$

It also has been shown that a strain  $\epsilon$  is produced by the application of an electric field of intensity  $E$ , with  $\epsilon$  being proportional to  $E$  (converse piezoelectric effect). The physical law can be described as

$$\epsilon = dE, \quad (1.2)$$

with  $d$  being the same coefficient measured for the direct effect.

Instead of  $P$  the variable  $D$  (electric displacement) is often used, being

$$D = \epsilon_0 E + P = \epsilon_r \epsilon_0 E, \quad (1.3)$$

where  $\epsilon_0 = 8.854 \cdot 10^{-12}$  F/m is the vacuum permittivity and  $\epsilon_r$  is the relative permittivity of the material. For most materials  $\epsilon_r \gg 1$ , so one can also assume as a first approximation that  $P \cong \epsilon_r \epsilon_0 E = \epsilon E$ . In this way another coefficient  $g$  can be defined that relates the mechanical stress applied to the electrical field  $E$  produced:

$$E = g\sigma = \frac{d}{\epsilon}\sigma. \quad (1.4)$$

The coefficients  $d$  and  $g$  are very significant for the performance of the piezoelectric material considered as a smart material capable of actuation and sensing functionalities. In fact once assigned the level of the electric field available, a material with a high  $d$  value is best suited for performing actuation while a high  $g$  value is of interest for maximizing the performances of sensors of the state of stress  $\sigma$ .

In Table 1.1 the characteristics of some typical piezoelectric materials are compared. The meaning of subscripts to  $d$  and  $g$  is explained later in this section.

The first material is quartz, the low temperature form of  $\text{SiO}_2$  single crystal. The second one is PZT,  $\text{Pb}(\text{Zr},\text{Ti})\text{O}_3$ , the typical polycrystalline piezoelectric material. This material lies at the phase boundary on the  $\text{PbZrO}_3$  (52%) and  $\text{PbTiO}_3$  (48%) phase diagram, between the tetragonal and rhombohedral ferroelectric phases. For that composition PZT exhibits the best coupling coefficients. Another typical piezoelectric material is PVDF, polyvinylidene flouride, which is not a ceramic but a polymeric material characterized by a very large  $g$  constant, and consequently has good behaviour as a sensor. Also in the case of this polymeric material, the piezoelectric behaviour is present due to the lack of a centre of symmetry in the structure of the material.

**Table 1.1** Physical properties of typical piezoelectric materials.

Material	( $T_c$ )	$d_{33}(\cdot 10^{-12} C/N)$	$g_{33}(\cdot 10^{-14} C/N)$	$\epsilon_r$
Quartz	573	$-2.3^a$	$-57.5^b$	4
PVDF	41	30	200	15
PZT 52/48	386	223	39.5	1500
BaTiO <sub>3</sub>	125	191	11.5	2000

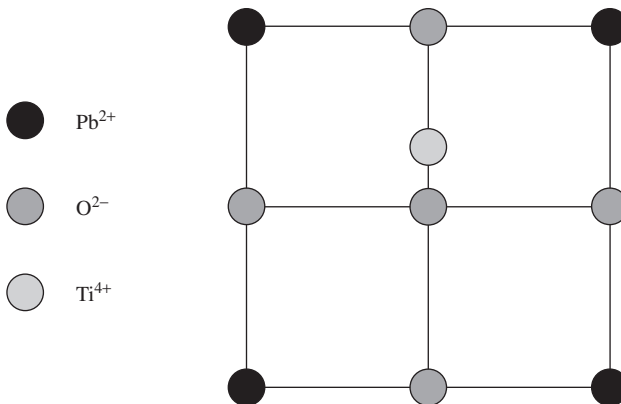
<sup>a</sup>Refers to  $d_{11}$ .

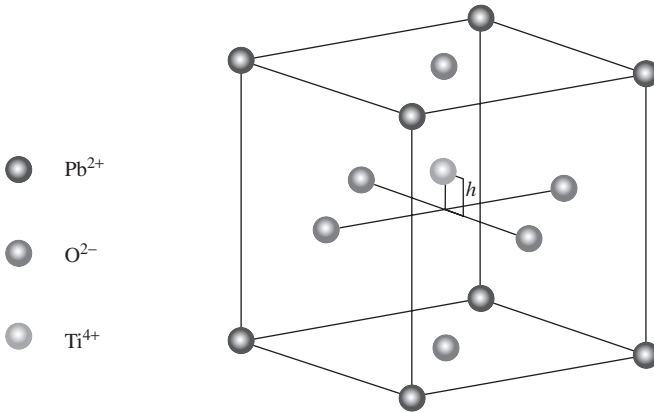
<sup>b</sup>Refers to  $g_{11}$ . Both are considered equivalent for comparison purposes.

In order to gain deeper physical insight on the direct piezoelectric behaviour it is possible to investigate the effect of a mechanical stress applied to the crystalline structure of a piezoelectric material. Following [11] we might consider a simplified sketch of a lead titanate PbTiO<sub>3</sub>. In the planar representation the polarization is due the position of the Ti<sup>4+</sup> ion only, that is off-centre of the unit cell, as required for the presence of polarization (Figure 1.1). The three-dimensional (3D) structure of lead titanate is illustrated in Figure 1.2.

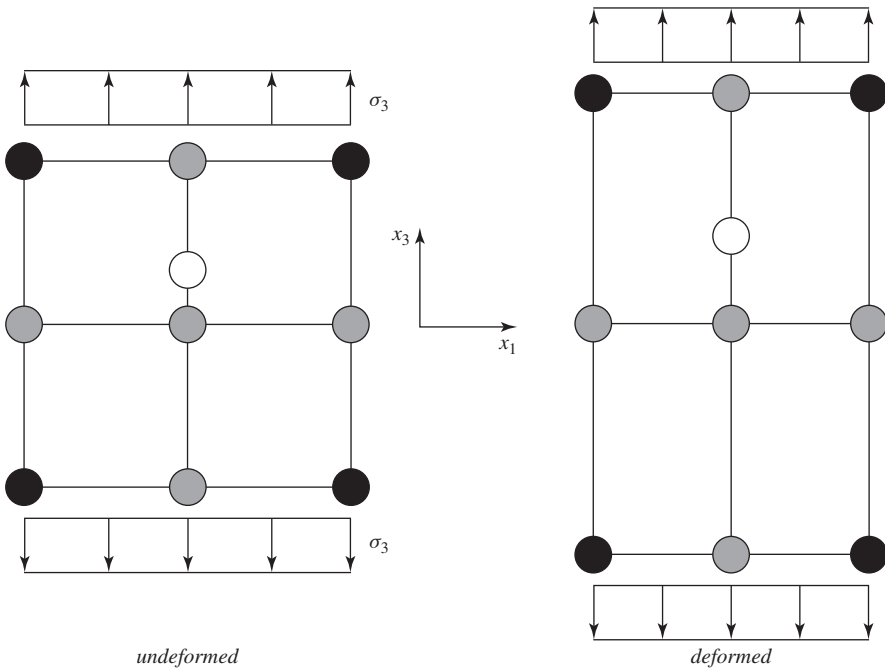
Actually the transition from a cubic  $m3m$  crystal form (stable at high temperature) to a tetragonal  $4mm$  symmetry is due to a shift of both the Pb and the Ti atoms with respect the oxygen atoms. For sake of simplicity the presence of polarization in PbTiO<sub>3</sub> is represented here only by the shift of the Ti atoms, without any loss of generality. It is now necessary to introduce a three-dimensional system of reference in the representative unit cell. The axis  $X_3$  has been chosen aligned with the polarization direction, as illustrated in Figure 1.3.

If we apply a mechanical stress  $\sigma_3$  directed along  $X_3$  to the surface of the cell of normal  $X_3$ , the cell will strain along  $X_3$  with the result of increasing the distance between the atom of titanium and the geometrical centre of the unit cell. This can be viewed as an increase of the polarization of the material from the spontaneous

**Figure 1.1** Planar representation of PbTiO<sub>3</sub>.

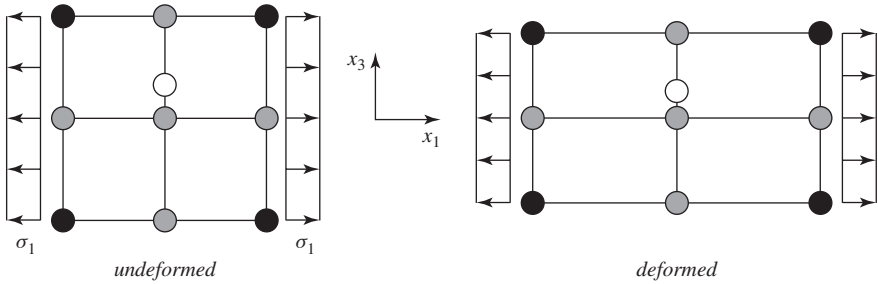


**Figure 1.2** Tridimensional representation of  $\text{PbTiO}_3$ .



**Figure 1.3** Undeformed and deformed configuration of a  $\text{PbTiO}_3$  cell under the action of a stress  $\sigma_3$  applied along the direction of polarization  $X_3$ .





**Figure 1.4** Undeformed and deformed configuration of a  $\text{PbTiO}_3$  cell under the action of a stress  $\sigma_1$  applied along a direction  $X_1$  normal to the direction of polarization.

polarization  $P_s$  to  $P_s + \Delta P$  measured along the  $X_3$  axis, and for this reason is identified as the component  $\Delta P_3$  of the polarization vector. For small values of the applied stress the  $\Delta P_3$  is proportional to  $\sigma_3$

$$\Delta P_3 = d_{33}\sigma_3, \quad (1.5)$$

with  $d_{33}$  a positive constant with two pedices indicating the direction of polarization ( $X_3$ ) and that of the applied stress ( $\sigma_3$ ).

In contrast if the mechanical tensile stress is produced along a direction ( $X_1$ ) normal to polarization, the effect on the displacement of the titanium atom with respect to the centre of the cell will be the opposite (Figure 1.4), resulting in a negative  $d_{31}$

$$\Delta P_3 = d_{31}\sigma_1. \quad (1.6)$$

An identical behaviour is observed along the third axis  $X_2$  with

$$\Delta P_3 = d_{32}\sigma_2, \quad (1.7)$$

with  $d_{32} = d_{31}$ . In the case of a shear stress  $\sigma_5$  the  $\text{Ti}^{4+}$  is displaced on the right (Figure 1.5), aligned with  $X_1$ , resulting in a positive coefficient  $d_{15}$

$$\Delta P_1 = d_{15}\sigma_5. \quad (1.8)$$

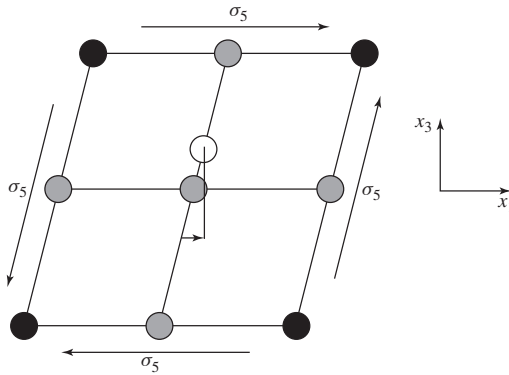
An identical behaviour can be observed in the case of a shear stress  $\sigma_4$  for which we have

$$\Delta P_2 = d_{24}\sigma_4, \quad (1.9)$$

with  $d_{24} = d_{15}$ .

We also recognize that no variation in the polarization of the crystal structure can be obtained if applying a  $\sigma_6$  stress, that is a shear stress contained in the  $X_1X_2$  plane.

In conclusion by ordering the  $d_{ij}$  coefficients in a  $3 \times 6$  matrix and recognizing all the cases where no effect of variation of polarization in  $X_3$  or of polarization



**Figure 1.5** Deformed configuration of a  $\text{PbTiO}_3$  cell under the action of a shear stress  $\sigma_5$ .

along  $X_1$  and  $X_2$  is observed, we obtain the direct piezoelectric coupling matrix  $\underline{d}$

$$\underline{d} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix}, \quad (1.10)$$

with

$$\underline{\Delta P} = \underline{d} \underline{\sigma}, \quad (1.11)$$

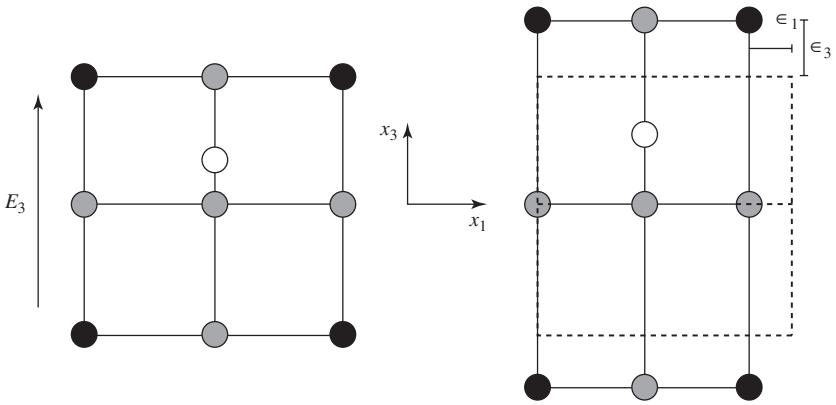
being  $\underline{\Delta P} = \{\Delta P_1, \Delta P_2, \Delta P_3\}^t$  and  $\underline{\sigma} = \{\sigma_1, \sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6\}^t$ . Since the vector  $\underline{\sigma}$  lists the second-order tensorial components of the stress, we will recognize in the next section that the operator  $d$  has the mathematical nature of a third-order tensor. We also notice that for the equivalence of the component of the vector  $\underline{\sigma}$  with the tensorial component of stress  $\sigma_1 = \sigma_{11}, \sigma_2 = \sigma_{22}, \sigma_3 = \sigma_{33}, \sigma_4 = \sigma_{23} = \sigma_{32}, \sigma_5 = \sigma_{13} = \sigma_{31}, \sigma_6 = \sigma_{12} = \sigma_{21}$ .

In an analogous way the physical reason for the converse piezoelectric effect could be investigated.

The effect of the application of an electric field along the  $X_3$  direction will be the moving in the positive direction of  $X_3$  the positive charges and in the opposite direction the negative charges (Figure 1.6). This will result in stretching of the cell along  $X_3$  and squeezing along  $X_1$  or  $X_2$ . In terms of strain components  $\epsilon_1, \epsilon_2$  and  $\epsilon_3$  we will then obtain

$$\begin{aligned} \epsilon_3 &= d_{33} E_3 \\ \epsilon_1 &= d_{13} E_3 \\ \epsilon_2 &= d_{23} E_3, \end{aligned} \quad (1.12)$$

with  $d_{13} = d_{23}$  for reasons that are analogous to those discussed for the direct piezoelectric case.



**Figure 1.6** Deformation of a  $\text{PbTiO}_3$  unit cell under the effect of an electric field  $E_3$  applied in the direction of polarization  $X_3$ .

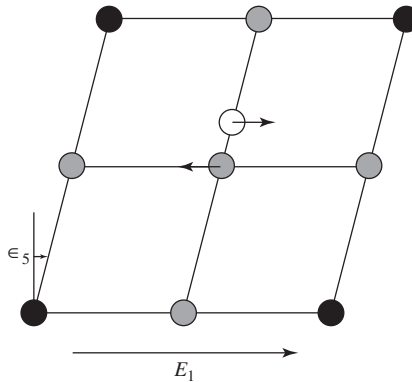
Similarly, by applying an electric field  $E_1$  along the  $X_1$  direction, due to the laws that regulate the action of an electric field on a charged particle, the centre of positive charges (in our simplification the Ti atom) will move along  $X_1$  while the centre of negative charges will move in the opposite direction. Due to the position of Ti along  $X_3$  this will result in a positive shear strain of the unit cell as represented in Figure 1.7. In this case we will obtain

$$\epsilon_5 = d_{51} E_1 \tag{1.13}$$

and in analogous way the remaining coefficient would be obtained

$$\epsilon_4 = d_{42} E_2, \tag{1.14}$$

with  $d_{42} = d_{51}$ .



**Figure 1.7** Effect of the application of an electric field  $E_1$  in the direction  $X_1$  normal to the polarization direction.

In this case, by putting in an ordered matrix for all the  $d$  constants we obtain a  $6 \times 3$  matrix, which happens to be the transpose of the matrix obtained for the direct piezoelectric coupling

$$\underline{d}^t = \begin{bmatrix} 0 & 0 & d_{13} \\ 0 & 0 & d_{13} \\ 0 & 0 & d_{31} \\ 0 & d_{51} & 0 \\ d_{51} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad (1.15)$$

being  $d_{13} = d_{31}$ ,  $d_{15} = d_{51}$ , with

$$\underline{\epsilon} = \underline{d}^t \underline{E} \quad (1.16)$$

where  $\underline{E} = \{E_1, E_2, E_3\}^t$  is the electric vector and  $\underline{\epsilon}$  is the vector that links the second-order tensorial components of the strain  $\underline{\epsilon} = \{\epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4, \epsilon_5, \epsilon_6\}^t$ . For the strain tensorial components it is worth noting that  $\epsilon_1 = \epsilon_{11}$ ,  $\epsilon_2 = \epsilon_{22}$ ,  $\epsilon_3 = \epsilon_{33}$ ,  $\epsilon_4 = 2\epsilon_{23} = 2\epsilon_{32}$ ,  $\epsilon_5 = 2\epsilon_{13} = 2\epsilon_{31}$ ,  $\epsilon_6 = 2\epsilon_{12} = 2\epsilon_{21}$  for the well known relation between the engineering shear component  $\gamma_{ij}$  and the tensorial component  $\epsilon_{ij}$  of the strain tensor, for which  $\gamma_{ij} = 2\epsilon_{ij}$  with  $i, j = 1, 2, 3$ .

The circumstance that the piezoelectric matrix obtained for the direct effect is the transpose of the one obtained for the converse effect makes symmetric the overall constitutive matrix. This evidence is related to the conservative nature of both elastic and electric forces.

The characteristics of the piezoelectric coupling matrix are variable according to the class of crystal for which the piezoelectric behaviour is considered, as reported in [12]. The structure presented in the example below is representative of the  $4mm$  tetragonal system and well represents the behaviour of PZT ceramics that are one of the most common piezoelectric materials.

In this intuitive explanation of the direct and the converse piezoelectric effect we can return to (1.3) and re-write it in matrix form as

$$\underline{D} = \underline{\underline{\epsilon}}_0 \underline{E} + \underline{P}, \quad (1.17)$$

and also

$$\underline{D} = \underline{\underline{\epsilon}}_0 \epsilon_r \underline{E}, \quad (1.18)$$

by the introduction of the relative permittivity coefficient  $\epsilon_r$ . The presence of an additional polarization  $\underline{\Delta P}$ , due to the direct piezoelectric effect, also can be viewed as an additional term to the electric displacement vector  $\underline{D}$ . This means that the final form for the expression of the electric displacement can be written as

$$\underline{D} = \underline{\underline{\epsilon}} \underline{E} + \underline{d} \underline{\sigma}, \quad (1.19)$$

where  $\underline{\underline{\varepsilon}}$  is the dielectricity (permittivity) matrix obtained for zero stress, which for the tetragonal system of symmetry  $4mm$  can be written as

$$\underline{\underline{\varepsilon}} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \quad (1.20)$$

with  $\varepsilon_{11} = \varepsilon_{22}$ .

In an analogous way the expression of strain obtained from the piezoelectric effect can be extended for including the strain due to stress assuming a linear elastic behaviour of the piezoelectric material:

$$\underline{\underline{\epsilon}} = \underline{\underline{F}} \underline{\underline{\sigma}} + \underline{\underline{d}}^t E \quad (1.21)$$

where  $\underline{\underline{\sigma}}$  is the stress vector and  $\underline{\underline{F}}$  is the compliance matrix obtained for a generalized Hooke law.

From the elastic viewpoint, by assuming the same pattern of material distribution, the material is considered to be transversely isotropic, being the plane normal to the direction of polarization, which is the isotropy plane. In this case

$$\underline{\underline{F}} = \begin{bmatrix} F_{11} & F_{12} & F_{13} & 0 & 0 & 0 \\ F_{12} & F_{11} & F_{13} & 0 & 0 & 0 \\ F_{13} & F_{13} & F_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & F_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & F_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & F_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \quad (1.22)$$

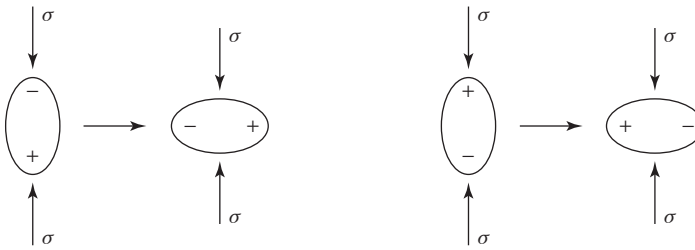
with  $F_{66} = 2(F_{11} - F_{12})$ .

In all the preceding steps we have assumed that the behaviour of the material was linear.

### 1.3.1.2 Polarization Reversal in a Crystal

By applying an electric field on a crystal the charged particles have a tendency to displace, because they are loaded by the electrostatic forces. When a polarized crystal is charged with an electric field opposite to the polarization direction, at the coercive level of the field the polarization will be reversed and a sudden change in the shape of the crystal will occur during the instability phase as it changes from one crystal state to another. The electrostatic forces have reached a level sufficient to change the shape of the crystal by shifting the position of positive and negative charges.

In a piezoelectric crystal such as  $\text{BaTiO}_3$  material there might be six different possible poling directions. A change from one polarization direction to another can occur as mentioned above by applying an electric field (ferroelectric property) or by applying a stress (ferroelastic property) at appropriate levels. The latter effect



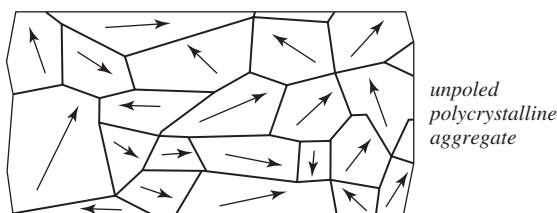
**Figure 1.8** Change in the direction of polarization for the effect of an applied stress along the direction of polarization.

can be explained by examining the mechanical response of a dipole loaded in compression along its axis of polarization (Figure 1.8). No matter what the original positive direction of polarization is, the dipole will rotate and displace with an axis of polarization normal to the applied stress in order to attain a stable configuration.

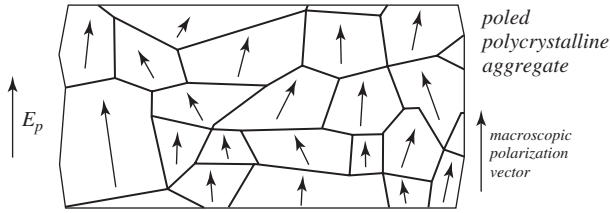
### 1.3.1.3 Polycrystalline Aggregates

Piezoelectric properties require that the material is polarized. As discussed previously, a number of crystalline classes of materials are intrinsically polarized (spontaneous polarizations). The piezoelectric properties of a single crystal were discussed above, but it is important to consider that the piezoelectric materials are often present, and currently produced, as aggregates of crystals, that is in polycrystalline form, as shown in Figure 1.9.

Usually the elemental crystals that constitute the aggregate combine to each other in such a way that the direction of polarization in each crystal differs from the others, such that at a global level the aggregate is not polarized. Polarization of the material can be obtained by applying an electric field of a significant amplitude (coercive field) so that each crystal changes its polarization direction along the applied field and, at the removal of the external field, the material remains with a degree of polarization. It is worth noting that, because for every crystal only six directions of polarization are possible, the level of polarization of the aggregate can never reach that of a single crystal. In Figure 1.10 it is possible to note that, after



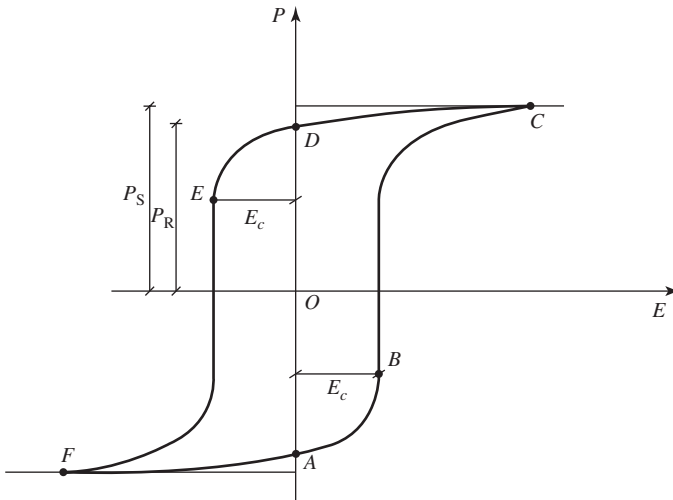
**Figure 1.9** Direction of polarization in the crystals of an unpoled ceramic aggregate.



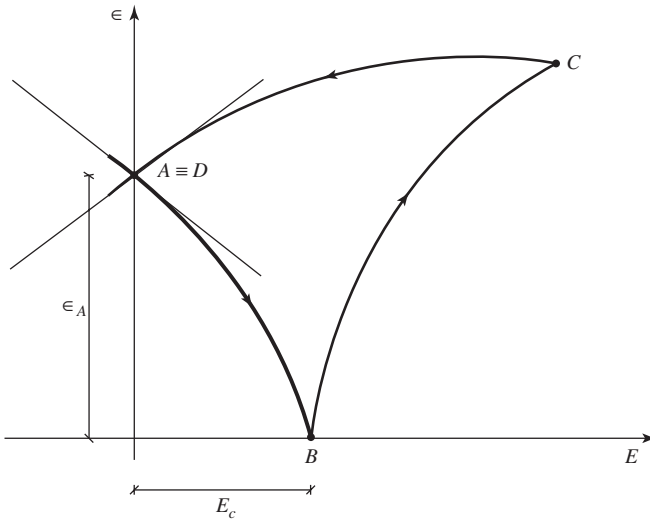
**Figure 1.10** Polarization of a polycrystalline aggregate.

polarization the elemental poling directions are mostly aligned in the direction of the coercive field.

Let us now follow the process of polarization reversal in a polycrystalline material such as PZT by assuming that the material has been polarized in the negative direction of  $X_3$ . In Figure 1.11 the variation of the intensity  $P$  of the polarization vector is illustrated versus the intensity of the electric field  $E$  in the applied  $X_3$  direction. Starting from point  $A$  in the diagram we apply a positive electric field and see a decrease of the polarization  $P$  until the point  $B$ , where the coercive level of the electric field  $E_c$  is reached. At this point the process of polarization reversal in the polycrystal starts to proceed up until the saturation level  $P_s$  is obtained (point  $C$ ). By diminishing the field a residual polarization  $P_R$  is obtained at zero electric field (point  $D$ ). The polarization now has been completely inverted. A symmetric process can be observed by applying negative electric fields and by following the points  $E$ ,  $F$  and finally  $A$  of the diagram. The scheme reported in Figure 1.11 is



**Figure 1.11** Variation of polarization of a piezoelectric polycrystalline in terms of the applied electric field.



**Figure 1.12** Effect of polarization reversal on the strain of a piezoelectric polycrystal.

obtained from experimental diagrams in which the level of the coercitive field  $E_c$  is often not a single value but a range of values.

It is important to note that if the material is charged by an electric field of increasing intensity, one can reach the dielectric strength of the material, that is the level sufficient to produce a burst of current which bridges the metal electrodes. When the material reaches the dielectrical strength an irreversible failure occurs.

We now move to consider the effect of the polarization reversal in terms of a strain component. Let us follow the process with the help of Figure 1.12 where the strain–electric field behaviour is illustrated for the component of strain in the polarization direction  $X_3$ , produced by the application of an electric field in the same direction.

The process starts at point  $A$  at which the material has already been polarized in the negative direction. The process of polarization has created a residual strain level  $\epsilon_A$ . Let us now charge the material with a positive electric field, creating a compression in the material and a reduction of the strain level until the point  $B$ , where the field reaches the level of polarization. Two observations can be made at this point. First, after a linear behaviour between  $\epsilon$  and  $E$ , for higher intensity of  $E$  the curve starts to exhibit nonlinear behaviour. This means that the piezoelectric coefficient, in this case  $d_{33}$ , starts to be field dependent,  $d_{33} = d_{33}(E)$ , and that the assumption of a linear behaviour becomes less and less accurate for high fields. Second, the residual strain  $\epsilon_A$  could be considered as an offset and, after the first polarization, the diagram could be drawn by assuming that  $A$  is coincident with the zero.

After reaching point  $B$  the material starts changing the polarization until the point  $C$ , which can be considered as the saturation level of polarization. During the  $B$ – $C$  range of the curve the reversal of polarization causes the strain to increase

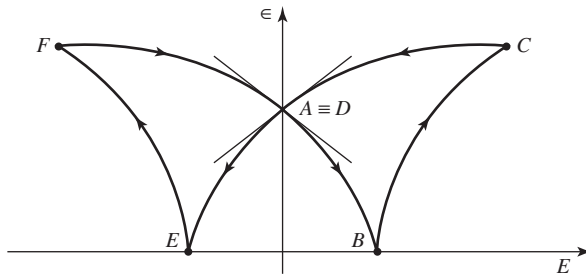


as the field is increased. Now if we start diminishing the field from point  $C$  to point  $D$  the material behaves in accordance with its new direction of polarization and a decrease in strain is observed. Also in this case it is important to note that the strain–field behaviour is linear only for low values of  $E$ , that is close to the point  $D$ . Although the points  $A$  and  $D$  occupy the same place on the diagram it is important to note that  $A$  represents a state of the material with negative polarization, whereas  $D$  represents the material with a positive polarization.

From this point onwards we proceed in symmetrical conditions. From  $D$  to  $E$  a negative strain is observed for negative  $E$  up until the coercive field is obtained once again, but for negative values. Then the polarization reversal occurs and at the point  $F$  the saturation level can be assumed. The material can proceed to  $A$  from  $F$  by decreasing the amplitude of the negative electric field.

Butterfly-shaped curves of the strain–electric-field diagrams of piezoelectric materials are influenced by the presence of a mechanical loading that, as already mentioned, has an effect on the reversal of polarization. In the strain–electric-field diagram of Figure 1.13 the nonlinear nature of the piezoelectric coupling is clearly illustrated. This means that for high-level fields this characteristics has to be properly taken into account in the analyses. Nevertheless around the states described by point  $A$  and  $D$  (which we recall have opposite polarization directions) it is possible to consider the piezoelectric coupling as linear behaviour, that is assuming that the piezoelectric coefficients are not dependent on the electrical field. In Figure 1.13 the values of  $d_{33}$  in  $A$  or  $D$  correspond to the slopes of the tangent to the strain–electric-field diagram. This assumption is one of the basic hypotheses of the linear theory of piezoelectricity, developed by Voigt [13] on the basis of the preliminary experiences described in the previous sections, currently used in many applications and reasonably accurate for low electric fields.

An extended theory on piezoelectricity can be found in the classic books by Tiersten [14], Cady [15] Mason [16] and in [17] authored by Mindlin. Other important aspects of the behaviour of piezoelectric materials, such as hysteresis (see e.g. [18]) or crack propagation phenomena (well addressed by Shindo [19]), are not treated here but the reader is advised to give them the attention they deserve.



**Figure 1.13** Complete strain–electric-field diagram in the presence of polarization reversal in a piezoelectric polycrystal.

### 1.3.2 Electrostrictive Materials

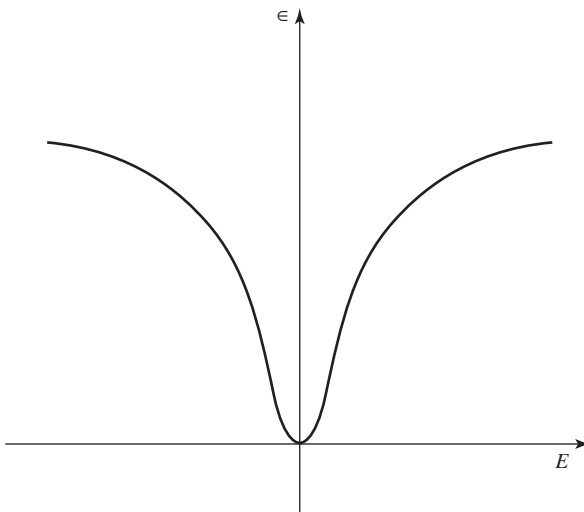
The previous section clarified that in order to exhibit a piezoelectric behaviour the material needed to exhibit polarization, both for single crystal forms and for polycrystalline aggregates. It should be recalled that materials such as lead zirconate titanate, a typical piezoelectric material, lose piezoelectricity if treated above the Curie temperature. At that temperature the material evolves into a form of higher symmetry and loses its natural polarization. In the absence of polarization another physical coupling between the electric and the elastic behaviour of a dielectric material, called electrostriction, can be observed. Electrostriction is characterized by a quadratic dependence of the strain from the applied electric field:

$$\epsilon = mE^2, \quad (1.23)$$

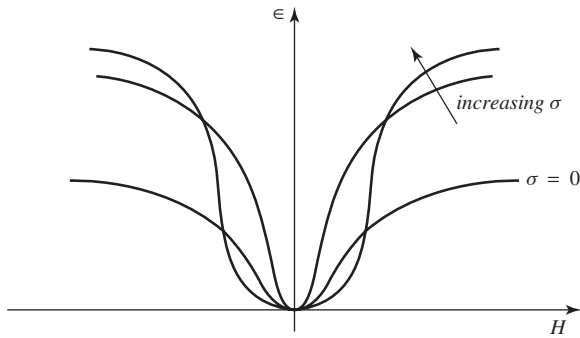
where  $m$  is the electrostrictive constant, as illustrated in Figure 1.14. Although performance of an electrostrictive material is very sensitive to temperature, the electromechanical coupling of materials such as PMN-PT (lead magnesium niobate with 10% of lead titanate) can reach values three times larger than PZT (see [10]).

### 1.3.3 Magnetostrictive Materials

In analogy with experiences that demonstrate the presence of the converse effect in piezoelectric material, experimental evidence shows that some materials, namely ferromagnetic, exhibit strain when subjected to a magnetic field. This effect, called the magnetostrictive effect, has the characteristic that no matter what the sign of



**Figure 1.14** Strain–electric-field diagram in an electrostrictive material.



**Figure 1.15** Strain–magnetic-field diagram in a magnetostrictive material under increasing compression.

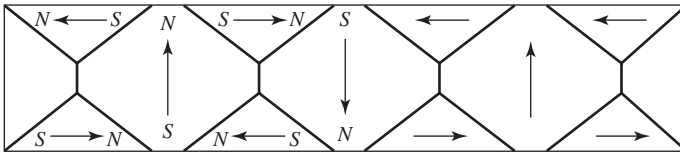
the magnetic field  $H$ , the result is always positive (elongation strain). It has also been shown experimentally that a compressive stress applied in the same direction of the magnetic field has a significant impact on the response.

Figure 1.15 shows the strain–magnetic-field curves obtained for Terfenol D (a Terbium Iron compound developed at Naval Ordnance Laboratories) in the presence of different compressive stresses. It is useful to investigate the reasons for their different physical behaviour, which resembles the nonlinear behaviour of electrostrictive material. Without going into the topic in too much detail (as done in [20]), one can just argue that the reasons for this behaviour are based on the physical nature of ferromagnetic materials and in particular their organization in magnetic domains.

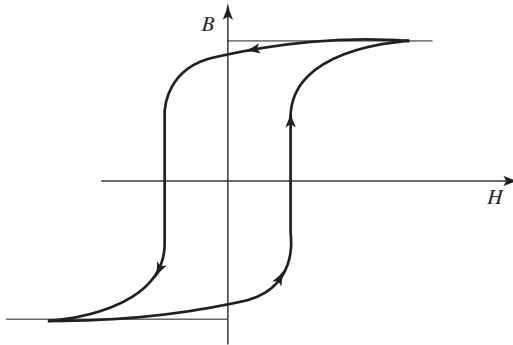
As well known from physics, magnetic phenomena cannot be explained in terms of positive or negative charges but in terms of magnetic dipoles. In fact, although north and south poles of a permanent magnet or of a solenoid can be identified, it is impossible to separate north from south and isolate a magnetic charge. In classic physics, the presence of magnetism can be explained by assuming the presence of an electric current at the atomic level, as the ones possibly generated by the electrons moving around atomic nuclei. One can assume at a macroscopic level the presence of an internal magnetization equivalent to those produced for each internal current. These magnets add up to the one already present if an external magnetic field is applied.

It is possible to observe experimentally that crystal (mono- and polycrystals) of ferromagnetic materials are organized in domains, which are regions of the material where the magnetic dipoles are parallel (Figure 1.16). It is also possible to observe that there are certain preferable directions along which the domains align their magnetization. In the material along the same direction there are the same number of domains with opposite orientation, so that, in absence of an external magnetic field or of previous cycles of magnetization, no net magnetic moment is present.

Under the effect of an external field the domains are subjected to a complicated series of phenomena that leads either to domain rotation or motion of the



**Figure 1.16** Structure of magnetic domains in a ferromagnetic material.



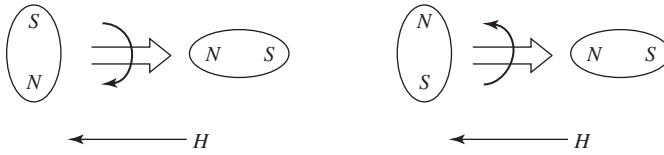
**Figure 1.17** Magnetic polarization diagram in a ferromagnetic material.

walls between one domain and another. In this circumstance a magnetization of the material is produced. At the removal of the external magnetic field  $H$ , a residual magnetization remains present in the material. A cycle of magnetization can be easily described. For polycrystals it resembles the polarization cycle of piezoceramic materials, with the vector of magnetic induction  $B$  (Figure 1.17) playing a role similar to the electric polarisation  $P$ .

In order to study the mechanical effect in terms of the induced strain produced by the application of an external magnetic field  $H$  let us concentrate on single magnetic dipoles. If a magnetic field is applied in the direction of magnetization of the dipole, no significant effect is created apart from a negligible elongation. In contrast, if the field is applied in the direction normal to that of the magnetisation, rotation of the dipole occurs, with a net geometrical effect necessary to finally align the dipole with the induced magnetic field (Figure 1.18).



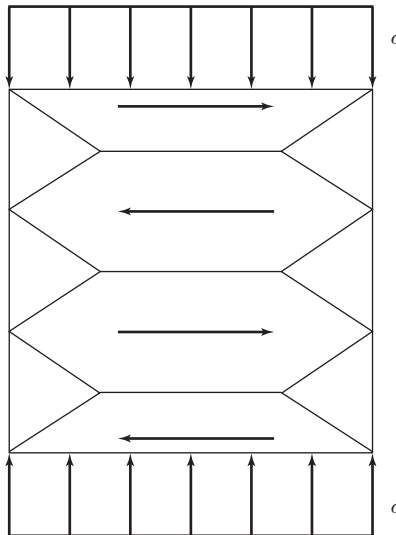
**Figure 1.18** Effect on a magnetic dipole of a magnetic field  $H$  applied in the direction normal to polarization.



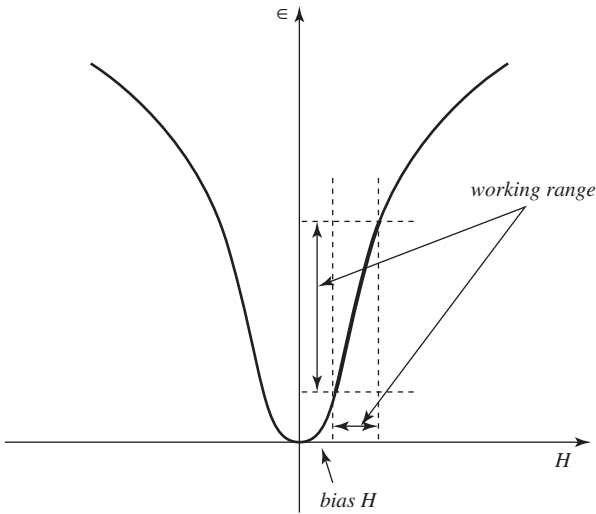
**Figure 1.19** Alignment of the magnetic dipole to the magnetic field for both positive and negative polarizations.

It is interesting to note that no matter what the orientation of the magnetization, the final geometrical effect is the same, an elongation in the direction of the magnetic field (Figure 1.19). This can also be viewed as applying an opposite magnetic field to the same dipole. This circumstance can explain the symmetry of the strain–magnetic-field diagrams of Figure 1.15 with respect to the strain axis. In fact one can expect that the rotation of the magnetic dipole corresponds to an expansion in the direction of the applied magnetic field.

In order now to explain the role of the compression stress on the induced strain produced by the magnetostrictive effect, recall the arrangement of domains in a ferromagnetic material, they combine themselves in such a way as to produce a net zero magnetization. When a stress field is applied the domains are arranged in such a way that the direction of magnetization becomes preferentially normal to the compression stress (Figure 1.20). This can be explained as a sort of buckling effect of domains that favour the dipoles to orient themselves in order to find a stable configuration.



**Figure 1.20** Alignment of the magnetic domains in the direction normal to the applied stress.



**Figure 1.21** Linear working range of the constitutive behaviour of a magnetostrictive material.

It is clear that the presence of compression produces a higher percentage of domains oriented in a direction orthogonal to the applied magnetic field, thus enhancing the elongation strain effect produced by the magnetic field. In contrast it is clear that in order to have a significant net elongation the compressive strain produced by the compressive stress needs to be overcome by the effect of the magnetic field. This fact is especially evident for low fields, for which the diagram corresponding to the cases where compression was applied shows negligible elongation strain. This means that an intermediate level of compression should be sought that balances the negative effect of compressive strain with the beneficial effect of domain realignment in an optimal fashion.

Actuation devices based on the magnetostrictive effect usually impose a bias magnetic field so as to let the material work around an almost linear path of its constitutive strain/magnetic field relations (Figure 1.21). In this case the coupled constitutive relation may be linearized and a piezomagnetic linear coefficient  $d_{33}^H$  set up, so that

$$\epsilon_{33} = d_{33}^H H_3. \quad (1.24)$$

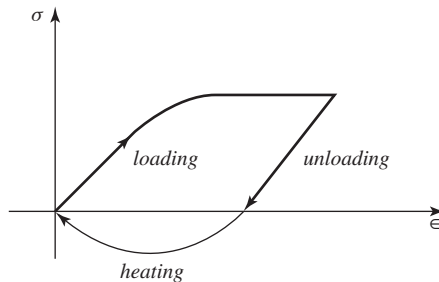
The magnetostrictive effect has been widely used for the production of axial actuators. A significant advantage from a practical viewpoint is a relatively high Young modulus with respect to ceramic materials. As a counterpart one has to highlight that, due to the intrinsic nature of the magnetic field, only devices based on the typical cylindrical shape of solenoids can be set up in most cases.

### 1.3.4 Shape Memory Alloys

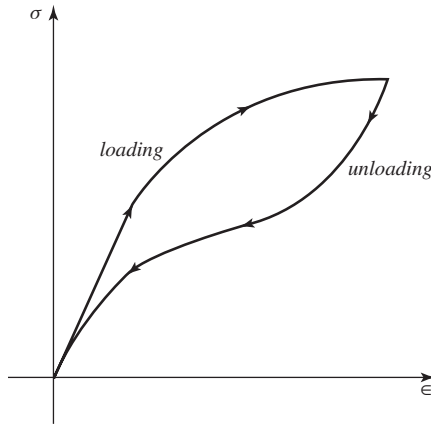
The shape memory effect was first reported extensively in 1951 by Chang and Read [21] for certain classes of metal alloys. Since then shape memory alloys (SMA) have attracted the attention of researchers and engineers for the specific feature of their thermomechanical behaviour. The shape memory effect is observed when a specimen of SMA is loaded, in a low-temperatures range, above an apparent plastic limit and then unloaded. The residual strain measured at zero stress can be recovered upon raising the temperature of the material and then letting it recover the original temperature, as shown in Figure 1.22. Very large strains of around 10% can be recovered thanks to the shape memory effect.

A second effect, called the pseudoelastic effect, is observed in the high-temperature range and below a characteristic temperature termed  $M_d$ , when a specimen of SMA, loaded above an apparent plastic limit, recovers the ‘plastic’ strain during the unloading following the pattern represented in Figure 1.23. Following an apparent plastic deformation the material returns to its original shape after describing a hysteresis loop. This is the reason for the ‘pseudo’ prefix in the name of the effect: in fact the recovery of the original shape (typical of elastic behaviour) is obtained by following a dissipative cycle (while elastic behaviour is conservative). A dissipative constitutive behaviour, which allows a large strain but includes a complete recovery of the initial configuration, is a very peculiar and attractive feature for many applications.

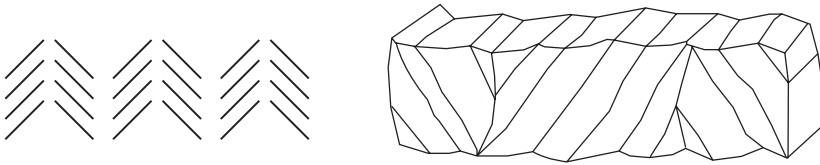
These two macroscopic effects, the first one obtained in a combination of mechanical and thermal loading and the second obtained at constant (and high) temperature, can be explained by looking at the microscopical structure of these materials, the corresponding aggregation phases and the transformation from one phase to other. In the absence of stress a shape memory alloy at high temperature is stable in its austenitic phase. When decreasing the temperature a transformation of the austenite into a martensite phase is observed. This phase change is characterized by the generation of no strain in the material. This is also due to the particular nature of the transformation that generates multiple martensitic variants



**Figure 1.22** The stress–strain diagram of the shape memory effect.



**Figure 1.23** The stress–strain diagram of the pseudoelastic effect.



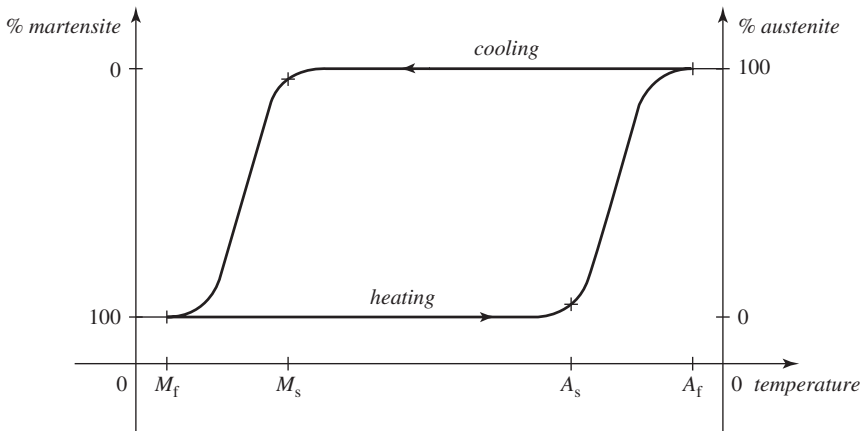
**Figure 1.24** The structure of twinned martensite.

and twins. These variants, all equivalent from a crystallographic viewpoint, self-accommodate themselves in twin structures, as represented in Figure 1.24.

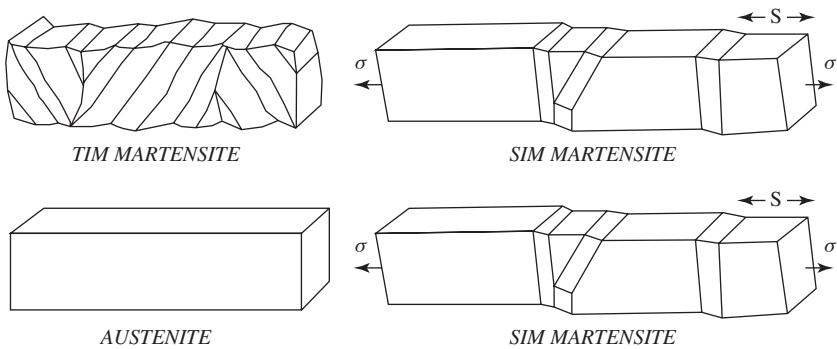
Four temperatures characterize the transformation from austenite to martensite (twinned temperature induced TIM martensite) and vice versa:  $M_f$ , martensite finishes, below which only martensite is present in the alloy;  $M_s$ , martensite starts, the temperature at which in the cooling process martensite starts to appear;  $A_s$ , austenite starts, the temperature at which in the heating phase austenite begins to be formed;  $A_f$ , austenite finishes, above which only austenite is present in the alloy. The transformation is represented in Figure 1.25, where the percentage of austenite or martensite is reported versus temperature.

In order to provide a basic physical explanation for the shape memory and pseudoelastic effects the behaviour of twinned martensite and austenite under mechanical loading is considered. The twinned structure of the temperature-induced martensite presents variants and twins all equivalent from the crystallographic viewpoint but with random orientation (Figure 1.26). At low temperatures under an uniaxial loading the material starts to detwin and create a single variant of martensite aligned with the axis of loading. This form of martensite is often called stress-induced martensite (SIM). This process produces high strain with respect to the increment of stress applied, resulting in an apparent plastic deformation. In fact, during the unloading, only a small elastic strain is recovered. If the process





**Figure 1.25** Percentage of austenite and martensite as a function of temperature.

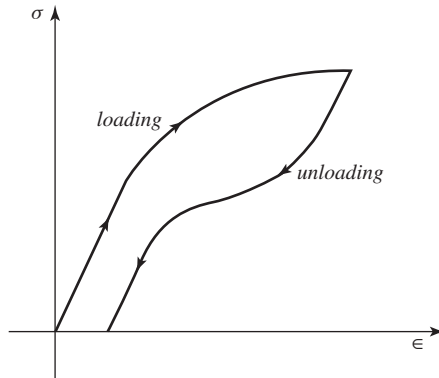


**Figure 1.26** Generation of detwinned martensite from twinned martensite or austenite by the application of a stress.

has been performed at low temperature there is no possibility to create the twinned structure again.

In order to obtain the shape memory effect we now raise the temperature and the stress-induced martensite will transform into the austenite phase that has not variants or twins. In this way the material recovers its original shape. At this point the temperature can be decreased again below  $M_f$  to obtain the material in the original configuration.

In the analysis of the behaviour of the austenite under loading it is now necessary to explain the pseudoelastic effect. At high temperature ( $T > A_f$  and  $T < M_d$ ), where austenite is stable, we subject a specimen of the alloy to an axial loading. At a critical level of stress, an apparent yielding stress, the crystal phase transforms from the body-centred austenite to the face-centred martensite. The presence of stress does not allow the process of self-accommodations of randomly oriented



**Figure 1.27** Partial pseudoelastic effect.

variants and twins and produces a single variant martensite, that is a detwinned stress-induced martensite. This process induces an apparent plastic deformation.

During unloading the strain induced in the transformation from austenite to stress-induced martensite cannot be maintained because at high temperatures martensite is not stable. Once the load is removed the material transforms back into austenite, recovering the (apparently) plastic strain produced under the effect of the load.

Between  $A_s$  and  $A_f$ , where a percentage of martensite is present together with the austenite, the pseudoelastic effect could be only partial, as shown in Figure 1.27.

As with most metals, shape memory alloys also experience a real plasticity behaviour, that is, once a real yielding stress is reached no recovery of plastic deformation of the kind explained above is observed at temperature  $T > M_d$  or when maximum recoverable strains are exceeded. A mathematical model of the constitutive behaviour of shape memory alloys has been proposed by Brinson [22], and a comprehensive treatise on the topic can be found in the book by Lagoudas [23]. Typical SMA are Cu-tu and Ni-Ti alloys, as the NiTiNol, developed at the Naval Ordnance Laboratory.

## 1.4 Motivations for the Use of Smart Structure Technologies

In the previous sections it has been shown that in active materials such as piezoelectric materials, magnetostrictives or shape memory alloys, induced strain fields can be produced, respectively, by applying electric or magnetic fields or by a specific combination of mechanical and thermal fields. This induced strain can be viewed as the generator of the actuation capability. Conversely in piezoelectric materials it is possible to see the generation of an electric charge or current under the action of a stress field. This effect can be used for generating a sensing capability. The piezoelectric effects also can be viewed as a powerful source of power transduction from different physical fields. Moreover a proper combination of sensing

and actuation will make feedback control possible. In other words active materials such as those just mentioned allow additional functions, such as actuation, sensing, feedback control actions and power transduction.

This behaviour, resulting from an optimal combination of physical (natural) phenomena and good technical capabilities of analysis, design and implementation, is very interesting in respect of structural mechanics science and technology, but on its own will not lead to the technology of smart structures being developed in commercial applications with a real impact on the market. However, why should engineers use smart structures in real practice and incorporate this technology in large systems or in simple components? One can identify at least four areas of application directly linked to smart structures:

- monitoring of the structural integrity of mechanical systems;
- shape morphing;
- vibration control (and accurate location);
- energy harvesting.

Actually these areas of application do not cover the entire spectrum possible. In fact one might also include, as a major area of present and future application, motors based on some 'smart' capability (such as ultrasonic motors) or micropositioning devices. In the following sections we will try to explain the advantages for using smart structures in real practice. An attempt will be made towards understanding the demand for such technology, the potential benefit that it can produce, and the potential commercial impact.

## 1.5 Monitoring Structural Integrity

Structural systems are designed to have no failures during their operational life. For this reason the failure levels of structural materials are investigated and measured accurately. Design procedure guarantees that these level are not reached under the worst combination of expected loading and a safety margin is also taken into account. All known failure modes are usually considered, i.e. not only static failure but fatigue as well. Depending upon the function of the structure considered, it is assumed that no structural failure will occur in the expected life of the component or, in some fields such as aeronautics, that no failure will occur between two structural inspections.

In fact structural safety is of utmost importance where critical functions are performed by the engineering system or, and even more so, when human life is involved, such as in passenger transportation by car, train, ship or aeroplane. In a car or aeroplane the failure of a structural component can well induce a dramatic failure of the entire mechanical system.

In the sectors of engineering where structures are very critical, such as in aeronautics, and the saving of weight induces very low margins of error in structural behaviour, inspections are assumed to be performed at prescribed time intervals of

the operative life of the aeroplane. For assuring the performance of a lightweight aircraft structure in the severe mechanical environment that characterizes its life (high loading levels and cyclical nature of the forcing action) one can assume that in the maintenance programme of the plane structural inspections will be undertaken. During maintenance the aeroplane is taken out of service and this has an impact on costs because the operative life is shortened. The possible reduction of maintenance time and cost therefore is a real incentive for the introduction of integrating a structural health monitoring system in the structural system and operating it continuously during the operational life of the aeroplane.

Structural health monitoring systems would be applicable in many other areas of engineering. For example, in space transportation systems for human flight, the monitoring of structural integrity and, more in general, the management of the 'health' of the system has become a general requirement for future vehicles, especially if reusable. Another important application is for structural systems that are designed with good safety margins, such as in the case of the automotive industry, where there is the opportunity for detecting in time a mechanical failure in a critical component, such as wheels, brakes and steering wheels, which could dramatically reduce the loss of life. In addition, industrial plants, or any engineering component within a structure, such as the air conditioning system in a building, can profitably introduce structural health monitoring with a view to better and faster maintenance and reduction of damage produced by unexpected failures.

From the examples cited above, the introduction of structural integrity monitoring of mechanical systems can be considered as a worthwhile use of smart structures. In practice the basic element of a structural health monitoring system can in fact be a sensing device made from some type of active material (e.g. piezoceramics). The working principle of monitoring is the sensing capability of the material itself and, as a consequence, of the passive structural component to which the sensor is attached or integrated. Piezoelectric materials have been used successfully in research activity relevant to this particular field of application, where their excellent sensitivity and their capability of working at very high structure frequencies are especially suitable, making possible the sensing of a time varying stress field. A comprehensive overview of the field can be found in a review article by Park *et al.* [24].

In order to transform the electrical response of pressure mechanically stimulated in the monitoring of the structural health of a system – or in other words – in the evaluation of its possible mechanical failure, a clear definition of structural damage is required. This is needed for focusing the target of the application and restricting the monitoring only to the physical quantities that are really critical for the system. Once the target of the monitoring has been established, the sensing signals produced during the operative life are analysed and compared in order to detect any variation of the response that could have been produced by the presence of a failure.

In practice it has been proposed to examine any variation of structural response in both the time and frequency domains. As an example any variation of an engine frequency detected by observing the modification of the frequency response spectrum of a system could be related to a failure both from the qualitative and the

quantitative points of view. In this application, as an alternative with respect to active structural materials such as piezoelectric ceramics, other sensor devices have been proposed, in particular fibre optics. Although due to the use and success of optical fibres sensors for monitoring structural behaviour they have frequently been compared with the performance of other smart materials, one should consider that the mechanical behaviour of such materials is significantly lower than the other smart materials, namely piezoceramics and shape memory alloys.

Monitoring of structural integrity is a complicated engineering function. In fact in conjunction with the presence of sensing device, a diagnosis algorithm should be set up and made available to the final user as a warning or alarm device. This also means that the information produced by the sensors should be received and treated properly, particularly for the purpose of avoiding false alarms.

Although structural health monitoring is a capability that is much more complex than the sensing functionality possessed by an active material, one should not forget that for this application the other capabilities of the active materials, such as the actuation, are not used. If we assume in principle, however, that a smart structure should demonstrate several capabilities, such as sensing, actuation, feedback control, etc., then in practice the exploitation of only one of these capabilities could be enough to generate a structural system that is fundamentally different from traditional structures. The same will be true for the shape morphing application, where basically only the actuation capability of active materials is really exploited.

## 1.6 Shape Morphing

By assuring support to all the parts that constitute an engineering system, structures are often also responsible of manifesting the shape of the system in all its geometrical details. This is very clear in many of the structural components that have an interaction with a fluid medium, such as in the case of a wing. For various reasons the operational life of the system could require that this shape is changed. This could mean drastic variation of the general configuration, such as the case of deployable space-structures. They could assume at least two shapes: one that minimizes the envelope volume occupied by the system, which is useful for storage considerations; the other, with all possible appendages and parts completely deployed, necessary for the full capability of the system at least in some major phase of its operational life.

In the case of the above-mentioned wing, the shape change is necessary to vary the aerodynamics generated by the interaction with air and as a consequence to create the capability of executing a manoeuvre. In the airplanes this usually is obtained by a rigid body motion of a movable part of the wing (e.g. flaps or ailerons). In nature this has been achieved by a smooth variation of the shape of deformable bodies, such as the wings of birds. In fact there is not better example than this of what effects a shape morphing capability can produce.

As just discussed, a major interest for shape morphing relies on the fluid–structure interaction by means of a prescribed variation of the structural

shape. A prescribed shape morphing can also be used as the working principle of many energy transduction devices or motors to transform the kinetic and elastic energy possessed by a structural element into the energy associated with fluid motion. Conversely, fluid motion can be damped or, more generally, the characteristics of its motion changed by the transformation of the energy associated with the motion of the fluid into the kinetic and elastic energy of a solid element interacting with the fluid.

Fluid–structure interactions are not the only case for which a structural shape morphing could be of practical interest. Reflective surfaces, such as antenna reflectors or mirrors, are very sensitive to any shape variation. On the one hand any deformation produced by either a natural or an artificial environment could disable the reflector. On the other hand, a change in the reflection could be necessary for a specific purpose. In both cases the capability of shape morphing could well cope with the technical problem and provide an effective tool that can also be advantageous from the viewpoint of volume and mass. In fact in the absence of such a capability stiffer and often larger and heavier structures would be used. In some cases, increased requirements in terms of regularity of the shape of the reflector and the directional accuracy of the device will make the use of a shape morphing capability very likely.

The shape morphing of a structure can be realized by using the actuation capability of a smart material, that is its capability of deforming under the effect of a nonmechanical stimulus. This means that, similar to the case of structural health monitoring, the practical realization of this capability is much more complicated than the simple physical reaction of an active material under a particular stimulus. In fact also in this case a target performance needs to be reached, e.g. the containment within assigned limits of the root mean square (RMS) deviation of the shape of an antenna reflector with respect to the nominal one.

Therefore a logic of actuation needs to be established, including proper interfaces between the active and the passive parts of the structure, as well as all the proper arrangements and connections with the stimuli that will eventually create the deformation. The actuation capability of a smart structure is particularly evident when a shape morphing application is developed. This may or may not require a closed loop control, which is discussed in more detail in the following.

## 1.7 Vibration Control

The control of structural vibration is a matter of interest in many engineering fields. In fact the dynamic response of structures under a mechanical environment strongly varying with time is a matter of concern for many engineering applications. A first example could be the noise generation produced by a vibrating structure in the structural high-frequency range. The noise generated by any vibrating machine makes the surrounding environment very uncomfortable and requires proper isolation. The vibrating structure of an automobile proceeding at a certain speed is also generating, in addition to noise, an uncomfortable situation for the driver and the

passengers. Similar examples can also be considered for the vibrations generated in an industrial plant environment. If the vibrating component is part of an operating machine or a robotic arm, structural vibrations are a problem with respect to the direction and precision of the operation and need to be strictly controlled.

Many other cases of practical engineering problems concerning structural vibration can be identified. In most cases the reduction of vibration or isolation from them is achieved by means of several passive techniques that make use of dampers and profit from the classic concept of isolating high-frequency disturbances by installing a mechanical isolator containing a low band-pass filter. The increasing demand for vibration attenuation, even up to the cancellation of vibration in a certain range of frequencies and for directional accuracy, active vibration control has been increasingly used in engineering practice. In this respect smart structures can offer a wide spectrum of technical solutions, ranging from passive damping to active feedback control. Several active materials can be used for this purpose.

Piezoelectric materials have been demonstrated to be effective in passive vibration damping. The idea is that the direct piezoelectric effects not only induce an electrical response to a mechanical stimulus but generate a transformation of part of the mechanical energy introduced in the material system into electrical energy. In other words piezoelectric materials can work as power transducers. In order to damp out part of the mechanical vibration generated in a piezoelectric material by a dynamic excitation one can close-circuit electrodes covering that material on a resistive component. In this way the current generated by the direct piezoelectric effect in the circuit will allow the related electrical energy to be damped by the resistive component. Although only the part of the mechanical energy transformed into electrical energy by the piezoelectric effect can be damped, this passive mechanism has been implemented in practice.

Many sporting devices such as tennis rackets, baseball bats, skis and similar products have incorporated smart-structure passive damping devices. In most cases the optimal damping effect is obtained utilizing advanced piezoelectric devices such as active fibre composites and also by placing in the electrical damping circuits inductive elements improving the transduction of energy from the mechanical to the electrical parts of the structure. Since it is clear that only the parts made by an active material can generate this effect, an important driver of this technology is the design of structures that allow the active part to absorb the largest portion possible of the mechanical energy of the system. This can be obtained by selecting the volumes characterized by the highest energy density, which could of course be different for different vibrating modes, and placing the active material exactly there.

Shape memory alloys can also be utilized for passive damping by using the pseudoelastic effect that they exhibit at high temperature. Shape memory alloys do not exhibit such good behaviour at high frequency as the piezoceramics, but they can produce a high level of forces combined with large displacements. For this reason they can be used for damping very large amounts of energy, such as experienced by a building during an earthquake. In fact many passive devices used for protecting large civil infrastructures from the effects of earthquakes are now constructed with a shape memory alloy damping device.

In active vibration control, smart structures fully utilize their sensing, actuation and control functions. Let us take again the example of piezoelectric materials. In their sensing capability they can be used to measure the dynamics of the structural system. To this purpose and in order to guarantee the necessary requirements of the piezoelectric system, sensors need to be accurately placed at several points on the passive structure. This sensing system, integrated with the passive parts of the structure, will provide information on the state of the structural system to a feedback device. Then commands will be given to the actuators, to enable them to operate in order to achieve the required structural response.

Active materials can be used again at this stage, and returning once again to piezoceramics, for their actuating capability. The controller conveys the command to each piezoceramic actuator by means of an electric signal that, once amplified at the necessary power level, produces the actuating forces. In this case, as mentioned previously, one can conceive a smart structure with full capabilities of sensing, actuation and control. All the necessary components can be fully integrated in a structural component. Dosch, Inman and Garcia demonstrated that piezoelectric materials can be used at the same time as an actuator and as a sensor or, as they called it, a self-sensing piezoelectric actuator [25].

## 1.8 Energy Harvesting

As well known, the storage of energy is still a major technological challenge. This is particularly true for portable devices such as cellular telephones or similar devices. Their increasing demand of power has been balanced by the development of new generations of rechargeable batteries. However, the need for a frequent recharging of the device is still a limiting factor for these products.

For portable electronic devices, used for fun, business and even security reasons, and for all the cases where connection with an electricity line might not be easy or convenient, smart structures can provide the basis for a convenient technical solution. This is related to the electromechanical coupling of the behaviour of materials such as piezoelectric ceramic and the opportunity of using them as power transducers. One has to bear in mind that piezoelectric materials, due to their limited expansion in terms of displacement, cannot transduce large amounts of power. Nonetheless the power generated can be precious in the absence of other sources.

The working principle of energy harvesting application is in a way similar to that described for the passive vibration damping produced by piezoelectric materials. In fact in the presence of a structural vibration of any kind, if we design a smart structure in such a way that some piezoelectric parts are present in the volumes where the mechanical energy density is higher, we obtain a cyclic transformation of a fraction of mechanical energy into electrical energy. Here the aim is not to damp the vibration but to use the mechanical vibrations as a possible source for generating electric power. In fact an electric circuitry can be designed in order to extract the electrical energy from the piezoelectric material and provide it to a battery or directly to an operating device. Once again one possible area of application for



this is sport. By placing a piezoelectric device at the bottom of a pair of sporting shoes, the athlete, by walking or running, will allow the piezoelectric device to experience a structural vibration. As explained previously this could generate by piezoelectric effect a certain amount of electric power that could be used by the user for recharging the batteries of his cellular phone or other portable devices. The same application would be very useful for any person who during their work has the need of using many portable electronics and runs the risk of not being able to recharge them.

In some cases the ‘harvesting’ of electrical energy by means of piezoelectric devices could apply to many devices that are not reached by the wires of an electrical connection but have some vibrating parts, as proposed by Lesieutre [26]. A review of the research findings in the field can be found in [27]. For monitoring devices the amount of wires for setting up a monitoring system sometimes could be critical. Energy harvesting could be used in such a case both for letting the device function and as the energy sources for miniaturized antennae that could send a remote signal produced by the sensor.

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