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Introduction

In many national and international declarations, it has been stated that developments in advanced structures, in the automotive and shipbuilding industries, as well as in aeronautical and space sciences, are subordinate to the development of so-called *smart structures*.

The definition of smart structures has been extensively discussed since the late 1970s. A workshop was organized by the US Army Research Office in 1988 in order to propose a definition of smart systems/structures to be adopted by the scientific community (Ahmad 1988):

> A system or material which has built-in or intrinsic sensor(s), actuator(s) and control mechanism(s) whereby it is capable of sensing a stimulus, responding to it in a predeterminated manner and extent, in a short/appropriate time, and reverting to its original state as soon as the stimulus is removed.

According to design practices, smart structures are systems that are capable of sensing and reacting to their environment, through the integration of various elements, such as sensors and actuators. Smart structures can allow their shape to be varied to very high precision and without using classical mechanical actuators, alleviate vibrations and acoustic noise, and even monitor their own structural health.

Piezoelectric, piezomagnetic, electrostrictive, and magnetostrictive materials are of interest when designing smart structures. Shape memory alloys,

Plates and Shells for Smart Structures: Classical and Advanced Theories for Modeling and Analysis, First Edition.
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electrorheological fluids, and fiber optics should also be mentioned. This book deals with smart structures, taking advantage of piezoelectric effects.

Nowadays, it is difficult to foresee whether smart structures will be employed to any great extent in the future. However, interest in a better understanding of the topic appears essential and could lead to many other uses related to other extensive domains of application.

1.1 Direct and inverse piezoelectric effects

Piezoelectricity was discovered by Jacques and Pierre Curie in 1880, when they realized that several kinds of crystals were able to generate positive or negative electric charges when subjected to mechanical pressure (Curie and Curie 1880, 1881). When dealing with piezoelectric materials, a charge is generated when molecular electrical dipoles are caused by a mechanical loading: that is, the *direct effect (sensor configuration)*. Conversely, when an electric charge is applied, a slight change occurs in the shape of the structure: that is, the *inverse effect (actuator configuration)*. It has been demonstrated that piezoelectric materials can be used at the same time as actuators and sensors, obtaining the so-called *self-sensing piezoelectric actuator* (Dosh *et al.* 1992).

Piezoelectricity is a feature of some natural crystals (such as quartz and tourmaline) or synthetic crystals (lithium sulfate), and several kinds of polymers and polarized ceramics. The most common piezoelectric materials are the piezoceramic *barium titanate* ($BaTiO_3$) and *piezo lead zirconate titanate* (PZT). The crystal lattice of piezoelectric materials is of the *face-centered cubic* (FCC) kind. Metallic atoms are located at the vertex of the cube, while oxygen atoms remain at the center of the cube's faces. A heavier atom is located at the center of the cube and it can shift slightly to positions with less energy, with a consequent deformation of the crystal lattice (metastable structure). If an electric field is applied to the structure, the central atom can exceed the potential energy threshold and move to a lower energy configuration. This is followed by a rupture of symmetry and the creation of an electric dipole (Figure 1.1). The previous phenomenon is possible only below the so-called *Curie temperature*. Above this temperature, the piezoelectric effect disappears due to high thermal agitation. Polarized piezoceramics are obtained by heating them above their Curie temperature and subjecting the material to an intense electric field during thermal cooling. In so doing, all the dipoles become oriented in the same direction and the material obtains a stable polarization. Moreover, apart from a residual polarization, the crystal lattice of the polarized piezoceramic will also undergo a residual deformation. After the polarization process, a very small electric potential will be sufficient to obtain a temporary deformation and vice versa.

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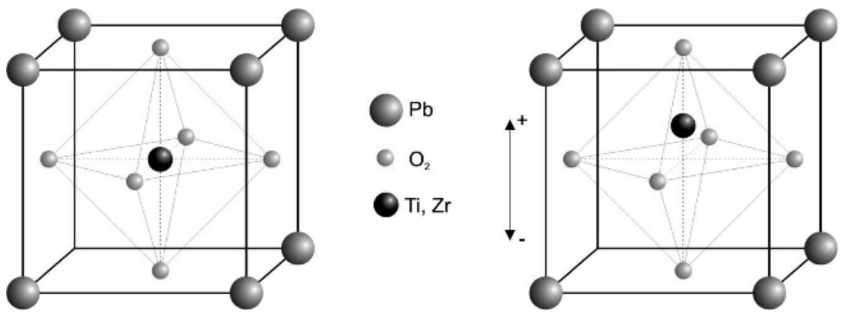

Figure 1.1 Piezoceramic cell before (left) and after (right) polarization.

Even if the electro mechanical coupling is a nonlinear phenomenon, piezoelectric problems are usually studied through linear analysis. This leads to the adoption of assumptions, which will be discussed in Chapter 2. Additional details on this topic can be found in the works by Cady (1964), Tiersten (1969), and Ikeda (1996).

1.2 Some known applications of smart structures

Smart structures have been used in sensing, actuating, diagnosing, and assessing the health of structures, depending on the external stimuli. Sensors and actuators should be integrated into the complete structures and this leads to unusual design solutions, compared to traditional structural design solutions (Srinivasan and McFarland 2001). In the most advanced design concepts, smart structures could have the ability to save and analyze information in order to perform a learning process.

Nowadays, smart structures are applied in many different domains, but they all share the common feature of having a highly cross-disciplinary design. Among other applications, the following current/potential ones can be mentioned.

Structural health monitoring The strain field of some critical locations of a generic structural system can be measured using embedded sensors in order to identify possible damage and retain structural safety and reliability. Damage is intended here as a variation of the material and/or geometric properties, which could affect the performances of the systems. *Self-diagnostic* ability plays a crucial role in the aeronautical and space industry, where sensing the strain field of some relevant structural subcomponents helps in the conduction of an appropriate maintenance program and in avoiding crack propagation. This topic appears of particular interest for composite materials, whose failure prediction is a challenging task. Composites are being progressively employed more and

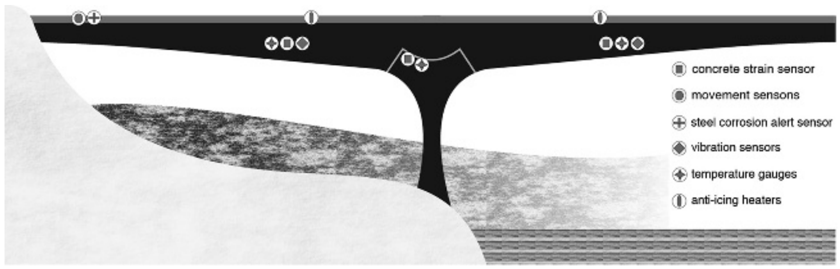

Figure 1.2 Smart system scheme of the Saint Anthony Falls Bridge for structural health monitoring.

more in aerospace engineering in order to replace metallic structures. As a consequence, structural health monitoring will become a very important task in the near future. In principle, crack propagation could be restrained by producing compressive stresses around the failure through a proper network of embedded actuators (Rogers, 1990). Rogers (1990) also mentioned the possibility of using skin-like tactile piezoelectric sensors to sense temperatures and pressures. Structural health monitoring is also applied extensively in civil engineering. The most well-known examples refer to the remote monitoring of bridge deflections, mode shapes, and the corresponding frequencies (Deix *et al.* 2009; Spuler *et al.* 2009). The scheme of the Saint Anthony Falls Bridge in Figure 1.2 represents an example of a smart system with embedded devices that offers optimal diagnostics (Foster 2009). Monitoring is usually performed by analyzing the dynamic response of a system through an array of properly located sensors. Periodic observations and comparisons to previous measurements and numerical simulations can indicate some local damage or structural/material degradation resulting from the operational environment.

Vibration control Due to their high strain sensitivity (Sirohi and Chopra 2000), piezoelectric sensors and actuators are easily employed for vibration damping/attenuation/suppression (Inman *et al.* 2001). Piezoceramics are used to reduce noise and improve the comfort of vehicles, such as cars, trucks, and helicopters, and to improve the performances of machine tools. The same technique is often employed in spacecraft carrying equipment in a pure operational dynamic environment. Active vibration control is usually applied in engineering practice in order to suppress dangerous vibrations over a certain range of frequencies, as in the case of helicopter blades (Chopra 2000). Piezoelectric materials are also effective in passive damping: a part of the mechanical energy introduced into the structural system is converted into electrical energy, according to the piezoelectric effect. Piezoelectric passive damping devices are commonly embedded in high-performance sports devices, such as tennis rackets, baseball bats, and skis (Gaudenzi 2009).

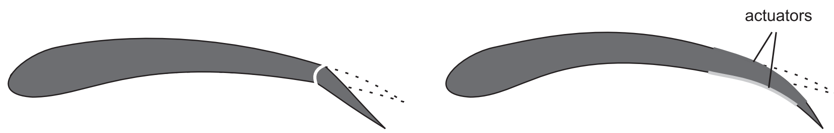

Figure 1.3 Wings with conventional flaps (left) and with smart flexible flaps (right).

Shape morphing Among the possible shape morphing industrial applications of structural components, focusing on the aeronautics field, it is worth mentioning the advantages of a wing with variable shape. Commercial aircraft have to respect increasing efficiency requirements and reduce emissions. One possible solution is to propose a variable shape wing that is able to optimize performances in all phases of the mission. The means that can be employed to vary the shape of the wing are quite challenging and can vary in complexity, depending on which properties have to be modified: sweep angle, profile, aspect ratio, etc. Swept wings (as a solution to reduce wave drag) were first used on jet fighter aircraft. Variable shape wings, in a broad sense, could play a significant role in future aircraft designs. The elementary wing shape changes for take-off/cruise/landing are currently obtained by means of rigid body motions of movable parts, e.g., flaps, slats, ailerons, and spoilers. It is understood that a smart flexible wing, without secondary parts, that would be able to perform proper shape changes, would lead to a remarkable reduction in drag, weight, and overall system complexity; see Figure 1.3 for an example of a hingeless flap that can be obtained from shape morphing.

Active optics Active optics, which are usually employed in large reflector telescopes and can be considered as a particular case of shape morphing, allow the shape of mirrors to be monitored and readjusted during operation. In this way, it is possible to avoid effects due to gravity or wind (in the case of an Earth-based telescope) or deformations due to thermo mechanical coupling or structural imperfections (in the case of space telescopes). The use of accurate actuators, together with an algorithm that is able to quantify the quality of images, allow a precision to be obtained that goes well beyond the possibilities of conventional reflector telescopes. Active optics are currently employed in 10 m class telescopes and are also going to be applied in the next generation of 40 m telescopes (Preumont *et al.* 2009).

Microelectromechanical systems (MEMS) MEMS consist of extremely small mechanical devices driven by electricity. A device's dimensions vary from 20 μm to 1 mm. MEMS devices can be used as multiple microsensors and microactuators (Varadan and Varadan 2002). MEMS are particularly promising in the medical field, where they can be employed as blood sugar sensors, insulin delivery pumps, micromotor capsules that unclog arteries, or filters that expand after insertion into a blood vessel in order to trap blood clots (Srinivasan and McFarland 2001).

Many potential benefits can be obtained due to the extensive use of smart structures in industrial applications. Reducing maintenance costs, in the case of self-diagnostic structural health monitoring, should be mentioned. In fact, maintenance time is a crucial point for airlines, which, according to the low-cost business philosophy, has greatly reduced profit margins. Another benefit consists of the possibility of producing new components, according to new design concepts, like shape morphing and the integration of MEMS in structures. It should also be emphasized that MEMS are currently enlarging medical perspectives, and opening up new scenarios for the future of health care programs.

Aim of this book This book aims to illustrate the classical techniques and some advanced models that are able to describe mechanical and electrical variables in plate/shell structures that have piezoelectric layers embedded in the lamination stacking sequence. Two-dimensional axiomatic models are considered through analytical and finite element approaches. Classical models (e.g., Kirchhoff, Mindlin, and equivalent single-layer kinematic descriptions) are compared to advanced theories (mixed, layer wise, and higher order descriptions) through several numerical examples. Most of the presented theories are derived on the basis of the Carrera Unified Formulation, which probably is one of the most modern and advanced tools for dealing with the theory of structures.

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