DESIGN OF SMART STRUCTURES DEVICES AND STRUCTRONIC SYSTEMS

智能结构、装置设计及结构电子系统

主编：TZOU Hornsen / 邹鸿生

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哈爾濱工業大學出版社

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PREFACE

Many electro-active functional materials have been used in small- and micro-scale transducers and precision mechatronic control systems for years. It was until the mid-80s in the 20th century that scientists started integrating electro-active materials with large-scale structures as sensors and/or actuators, and thus introducing the concept of smart materials, smart structures and structronic systems. This book is to provide an overview of present smart materials and their sensor/actuator/structure applications. Fundamental multi-field opto-magneto-piezoelectric-thermoelastic behaviors and novel transducer technologies applied to complex multi-field problems involving elastic, electric, temperature, magnetic, light, etc. interactions are emphasized. Material histories, characteristics, material varieties, limitations, sensor/actuator/structure applications, etc. of piezoelectrics, shape memory materials, electro- and magneto-strictive materials, electro- and magneto-rheological fluids, polyelectrolyte gels, pyroelectrics, etc. are thoroughly reviewed. Based on a large number of patents, various applications to engineering devices and systems are emphasized. This book can be used as a textbook or reference for senior and graduate students, as well as for researchers in the related fields.

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION TO SMART MATERIALS

The concepts of smart, intelligent, and adaptive materials and structures originated in the mid-1980s in an attempt to describe the newly emerging research area of integrating electro-active functional materials into large-scale structures as in-situ sensors and actuators. Previously, electro-active materials had only been used in small and micro-scale transducers and precision mechatronic (mechanical + electronic) control systems. The general perception of smart, intelligent, and adaptive materials or structures implies an ability to be clever, sharp, active, fashionable, and sophisticated. However, in reality, materials or structures can never achieve true intelligence or reasoning without the addition of artificial intelligence through computers, microprocessors, control logic, and control algorithms. Accordingly, the materials can only be active and the structures could ultimately be intelligent. Furthermore, the synergistic integration of smart materials, structures, sensors, actuators, and control electronics has redefined the concept of structures from a conventional passive elastic system to an active or adaptive (life-like) multi-functional structronic (structure + electronic) system with inherent self-sensing, diagnosis, and control capabilities[1-4]. Thus, the goal of this paper is to review the fundamental characteristics, design principles, and practical applications of key smart materials as outlined in TAB 1.1. The smart materials examined include piezoelectrics, shape memory materials, electrostrictive materials, magnetostrictive materials, electrorheological fluids, magnetorheological fluids, polyelectrolyte gels, pyroelectrics, photostrictive materials, photoferroelectric materials, magneto-optical materials, and superconducting materials. The requirements for multi-field opto-thermo-electro-magneto-mechanical systems applied to complicated multi-field control problems coupling elastic, temperature, electric, magnetic, and light interactions are also discussed.

TAB 1.1 COMMON SMART MATERIALS AND THEIR MILESTONE YEARS.

Piezoelectrics (1880) Pyroelectrics(315BC)	Shape-memory Materials (1932)	Electro- and Magneto-strictive Materials (1954/1840)	Electro- and Magneto-rheological Fluids (1784/1947)
Polyelectrolyte Gels (pH Muscles) (1949)	Photostrictive Materials (1974); Photovoltaic Materials	Superconductors (1911)	Liquid Crystals
Optical Fibers	Electro-luminescence Particles	Magneto-optical, Electromagnets, Magneto-elastic Materials	Electro-static Materials

1.1 PIEZOELECTRIC MATERIALS

Curie brothers (Jacques and Pierre) observed electric field generations on quartz crystals when subjected to mechanical forces in 1880. (Piezo means press in Greek.) They consequently also observed strain generations when the crystal was subjected to electric fields. Piezoelectricity is, in general, an electromechanical phenomenon coupling the elastic (***dynamic coupling***) field and the electric (***static coupling***) field. A piezoelectric material responds to mechanical forces/pressures and generates electric charges/voltages, which is referred to as the ***direct piezoelectric effect***. Conversely, electric charges/fields applied to the material can induce mechanical stresses or strains, and this is called the ***converse piezoelectric effect***, FIG 1.1[5]. Usually, the direct effect is the basis for sensor applications and the converse effect is for precision actuation and manipulation in control applications. The actuation stroke ranges from nano-, micro-, mm- scales, depending on configurations and designs or with/without mechanical amplifications or deductions via lever systems. Note that at low electric field, piezoelectricity is a first order effect that produces a strain proportional to the electric field and the direction of the displacement dependent on the sign of the electric field[6]. However, as the electric field increases, electromechanical hysteresis appears and its domain grows at strong electric fields, which can cause servo-displacement control problems in large-stroke precision actuation of piezoelectric actuators.

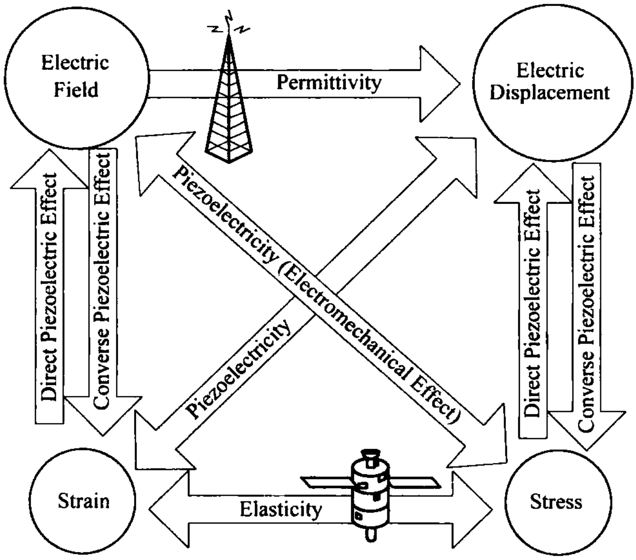

FIG 1.1 PIEZOELECTRICITY—AN ELECTROMECHANICAL COUPLING.

Many natural and synthetic materials exhibit piezoelectric properties[7], which can be classified into (1) ***natural crystals***, (2) ***liquid crystals***; (3) ***noncrystalline materials***, (4) ***textures***, (5) ***synthetic piezoelectric materials***, TAB 1.2. Note that raw synthetic materials are usually isotropic and non-piezoelectric. They become anisotropic and piezoelectric only after the *poling process* that involves applying a high electric field at an elevated temperature. The field aligns the molecular dipoles in the material and the dipoles are then fixed into the aligned orientation in the structure when the material is cooled while maintaining the strong field. The poled piezoelectric will deform in the presence of an electric field and polarize when subject to mechanical stress. Since synthetic materials (e.g., PZT & PLZT) and polymers (e.g., PVDF) can be fabricated into arbitrary geometries and shapes, they are very popular in many sensor and actuator applications.

TAB 1.2 COMMON PIEZOELECTRIC MATERIALS.

Natural crystals	Quartz, Rochelle salt, ammonium phosphate, etc.
Liquid crystals	
Noncrystalline materials	Glass rubber, paraffin, , etc.
Textures	Bone, wood, etc.
Synthetic piezoelectric materials	a) Piezoceramics: lead zirconate titanate (PZT), barium titanate, lead niobrate, lead lanthinum zirconate titanate (PLZT), etc.
	b) Crystallines: ammonium dihydrogen phosphate, lithium sulfate, etc.
	c) Piezoelectric polymer: polyvinylidene fluoride (PVDF or PVF2), etc.

Fundamental theories on piezoelectricity, piezothermoelasticity, and opto-piezothermoelasticity have been proposed and refined over the years[6,8-22]. Engineering application of the piezoelectric materials started with a depth-sounding device, based on Rochelle salt, invented by Langevin in 1917. Novel piezoelectric devices were invented and applied to a variety of engineering applications[2-4,23-26]. Many other sensors (e.g., accelerometers, pressure transducer, force transducers, microphones, etc.), actuators (precision manipulator, robot manipulator, ultrasonic motors, driving mechanism for scanning tunneling microscopes, etc.), smart structures and structronic systems (e.g., helicopter rotor blades, airplane wings, space structures, precision trusses, etc.) have been documented. (In fact, the area of smart structures and structronics started with the distributed piezoelectric sensing and control research in the early 80s.) New devices are being invented and patented every year. TAB 1.3 gives a list of sample applications.

TAB 1.3 SAMPLE APPLICATIONS.

Sensors	Accelerometer, pressure transducer, force transducer, noise/acoustic sensor, microphone, impact transducer, distributed sensor, orthogonal (modal) sensor, health monitoring, etc.
Actuators	Precision manipulator, pressure generator, ink/fuel injection, displacement actuator, vibration isolation, vibration and noise control, ultrasonic motors, distributed control, constrained layer damping, passive shunt damping, orthogonal (modal) actuator, self-sensing actuator, active structures, smart composites, etc.
Structures	Vibration, noise, stress, strain, health monitoring, measurements (e.g., flow, pressure, force, impact, etc.), morphing, etc.

TAB 1.3 (Continued)

Machines and mechanical systems	Vibration and noise (monitoring and control), strength, stress, strain, health monitoring and diagnosis, optical systems, measurements (e.g., force, acceleration, pressure, impact, noise, etc.), rotor control, etc.
Medical and bio-medical applications	Disposable sensors, ultrasonic devices, precision drives and control (e.g., scanning tunneling microscopes, manipulators, etc.),
Robotics and mechatronic systems	Precision actuation, manipulation, control, precision/micro robots, robot grippers, flexible robot control, micro-electromechanical systems (MEMS), micro sensor/actuator, etc.
Smart structures and structronic systems	Adaptive structures and composites, structural control, adaptive geometry and shape control, adaptive aircraft wings or helicopter blades (morphing), noise and vibration control, damage detection, health monitoring, self-sensing actuators, damage repairs, precision truss structures, positioning, aerospace structures and satellites, etc.

Recent development of adaptive (or smart) structures and microelectromechanical systems further integrate piezoelectrics with structures and control electronics, etc. in both static and dynamic applications. Examples include aerospace/aircraft structures[27-28], robot manipulators[29], vibration controls and isolations, highprecision devices, microsensors/actuators, thinfilm micro electromechanical systems (MEMS)[30], health monitoring[31], microdisplacement actuation and control, etc.[25]. Additional applications in smart structures and structronic systems encompass distributed structural control[16,32-36], rotor dynamics control[37], self-sensing actuators[38-40], orthogonal modal sensors/actuators[41-43], space truss members[44], noise control[45], vibration isolators[46], active constrained damping[47], morphing of wings and blades[48], microscopic neural-sensing and actuation characteristics of conical, paraboloidal, toroidal and spherical structronic shells[49-55], etc. Other recent practical applications include piezoelectrically damped skis, control of aeroelastic wing flutter, optical metering truss control, helicopter blade control, noise reduction, biomedical applications, and ultrasonic motors[56-61]. Note that although TAB 1.3 summarizes sample applications of piezoelectrics, most of these applications can also achieved by many other smart materials, e.g., electro- and magneto-strictive materials, shape-memory materials, etc., with different design principles, due to their individual material characteristics.

1.2 SHAPE MEMORY MATERIALS

Shape memorylike behavior was first observed in a sample of goldcadmium (AuCd) by Chang and Read in 1932. This shape transformation was later observed in brass in 1938, and also in an AuCd bend bar in 1951. It was not until 1962 that a full shape memory effect was observed in a series of nickeltitanium alloys by Buehler, Gilfrich and Wiley. This shape memory alloy (SMA) is now called Nitinol (Ni-Ti), and is the most commercially known shape memory alloy[62]. Not only does this alloy exhibit excellent shape memory characteristics but it can also have variable transformation temperatures by changing its chemistry or composition. Other alloys have also been tested for the effect, however, Nitinol proves to be the most commercially attractive SMA material. Note that while the shape memory effect is predominately found in metal alloys, certain ceramics and polymers also exhibit the shape memory effect.

Mechanically deformed SMA, by raising its temperature, can return to its original shape, which is known as the ***shape memory effect.*** At low temperature, the SMA crystalline structure exhibits a needlelike structure, called ***martensite***, and it exhibits a strong cubic structure, called ***austenite***, when heated. The different physical properties at the martensitic and the austenitic crystal structures produce the shape memory effect. While in the martensitic crystal structure, the material is more compliant (lower Young's modulus) than that in the austenitic crystal structure. The austenitic crystal structure is considerably more rigid (higher Young's modulus). The temperature range at which SMA's undergo martensitic transformation depends on several factors, some of which can be altered to fit specific needs. The temperature at which the martensite starts to form can be varies for different materials and different ratios of metal in shape memory alloys. In Ni-Ti alloys, the temperature at which the martensite forms can be varied from −200℃ to +100℃ depending on the nickel to titanium ratio. Cu-Ni-Al alloys can produce martensitic transformations as high as 200℃[63]. The temperature range between the martensitic and austenitic states is also an important factor for SMA applications. The typical range is about 5℃ to 10℃[64]. The other important property of this crystalline transformation is the existence of temperature hysteresis. This means that the transformation from martensite to austenite occurs at higher temperature while heating, and the transformation from austenite to martensite upon cooling. The extent of this hysteresis can be quite significant, 30℃ to 50℃ for common Ni-Ti SMAs. Material modifications can either decrease the hysteresis to as low as 15℃ or as high as 100℃[65]. There are three fundamental shape memory effects: (1) the one-way effect, (2) the two-way effect, and (3) the pseudo-elasticity (or super-elasticity). FIG 1.2 illustrates the characteristics of the one-way effect, the two-way effect, and the pseudo-elasticity. Plastically deforming a SMA in the martensitic form and recovering its original shape at a higher temperature is known as the ***one-way effect.*** This effect is particularly useful in Ni-Ti alloys due to the existence of two yield points. This alloy exhibits a low yield point and a significantly high yield point[65]. Deformations above the first yield point are easily recoverable by heating, but deformations above the second yield point are not recoverable by heating. The typical amount of recoverable deformations is as high as 3% ~4% for copper based alloys and 6% ~8% for Ni-Ti alloys[63]. The second effect of SMA's is the ***two-way effect.*** This is probably the most widely used and beneficial effect of shape memory alloys. Thermal energy can be efficiently translated into mechanical energy using the twoway effect. If a force is applied to a shape memory alloy in the martensitic state, heating above the martensitic transformation temperature while applying the same force will cause the strain in the alloy to be reduced. (That is the same stress that will cause less strain in the austenitic state than in the martensitic state.) This is due to the decreased elasticity of the austenitic state. The force generated during the transformation between the two states is quite significant, and it makes SMA's useful for a number of applications. The third effect exhibited by

SMA's is the ***pseudoelasticity*** (or ***superelasticity***) that only occurs when the shape memory alloy is slightly above its transition temperature. When an alloy is in the austenitic state, a stress induced martensitic transformation can occur. However, since the material is above its transition temperature, ambient thermal energy converts the martensite back to the austenite after the stress is relieved. The material is forcefully transformed back to its previous austenite shape providing a very springy or rubber-like elasticity in the alloy. This effect allows the shape memory alloy to have recoverable strain beyond that of most materials. Strain as high as 5% can be repetitively recovered using Ni-Ti wires, however, fatigue is a problem[66]. There has been continual research devoted to finding new alloys exhibiting the shape memory effect. Patents in recent years have shown such alloys as copper, zinc and aluminum combined with lesser amounts of nickel and titanium.

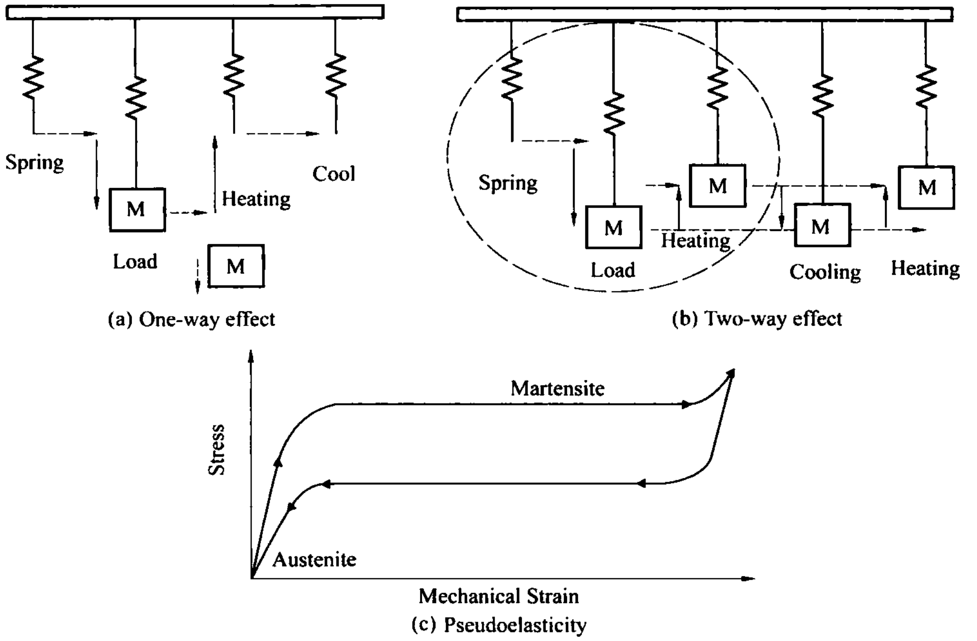

FIG 1.2 CHARACTERISTICS OF THREE FUNDAMENTAL SHAPE MEMORY EFFECTS.

In 1969, Raychem successfully produced a Ni-Ti hydraulic pipe coupling called Cryofit and it was used in military high-performance hydraulic systems. Interest in SMA products increased greatly in Japan in the 1970's. Recall that the twoway effect can be utilized in a number of different actuators both thermal and electrical. Since the twoway effect works with both normal and shear stresses, a wide range of geometrical configurations can be used as actuators. SMA's can be made into straight wires, helical springs, cantilever springs, wavewasher springs, torsion wires/rods, torsion tubes, etc. Straight wires and wavewasher springs tend to produce a higher force and a smaller motion than helical springs. The twoway effect can also be achieved without the application of an external force. This requires a special heat treating process involving prestressing the material at different temperatures. The true twoway effect produces less motion and force and is less well understood than the twoway effect involving an external force. The heat treatment procedure is also more expensive making this type of twoway effect less desirable than the external force method[65].

Many SMA applications include SMA prosthetic arms[67], coffee makers, seals and fasteners, blood clot filters, deep fryers, Expresso etc.[64] Proposals for new applications include wing morphing, circuit breakers, fire dampers, auto-vent system, door panel control, etc.

1.3 ELECTROSTRICTIVE MATERIALS

Both electrostrictors and piezoelectrics belong to the ferroelectric family. Piezoelectricity is a first order effect, however, electrostriction is a second-order (quadratic) effect, i. e., the induced strain is proportional to the square of the applied electric field. Thus, the induced strain is independent of the direction of the applied field and the same deformation (direction and magnitude) occurs when the field is reversed, FIG 1.3.

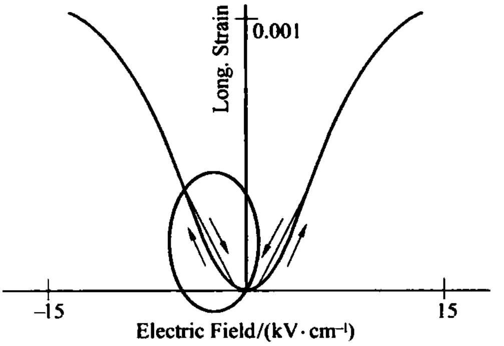

FIG 1.3 ELECTROSTRICTIVE RESPONSE.

Electrostriction is usually present in all dielectric materials but is very weak due to the dominating stronger first-order piezoelectric effect. Thus, during the development of piezoelectric applications, the smaller, second-order electrostrictive effect is ignored for most practical purposes. However, materials that have high dielectric constants (high polarizations), such as relaxor ferroelectrics, can exhibit very large electrostrictive strains. Unlike piezoelectrics, the spontaneous polarization in a relaxor ferroelectric does not disappear at certain Curie temperature, but slowly decays with increasing temperature. This phenomenon might be caused by the diffuse nature of the transition related to a partially disordered distribution of cations in a relaxor ferroelectric, permitting a mixture of *pyroelectric* and *paraelectric* phases existing over a wide temperature range. Hence, the dielectric hysteresis in the transition region disappears before the spontaneous polarization allowing significant electrostriction with minimal hysteresis above and below the nominal transition temperature. Also, strains on the order of 0.1% are typical for electrostrictors and the material is stable in nature since no electric manipulation of the domains is required to orient dipoles[68].

Lead magnesium niobate, $Pb(Mg_{1/3}Nb_{2/3})O_3$(PMN), or its solid solutions with lead titanate, $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$(PMN-PT) are the most significant relaxor ferroelectrics commonly used in actuator applications. Electrostrictive effects in ferroelectric material were first observed by Devonshire in 1954. In 1958, Smolenski and Agranovskaya also examined PMN, which is described as a relaxor ferroelectric perovskite with an average Curie temperature of about 0℃. It has a high dielectric constant with a wide temperature range. Materials with a PMN base and operating above the nominal transition temperature will typically have high induced strains (>0.1%) and low hysteresis (<5%) in fields of moderate intensity (~1 MV/m)[69]. Electrostrictive PMN is a purely nonpiezoelectric material in which the electrostrictive effect can be strongly distinguished. Note that polymeric electrostrictive materials were also reported in recent years.

However, electrostrictive materials might be more reliable than piezoelectric materials based on certain physical properties, such as hysteresis, poling, modulus, temperature effect, external interference, etc., discussed as follows. (1) Electrostrictive PMN exhibits a negligible hysteresis (<1%) which is essential in repeatedly locating and maintaining a set-point accuracy and open-loop controlled responses. (2) PMN requires no poling which means it remains stable with no aging or creep commonly found in piezoelectric devices. (3) PMN has a very high elastic modulus (17×10^6 psi) which produces relatively high stiffness enhancing the force/deflection capability. (4) PMN actuators have negligible thermal growth since the thermal expansion coefficient dissipates very little power. Its high maximum service temperature further allows PMN devices to operate in very harsh environment. (5) PMN also has improved strain sensitivity that reduces the operating voltage below 150 V. (6) PMN produces little or no electrical or magnetic interference to other components. Accordingly, PMN components have replaced many piezoelectric actuators used in precision apparatus since the PMN drift is less than 3% over two days as compared with 10% ~ 15% of a comparable piezoelectric device under loading[68,70].

Precision actuators and displacement transducers are ideal applications of PMN based materials. Note that both electrostrictive and piezoelectric materials provide accurate displacements with a rapid response time in actuator applications. Comparing with electromagnetic actuators, electrostrictive or piezoelectric systems are more compact, consume less power, and have fewer overheating problems. Thus, these materials are open to a wide variety of commercial applications. Practical PMN applications include displacement actuators[71-72], motors[73], pumps[74-75], optical scanning systems[76], vibration isolators, tool bits, etc. One application in optical devices is in the positioning of deformable mirrors, such as those in Hubble Space Telescope (HST). PMN is arranged in an array on the back of the mirror surface, which can control the surface of the mirror reflection. This is especially useful in the precision control of a high-power laser light. Similar technology applies to the optical fiber polarization controlled by the actuator compression of single fibers. The other major application is the development of linear and rotational motors with typical range of motion of several micrometers for each centimeter of electrostrictor. Again, with lever systems, one can either extend or reduce its operation range. Recent development focuses on electrostrictive polymers and multi-field coupling theories[77-78].

1.4 MAGNETOSTRICTIVE MATERIALS

Magnetostriction is also a second-order (quadratic) effect, i. e., the induced strain is proportional to the square of the applied magnetic field, which is similar to electrostriction,