CHAPTER 23

Electromagnetic Smart Materials*

23.1 Introduction

Smart materials refer to a class of materials and/or composite media having inherent intelligence together with self-adaptive capabilities to external stimuli. Also known as *intelligent materials*, they constitute a few subsets of the material family that "manifest their own functions intelligently depending on environmental changes" [1]. Electromagnetic (EM) smart materials are specific subsets of smart materials which can adaptively change their EM characteristics when an external stimulus is applied proportional to a sensed EM response.

Classically, such intelligent material systems have been conceived in the development of mechanical structures which contain their own sensors, actuators, and self-assessing computational feasibilities so as to modify their structural (elastic) behavior *via* feedback control capabilities. The relevant concepts have stemmed from an intelligent form of natural (material) systems, namely, living organisms; and hence in modern concepts smart/intelligent materials/systems are conceived as those which "mimic the life functions of sensing, actuation, control, and intelligence".

The inherency of intelligence and self-adaptable control of man-made smart materials should be "programmable" in terms of the constituent processing, microstructural characteristics, and defects so as to permit the self-conditioning to adapt in a controlled manner to various extents of stimulus.

The dividing line between *smart materials* and the so-called *intelligent structures* is not, however, distinct. In simple terms, intelligent material systems are constructed of smart materials with a dedicated, discrete set of integrated actuators, sensors, etc; and the smart materials contain largely a built-in or embedded set of distributed sensors. In general, the term "smart materials" usually connotes the structural constituent in which the discrete functions of sensing, actuation, signal processing, and control are tangibly integrated. "Intelligent structures", as an extension, are constructed with smart materials so as to respond to the environment around them in a predetermined (desired) manner.

Intelligent or smart materials which manifest their own functions intelligently *vis-a-vis* the changes in the surrounding are capable of performing, in general:

- Primary functions specifying the adaptive roles of the sensor, the effector, and processor capabilities (including the memory functions)
- Macroscopic functions which enclave the extensive or global aspects of the intelligence inherent in the materials
- Built-in social utility aspects with an instilled human-like intelligence with hyper-performance capabilities

23.2 Smart and Intelligent Structures

The framework of intelligent structures as a subset in the gamut of conventional material-based systems is illustrated in Figure 23.1. This general classification of material structures refer to [2]:

- Sensory structures "which possess sensors that enable the determination or monitoring of system states or characteristics"

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[*] This chapter is largely adapted from the following author's contribution: Smart Materials, Chapter 55, *The Electrical Engineering Handbook* (R. C. Dorf, Ed.), (CRC Press, Boca Raton, FL: 1993), pp. 1173-1189.

- Adaptive structures which possess actuators to facilitate the alteration of system states or characteristics in a controlled manner
- Sensory systems which may contain sensors, but no actuators
- Adaptive systems which contain actuators, but no sensors

Referring to Figure 23.1, the intersection of sensory *versus* adaptive structures depict the controlled structures with a feedback architecture. That is, the active structure has an integrated controlled unit with sensors and/or actuators which have structural as well as control functionality. Hence, the logical subset that defines an intelligent structure is a highly integrated unit (with controlled logic, electronics, etc.) that provides the cognitive element of a distributed or a hierarchic controlled structure.

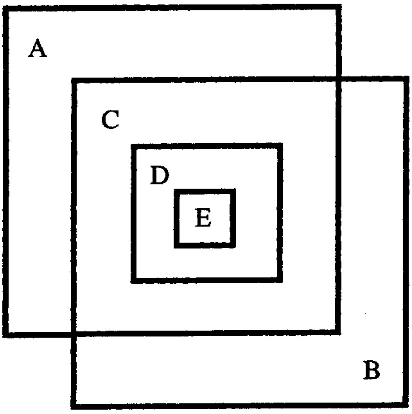

Figure 23.1 Set of structures. A. Adaptive structures; B. Sensory structures; C. Controlled structures; D. Active structures; E. Intelligent structures.

23.3 Classification of Smart/Intelligent EM Materials

Smart magnetic shielding materials: As warranted by the surroundings, the self-adaptive shielding effectiveness to magnetic fields at low frequencies (power frequencies such as 60/50 Hz) can be achieved by means of an integrated set of magnetic field sensors and actuators (magnetic biasing, current elements, etc.) plus a control system arrangement [3].

High-frequency smart shielding materials: Corresponding to radio and higher frequency environments, the shielding requirement warrants curtailing both electric and magnetic fields. Hence, the relevant self-adaptive intelligent shielding system would consist of an array of distributed electromagnetic sensors with appropriate elements (actuators) and a control system.

Smart radar absorbing materials (smart RAMs): Absorption of microwave/millimeter wave energy at radar frequencies is useful in *radar stealth* applications. Adaptively controllable smart RAMs can be synthesized with integrated distribution of electromagnetic detectors (sensors) with appropriate actuators and control system [4].

Smart optical surface materials: These can be envisioned as those in which the surface optical properties (hue, intensity, etc.) can be adaptively controlled by means of an intelligent sensor/actuator combinational control system.

Pyrosensitive smart materials: Electromagnetic active surfaces constituted by pyrosensitive inclusions have been successfully developed to manage the electromagnetic reflection and/or absorption characteristics from the active surface by means of thermal actuation of the pyrosensitive nodes embedded in the medium [4]. With the inclusion of a feedback system, "smart" operation in adaptively manipulating the active surface characteristics can be achieved.

Electroelastic smart materials: These are classical versions of smart materials using the mechanical/elastic properties of a structure which can be modified adaptively by means of an embedded distribution of such materials. *Piezoelectric materials* or their modified versions form the base materials for electroelastic smart applications.

Magnetoelastic smart materials: Applicationwise, these are smiliar in purpose to those of smart electroelastic materials. Their response, however, is magnetically wielded instead of by electric field force. *Magnetostrictive materials* are the core constituents for smart magnetoelastic applications.

23.4 Material Properties Conducive for Smart EM Applications

There are certain specific characteristics of materials which make them suitable for smart electromagnetic applications. The generic list of such properties is:

- Piezoelectric effect
- Magnetostrictive effect
- Electroplastic effect
- Electrorheological properties
- Nonlinear electrooptic properties
- Nonlinear electroacoustic properties
- Nonlinear electromagnetic properties
- Pyrosensitive properties

SMART / INTELLIGENT MATERIALS

STRUCTURAL APPLICATIONS

Electroelastic effect
(Piezoelectric effect)

Magnetoelastic effects
(Magnetostrictive effect)

Electrorheological effect

Shape-memory effect

Electroplastic effect

ACOUSTICAL APPLICATIONS

Piezoelectric effect

Magnetostrictive effect

Raman active effect

ELECTROMAGNETIC APPLICATIONS

Nonlinear feeroelectric effect

Nonlinear ferromagnetic effect

Pyrosensitive effect

OPTICAL APPLICATIONS

Nonlinear electro-optic effect
(Kerr effect & Pockel's effect)

Electrochromic effect

Figure 23.2 Application-specific classification of smart/intelligent materials.

23.4.1 Piezoelectric Effect

Piezoelectric property of a material refers to the ability to induce opposite charges at two faces (correspondingly to exhibit a voltage difference between the faces) of the material as a result of the strain due to mechanical force (either tension or compression) applied across the surfaces. This process is also reversible in the sense that a mechanical strain would be experienced in the material when subjected to opposite electric charging at the two faces by means of an applied potential.

In the event of such an applied voltage being alternating the material specimen will experience vibrations. Likewise, an applied vibration on the specimen would induce an alternating potential/charge between the two faces. The most commonly known materials which exhibit piezoelectric properties are the natural materials like quartz and a number of crystalline and polycrystalline compounds as well. More details on these materials are furnished in Chapters 13 and 14.

The strain *versus* the electric phenomenon perceived in the piezoelectric materials is dictated by a coefficient which has components referred to a set of orthogonal coordinate axes (which are correlated to standard crystallographic axes). For example, denoting the *piezoelectric coefficient* (ratio between piezoelectric strain component to applied electric field component at a constant mechanical stress or *vice versa*) as d_{mn}, the subscript n (1 to 3) refers to the three Euclidean orthogonal axes; and $m = 1$ to 6 specifies the mechanical stress-strain components. The unit for d_{mn} is meter/volt which is the same as coulomb/newton.

In the piezoelectric phenomenon, there is an electromechanical synergism expressed as a *coupling factor K* defined by K^2 which quantifies the ratio of mechanical energy converted into electric charges to the mechanical energy impressed on the material. Being a reversible process, a relevant inverse ratio is also applicable.

23.4.2 Magnetostrictive Effect

This refers to the structural strain experienced in a material subjected to a polarizing magnetic flux. A static strain of $\Delta\ell/\ell$ is produced by a d.c. polarizing magnetic flux density B_o such that $\Delta\ell/\ell = CB_o^2$ where C is a material constant expressed in (meter^4/weber^2) taking the units for B_o as weber/meter^2 (or tesla).

The magnetic stress constant (Λ) in (newton/weber) is given by $\Lambda = 2CB_oY_o$ where Y_o refers to Young's modulus of a linearly strained free bar. The coefficient (Λ) could be both positive or negative. For example, nickel contracts with increasing B whereas magnetic alloys such as 45 Permalloy™ (45% Ni + 55% Fe), and Alfer™ (13% Al, 87% Fe) exhibit positive *magnetostrictive coefficient* [5]. (For more information, see Chapter 15.)

23.4.3 Electroplastic Effect

The *electroplastic effect* (EPE) refers to the plastic deformation of metals with the application of high density electric current with an enhanced deformation rate (that persists in addition to that caused by the side effects of the current such as joule heating and the *magnetic pinch effect*). The plastic strain rate resulting from a current pulse is given by $\varepsilon_I/\varepsilon_A = \alpha J^2 \exp(\beta J)$ where ε_I is the strain rate occurring during the current pulse, ε_A is the strain rate in the absence of the current pulse, J is the current density, and α and β are material constants. Typically the EPE has been observed in zinc, neobium, titanium, etc.

23.3.4 Electrorheological Property

It is the property exhibited by certain fluids which are capable of altering their flow characteristics depending on an external applied electric field. These fluids have a fast response time, being only a few milliseconds. Once the external field is applied there is a form of progressive gelling of the fluid proportional to the applied field strength. Without the applied field the fluid flows freely. If the electrified *electrorheological (ER) fluid* is sheared by an applied force larger than a certain critical value, it flows. Below this critical value of applied shear force, the electrified fluid remains in the gel phase [6].

An electrorheological fluid requires particles (1 to 100 micro-meter in diameter) dispersed in a carrier fluid. Sometimes, a surfactant is also added to help the dispersion of particles in the fluid. The surfactant is used to prevent particle interaction which could otherwise result in a tendency for the particulates to clump together when the fluid is allowed to stand still over a stretch of time. The tendency of the particles to clump together is referred to as *settling*.

The applied electric field to perceive the electrorheological phenomenon is usually on the order of 4 kilovolt/millimeter. When the electric field is applied the positive and negative charges on the suspended particles are separated forming a dipole of charges. These dipoles then align (polarize) themselves by mutual forces of attraction and repulsion to other similar dipoles resulting in unique flow characteristics. In the absence of an electric field, there is no dipole separation of charges, and hence the fluid returns to its normal flow.

An ideal electrorheological fluid is one that has a low viscosity in the absence of an applied field and that transforms into a high viscosity gel capable of withstanding high shear stresses when the field is on. Further, it must also have a low power consumption. The first reported ER fluid consisted of finely dispersed suspensions of starch or silica gel in mineral oil nearly forty years ago. Comprehensive details on ER fluids are presented in Chapter 24.

23.4.5 Nonlinear Electrooptic Properties

In certain materials which are optically transparent when subjected to an external electric field the refractive index of the material would change. Invariably, the electric field *versus* optical effect experienced is nonlinear with the result that a time-varying electric field will modulate the refractive index and hence a phase shift is experienced by the light passing through the medium. In materials which have a central symmetry, this phenomenon is called the *Kerr effect*; in noncentrosymmetric materials, it is referred to as *Pockel's effect* [7]. See Chapter 17.

23.4.6 Nonlinear Electroacoustic Properties

Electroacoustic synergism is experienced in certain classes of materials in which the mechanical atomic vibrations are influenced by the electronic polarizability with the result the non-linear interaction between the atomic displacements *versus* the electric field would cause modulation effects resulting in the generation of new sideband frequencies. Such sidebands (labeled as *Raman frequencies*) and the response function of a *Raman active medium* has the form:

$$H(\omega) = A_1 E(\omega) + A_2\, E^2(\omega) + A_3\, E^3(\omega) + \ldots \tag{23.1}$$

23.4.7 Pyrosensitive Properties

The pyrosensitive property is governed by a class of materials known as *solid electrolytes* (Chapter 16). On thermally energizing such materials, they exhibit *superionic electric conduction* (also known as *fast-ion conduction*). With the result, the medium which is dielectric at cold conditions becomes conducting at elevated temperatures. Correspondingly, the media which are embedded with solid electrolytes show different extents of electromagnetic reflection/transmission characteristics at low and high temperatures, and hence can be manipulated thermally [4].

Typical solid electrolytes which can be adopted for such pyrosensitve applications are, for example, AgI and $RbAg_4I_5$. The materials such as β-AgI and β-alumina show increasing conductivity with increasing temperature. The compound β-AgI exhibits superionic conductivity with an abrupt transition at a temperature close to 147°C. This transition is known as the β- to α-phase transition and there are a host of other materials which exhibit this phenomenon. For example, material such as $RbAg_4I_5$ has a high electrical conductivity even at room temperature. It has also been observed that solid electrolytes provide sufficiently high electrical conductivity in the α–phase even when included in low volume fractions in a mixture with a non-solid electrolyte host [4].

23.4.8 Nonlinear Electromagnetic Properties

Basically, the nonlinear electromagnetic properties can manifest as two subsets of material characteristics, namely, nonlinear dielectric properties and nonlinear magnetic properties.

Nonlinear dielectric properties: Dielectric materials whose permittivity has a distinct dependence on the intensity of the applied electric field are referred to as active or *nonlinear dielectrics*. Such materials demonstrate very high values of permittivity (order of several thousands), pronounced dependence of dielectric parameters on the temperature and a loop of electric hysteresis under the action of an alternating voltage.

Ferroelectrics are the most typical examples of nonlinear dielectrics. Rochelle's salt (potassium sodium tartarate) was the first substance in which the nonlinearity was discovered. All ferroelectrics, however, possess the nonlinear properties only within a definite temperature range. The temperature transition points over which the ferroelectric materials gain or lose their ferroelectric properties are referred to as Curie points. The arsenates and dihydrogen phosphates of alkali metals are also examples of ferroelectric materials (Chapter 12).

Piezoelectrics also fall under the category of active dielectrics. *Electrets* which are capable of preserving an electric charge for a long period of time (hence regarded analogous to permanent magnets) exhibit highly nonlinear dielectric properties (Chapter 12 and 13).

Nonlinear magnetic properties: Ferromagnetic materials are materials in which the permanent magnetic dipoles align themselves parallel to each other. These materials have a characteristic temperature below and above which their properties differ greatly. This temperature is referred to as the Curie temperature. Above this temperature they behave as paramagnetic materials, while below it they exhibit the well-known hysteresis *B versus H* curves. Examples of such ferromagnetic materials are iron, Mu-metal™, Supermalloy™, etc. Ferrimagnetic materials are similar in their hysteresis properties to ferromagnetic materials but differ from them in that their magnetic dipoles align themselves antiparallel to each other. Ferrites are the most popular ferrimagnetic materials and they are of the greatest interest in electrical engineering applications (Chapter 15).

23.5 State-of-the-Art Smart EM Materials

23.5.1 *Piezoelectric smart materials*

These find applications primarily in intelligent structures deploying electroelastic synergism and a class of ceramics (popularly known as ferroelectric ceramics) has emerged in recent times for such applications. Typically such ceramics include the base polycrystalline piezoelectrics such as $BaTiO_3$, $CdTiO_3$, $PbZrO_3$, $PbTiO_3$, etc., formulated with various stoichiometric proportions. Another class of piezoelectric flexible composite which has the potential for smart applications is a compound consisting of $PbTiO_3$ and chloroprene rubber. A set of glass ceramic composites containing the crystalline phases of Li_2SiO_3, $Li_2Si_2O_5$, $Ba_2TiSi_2O_8$, $Ba_2TiGe_2O_8$, $Li_2B_4O_7$, etc. are also emerging materials in smart material engineering [2].

Piezoelectric smart materials can also be made from the family of polymers, namely, polyvinylidene fluoride (PVDF). The main advantage of using this polymer is that it can be formed into very thin sheets and has excellent mechanical strength combined with high sensitivity to pressure changes.

Another piezoelectric material recently developed in the NTK Research facility in Japan is a kind of rubber-based material referred to as piezoelectric rubber. This material is composed of a base material of synthetic rubber, namely, chloroben dispersed with fine particles of a popular piezoelectric ceramic, called PZT (lead zirconium titanate). Piezoelectric rubber combines the favorable properties of PZT, namely, high sensitivity, chemical inertness, linearity, and simplicity with that of the rubber base, namely, flexibility. The main drawback with piezoelectric rubber is in making an electrical contact with it. This problem has been circumvented by the development of a coaxial cable connection which is easier to use. See also Chapter 13.

23.5.2 *Magnetostrictive smart materials*

Materials with a high degree of magnetostriction are deployed in modern intelligent structures. Typically the amount of strain inducible with intelligent materials in the current state of the art is 2000 ppm. These are alloys made with iron and rare-earth materials such as terbium (Te), dysprosium (Dy), niobium (Nb), etc. A commercially known material of this category is Terfenol™ [5]. Magnetostrictive transducers for smart applications have also been developed with a certain class of metallic glass materials.

23.5.3 *Electroplastic smart materials*

Electroplastic materials are useful as smart elastic media inasmuch as the stimulus which modifies the elastic deformation is the electric current which can be controlled externally. The usefulness of these materials for smart systems under room temperature conditions is still under investigation.

23.5.4 *Electrorheological smart fluids*

Current research on electrorheological fluids is focused towards development of carrier-particle combinations which result in the desirable characteristics to achieve smart elastic behavior [6]. The earlier versions of electrorheological fluids contained adsorbed water which limited their operating temperature change (up to 80°C). Particles in the newer electrorheological fluids are, however, based on polymers, minerals, and ceramics which have a higher operating range (200°C). Also, increase in power consumption is lower with temperature increments in the recent anhydrous systems. The most commonly used carrier fluids are silicone oil, mineral oil or chlorinated paraffin which offer good insulation and compatibility for particulate dispersion.

23.5.5 *Electrooptic smart materials*

Typically, potassium dihydrogen phosphate (KDP) exhibits electrooptic behavior. Synthetic materials which have the ability to alter their refractive index (and hence the optical transmission and reflection characteristics) in the presence of an electric stimulus can be comprehended as viable smart sensor applications.

23.5.6 *Electroacoustic smart materials*

Though classically the nonlinear interaction of a vibrational (acoustic) wave and an electromagnetic wave have been studied in reference to Raman active media, relevant concepts can be exercised for smart engineering applications using those materials which exhibit a strong vibrational *versus* piezoelectric characteristics. NTK piezorubber, PZT ceramics, $LiNBO_3$, PZT with donor additives, insolvent additives, etc. are viable candidates for smart applications in addition to piezoelectric polymers.

23.5.7 *Pyrosensitive smart materials*

These are useful in realizing intelligent electromagnetic active surfaces, radar absorbing materials, electromagnetic shielding, etc. For example, it has been demonstrated in [4], that the microwave reflection characteristics at a surface of a composite medium comprised of thermally controllable, solid-electrolytic zones (made of AgI pellets) show broadband microwave absorption/reflection characteristics under elevated temperatures. This principle can be adopted in conjunction with an electromagnetic sensor to provide a controllable feedback for thermal activation of fast-ion zones reconfigurably so as to achieve smart active-surface characteristics. Exclusive for this application, depending on the temperature limited conditions, the solid electrolytes can be chosen on the basis of their α– to β–phase transition characteristics. In order to keep the cost of the system low, a mixture phase can also be adopted, in which, commensurate with the elevated temperature operation, the host medium of the mixture could be a ceramic (dielectric).

23.6 Smart Sensors

These refers to smart sensing transduction applications of electromagnetic materials. The following are relevant examples:

23.6.1 *Fiberoptic-based sensors*

The field of sensing technology has been revolutionized in the past decade by the entry of fiber optics. The properties of fiber optics which have made them suitable for communications are responsible for their being successful as sensors as well. Fiber optic sensors are of two types, namely, extrinsic and intrinsic. In the extrinsic type the fiber itself acts only as a transmitter and does no part of the sensing. In an intrinsic type, however, the fiber acts as a sensor by using one of its intrinsic properties such as induced birefringence, electrochromatism, etc. to detect a phenomenon or quantify a measurement. Relevant to smart systems, use of fiber optics in conjunction with optical (sensors) is based on changes in optical effects such as refractive index, optical absorption, luminescence, chromic properties due to alterations in the environment in which the fiber is embedded. Such alterations refer to strain or other elastic characteristics, thermal and/or electromagnetic properties as well [9]. Surfaces located with smart fiber sensors are known as smart skins.

23.6.2 *Piezoelectric-based sensors*

The most conventional form of sensing technology is that of piezoelectric materials which generate an electrical response to a stimulus. In recent times the piezoelectric materials have been improved to a large extent in mechanical strength and sensitivity. Pressure and vibration can be directly sensed as a one-to-one transduction effect resulting from elastic-to-piezoelectric effect. Bending on the other hand can be sensed *via* piezoabsorption characteristics.

23.6.3 *Magnetostriction-based sensors*

Use of metallic glass as a distributive magnetostrictive sensor has been studied. Typically, in the embedded smart sensing applications using the magnetostrictive property the magnetic field is in the submicrogauss regime and the nonlinearity associated with the hysteresis of magnetostriction provides detectable sensor signal. Pressure/force, which cause static or quasistatic magnetic fields, as well as the vibrations which induce alternating magnetic fields can be regarded as direct magnetostrictive sensor responses. In the bending mode, corresponding magnetostrictive absorption can also be sensed *via* loss in the Q-factor due to absorption losses in a magnetostrictively tunable system.

23.6.4 *Shape-memory effects-based sensors*

The latest form of sensing technology utilizes shape-memory materials, namely, Nitinol™ alloys. The Nitinol™ sensors are used for measuring strain and consist of superelastic Nitinol™ wires. The basic concept is to measure the change in resistance of a Nitinol™ wire used as the unbalanced arm of a Wheatstone bridge as a function of the strain. The desirable properties of Nitinol™ in such a sensing application are its high sensitivity and superelastic nature (which permits strains up to 6% to be accurately and repeatedly measured). The piezoelectric and Nitinol™ sensing materials can also be used for actuation applications [10].

23.6.5 *Electromagnetic-based sensors*

Smart electromagnetic sensors are simple deviations of classic electric/magnetic probes, more properly known as antennas or pickups. Depending on changes in the surroundings *vis-*

a-vis the electromagnetic characteristics, these sensors respond and yield a corresponding signal. Again, the environmental changes refer to possible alterations caused by elastic, thermal, optical, magnetic, electric, and/or chemical influences.

23.6.6 *Electroacoustic smart sensors*

These are embedded acoustic (vibration) sensors (similiar to a microphone) which adaptively yield a signal proportional to the acoustic input. Such inputs could result from changes in the alterations in the surroundings caused by elastic, thermal effects, etc.

As far as smart sensor technology is concerned, in fact all the synergistic responses and effects between the electric and nonelectric phenomena discussed before can be judiciously adopted. However, considering state-of-the-art technology and practical considerations the existing smart sensors are limited to the aforesaid versions. Future trends could, however, include other possible electric to nonelectric synergistic responses.

23.7 Examples of Intelligent/Smart Systems

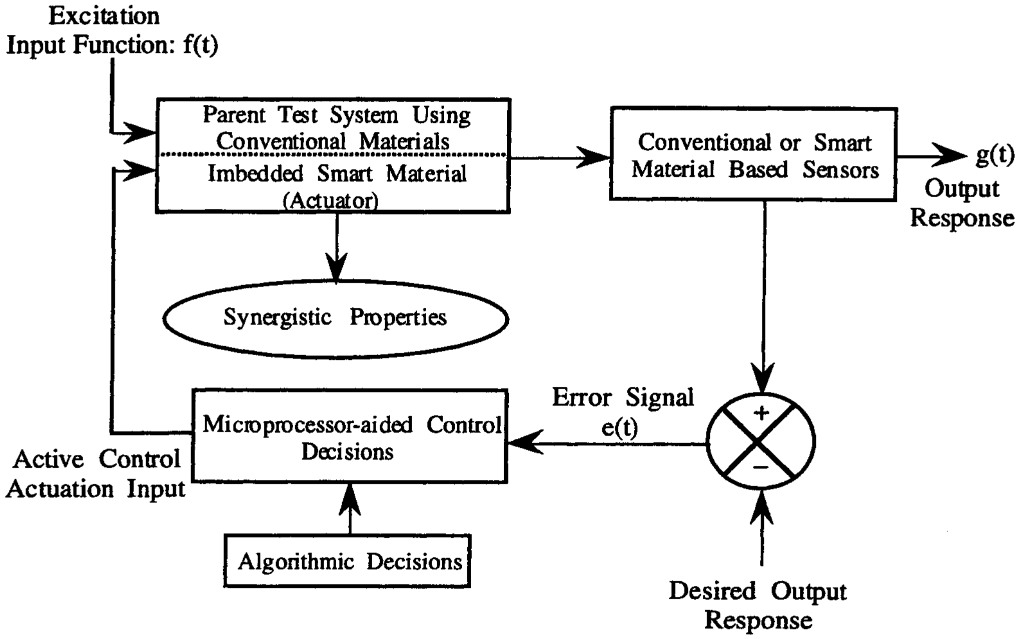

Figure 23.3 Schematic of a smart system.

The method of synthesizing a smart/intelligent system is illustrated in Figure 23.3. The output response under a given set of input condition(s) of a parent test system is normally decided by the properties of the constituent (conventional) materials. However, if the system states (changes) under the influence of external inputs are sensed, an appropriate feedback control can be used to "actuate" an embedded "smart" material in the parent unit so that output will track adaptively a desired response. The feedback path may include relevant electronic hardware (such as microprocessors) for on-line processing of the feedback signal to optimize the system performance.

Essentially, the smart materials can be adopted in two regimes of the system shown in Figure 23.3. The "sensing unit" can be zones of an integrated set of smart material which senses the response of the parent system on real time basis. (Sometimes, conventional sensors/tranducers can serve this purpose, as well.)

The "actuating unit", built-in as a part of the parent structure consists of a smart material, which upon receiving the electric signal from the feedback loop modifies the response of the parent system as dictated by the input signal. Thus, the actuation is based on the synergism between the electric input to the corresponding material property of the parent structure being altered.

The feedback control unit may consist of decision logics which can relatively modify the error-signal being fed to the actuator. The decision logic(s) refer to, for example, response linearization, time-averaged smoothing, amplitude-limiting, bandwidth control, etc. On the basis of the general schematic depicted in Figure 23.3, a few examples of application-specific intelligent systems using smart materials follow:

23.7.1. *Structural engineering applications*

Active control of vibrating beams: Illustrated in Figure 23.4, is a smart vibration control strategy in structural beams. Normally, the parent beam is made of conventional material(s) and its vibrational characteristics are decided by the elastic behavior of the constituent materials. Suppose a smart material is embedded in the test beam. This material could be one of the types indicated in Figure 23.2. A vibration sensor yields an electric output proportional to the vibration. Suppose the dynamic response of the beam (as observed at the output of the sensor) deviates from the desired characteristics. Then an error signal will be generated which in turn can be used to develop an optimal control signal; and this control signal can be fed back to the smart material whose elastic behavior is then altered as a function of the control input. As a result, the vibration characteristics of the entire (parent) structure are modified; or the system is dynamically tuned in an adaptive manner.

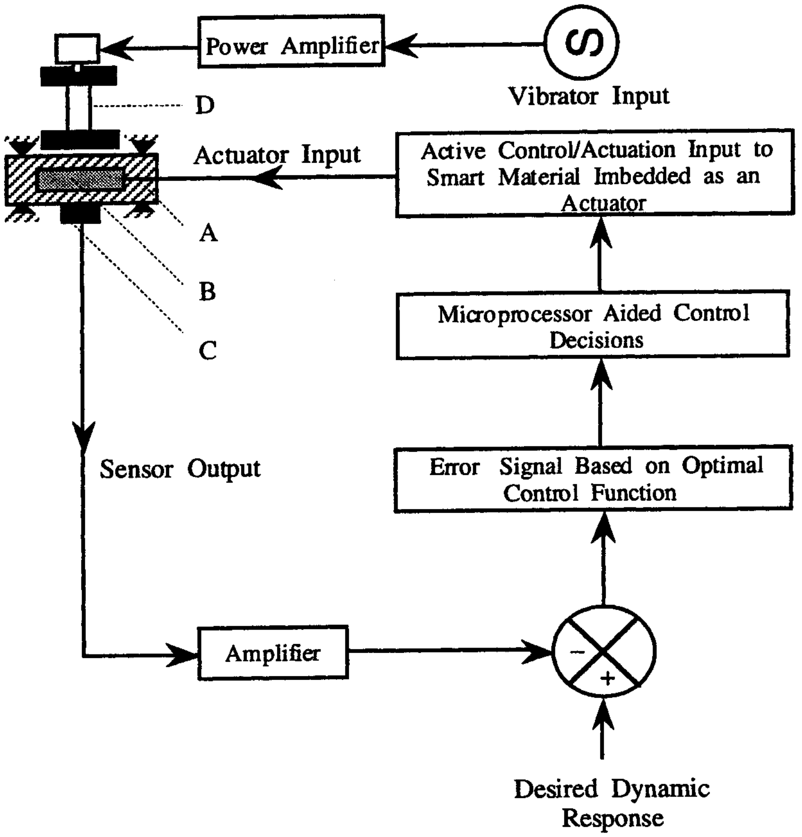

Figure 23.4 Active control of vibrating beams.

The vibration sensor used either can be a conventional transducer (such as resistive, capacitive, inductive or optical displacement versions) or it can be a smart sensor by itself.

For example, an optical fiber with a leaky sheath (which permits the light energy to leak from the core to the outside surface) can be embedded in the parent structure. When the structure is deformed, the extent of light leakage from the fiber to the surrounding will modify proportionately. Hence, the detected light signal from the fiber optics when detected delivers information on the deformation or the dynamic structural characteristics of the test beam. This sensor can be made "smart" by integrating a distributed set of fibers which can sense the strain, vibration, temperature (if needed), etc. so that the network implemented with appropriate algorithms will provide exhaustive data for a comprehensive adaptive feedback control strategy.

Though the scheme illustrated in Figure 23.4 refers to vibration control (or damping) in structures, judicious choice of subsystems, materials, etc. would also permit adaptive control of other structural aspects such as the strain, bending moment, and redistribution of load path in response to failures, etc.

23.7.2. *Electromagnetic applications*

The smart material/structural techniques can be adopted in electromagnetic systems. The following are possible applications:

- Smart low frequency magnetic shields
- Smart high frequency electromagnetic shields
- Smart electrostatic dissipative/conductive surfaces
- Smart radar absorbing materials (smart RAMs)
- Smart linear and aperture antennas

In all the above applications, the basic consideration is that the relevant structure can smartly and adaptively change its electromagnetic properties (normally specified *via* dielectric permittivity, magnetic permeability and electrical conductivity parameters) so that the desired electromagnetic performance is achieved. Two typical systems are detailed below.

Electromagnetic active surface embedded with ferroelectric inclusions

Figure 23.5 illustrates the concept. The surface is made of a mixture of polyacrylamide, ferrite and barium titanate on a ceramic substrate. This skin material which represents a lossy, nonlinear electromagnetic medium with anisotropic ferroelectric and ferromagnetic properties offers different extents of surface impedance in the presence and absence of an electric voltage stimulus applied to it. Hence, the reflection coefficient of this material to electromagnetic energy can be altered *via* electric stimulus. Relevant feedback can facilitate adaptive "smart" responsiveness of the system as illustated [4].

Smart electromagnetic aperture

The aperture radiation of microwaves can be "smartly" controlled by using a pyrosensitive material as illustrated in Figure 23.6. A set of solid-electrolyte (AgI) pellets interconnected *via* nichrome heating elements is placed at the aperture of a microwave horn. At room temperature, the pellets behave as dielectrics (β-phase AgI). However, when heated, the β-phase AgI changes to a highly conducting medium (α-phase) which would "mask" a part of the aperture, thus modifying the radiation pattern of the horn antenna. Again, an appropriate feedback loop would render the functioning of this system intelligent [4].

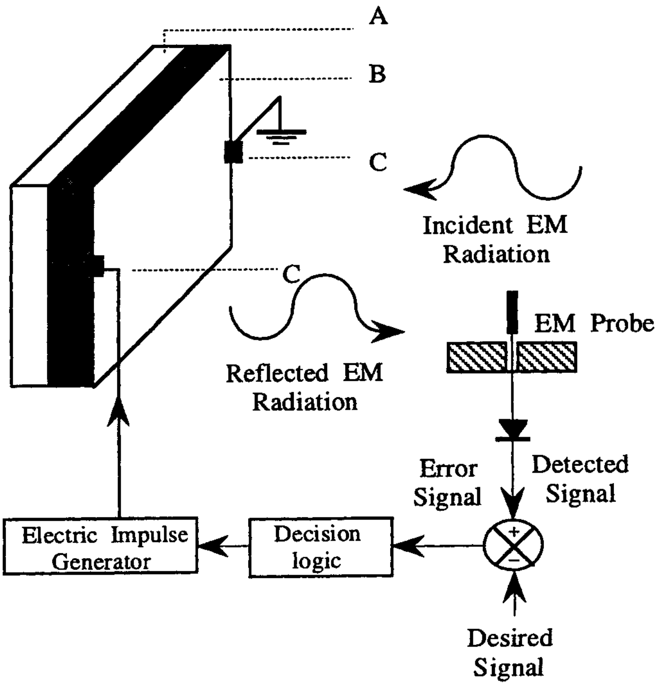

Figure 23.5 Smart EM active surface.

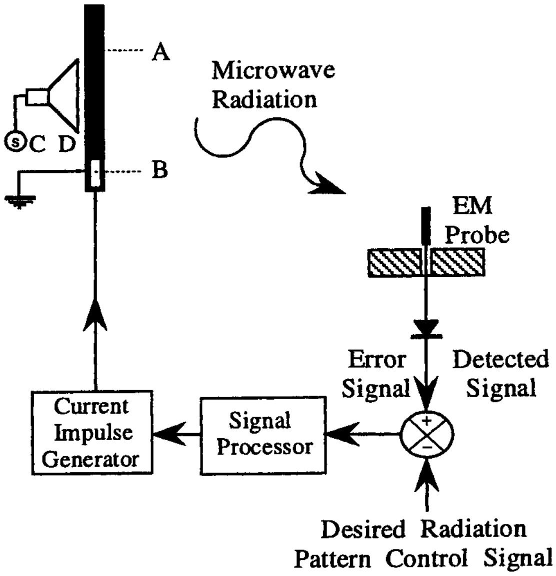

Figure 23.6 Smart electromagnetic aperture radiation control.

23.8 High-Tech Application Potentials

Though smart material technology is in its infancy pending significant efforts to make them usable on a wide-scale basis, the existing results and ongoing research have confirmed the usability of these materials in several avenues of modern high technology systems.

The use of intelligent materials currently imaginable enclaves not only structural engineering but also other areas such as electromagnetics, biomedical, optical, and biological techniques. Relevant research has also been focused heavily on aerospace, aeronautics, marine vessel, and robotic applications.

Adaptive, self-monitoring of well-being by a system which has an integrated set of smart devices to self-assess its performance, diagnosing any malfunctions/failures, and ability to change the system characteristics *vis-a-vis* the environment have been the objectives of the relevant seed-research pursued until now. For example, self-checks health by aircraft *via* a network of smart-skin sensors offer real-time monitoring of the structural well-being of tomorrow's aircraft [9]. The protocol in such efforts includes self-diagnosis, prediction/notification, and self-repair strategies relevant to mechanical structures (such as aircraft bodies).

Another domain of smart material application refers to self-induced morphologies in the infrastructure of the material with "self-adaptive" adjustments to the surroundings. Examples of this category include: Materials usable over a wide range of temperatures (as in space shuttles, etc.), with a smart adaptability to transform according to the environment. Similarly, in radar stealth applications, the target skin could offer variable electromagnetic absorption over a broadband of radar frequencies.

Extensions of smart material concepts can cover selective acoustical absorptions, adaptive chromic controls in glasses, mirrors, etc. In short, viable smart systems can be conceived with various combinations of material characteristics discussed earlier together with the advent of new conventional materials, innovative sensors, advances in microcomputers, artificial intelligence, neural networking, and other upcoming technologies. Currently imaginable "outlets" for smart materials are summarized below:

23.8.1 *Structural/mechanical engineering*

- Airborne/space-borne systems with "smart skins" for adaptive self-health check feasibilities
- Earthquake resistant intelligent buildings
- Large deployable space structures
- Nondestructive evaluation of large structures

23.8.2 *Thermal engineering*

- Adaptive heat transfers and heat-resistant structures (space shuttles, etc.)

23.8.3 *Optical engineering*

- Adaptive hue, optical transparency, reflection, opaqueness control in glasses and mirrors

23.8.4 *Electromagnetic engineering*

- Magnetic and electrostatic shielding
- High frequency shielding
- Radar absorbing materials
- Active surfaces
- Adaptive scattering/radiation control

23.8.5 *Acoustical engineering*

- Active absorption/reflection of sonar radiations
- Adaptive anechoic chambers

23.8.6 *Chemical engineering*

- Materials with adaptive adsorption characteristics
- Adaptive corrosion-resistant materials

23.8.7 *Biomedical engineering*

- Materials with "smart" structural properties usable as artificial limbs
- Materials with adaptive biochemical properties

23.8.8 *Warfare systems*

- Smart shelters
- Shock-resistant structures

23.9 Conclusions

The quest for new materials in scientific endeavors and engineering applications is everlasting. The emergence of the smart material concept has set a trend that science and technology in the coming years will rely on to a large extent in the development of exotic materials, with "intelligent materials" being the leading candidates. Such materials will be "hyperfunctional" with "unstereotyped purposeful response to novel and changing situations".

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Defining Terms

Electroacoustic smart materials: Materials which have self-adaptive characteristics on their acoustical behavior (such as transmission, reflection and absorption of acoustical energy) in response to an external stimuli applied as a function of the sensed acoustical response.

Electromagnetic smart materials: Materials such as shielding materials, radar absorbing materials (RAMs) and electromagnetic surface materials in all of which some electromagnetic properties can be adaptively controlled by means of an external stimuli dictated by the sensed electromagnetic response.

Electrooptic smart materials: Materials in which their optical properties are changed self-adaptively with an external electric stimulus proportional to the sensed optical characteristics.

Electroplastic effect: Plastic deformation of metals with the application of high density electric current.

Electroplastic smart materials: Materials with smart properties of elastic deformation changes proportional to a controlled electric current applied in proportion to the sensed deformation.

Electrorheological property: Property exhibited by some fluids which are capable of altering their flow characteristics depending on an externally applied electric field.

Electrorheological smart fluids: Fluids with smart flow characteristics dictated to change self-adaptively by means of an electric field applied in proportion to the sensed flow parameters.

Intelligent structures: Structures constructed of smart materials with a dedicated, discrete set of integrated actuators, sensors, etc., so as to respond to the environment around them in a predetermined (desired) manner.

Magnetostrictive effect: Structural strain experienced in a material subjected to a polarizing magnetic flux, or reversibly experiencing magnetic property changes to external mechanical stresses.

Magnetostrictive smart materials: A class of materials with elastic properties self-adaptively modifiable in response to a magnetic field applied in proportion to a sensed and fed-back stress-strain information.

Nonlinear dielectric property: The distinct dependence of the electric permittivity of certain dielectric materials on the intensity of an applied electric field.

Nonlinear electrooptic property: Nonlinear changes in the refractive index of certain optically transparent materials with change(s) in the externally applied electric field.

Nonlinear magnetic property: Nonlinear dependence of the magnetic susceptibility of certain materials on the intensity of an applied magnetic field.

Piezoelectric property: Ability of a material to induce opposite charges at two faces (correspondingly to exhibit a voltage difference between the faces) of the material as a result of the strain due to a mechanical force applied across the faces; reversibly, application of a potential across the faces would induce a mechanical strain.

Piezoelectric smart materials: Materials capable of changing their elastic characteristics (by virtue of their piezoelectric property), self-adaptively in response to an externally applied electric potential proportional to the observed elastic behavior.

Pyrosensitive properties: Exhibited by materials known as solid electrolytes whose electromagnetic properties could be altered by temperature.

Pyrosensitive smart materials: Materials which manage the electromagnetic surface characteristics of active surfaces constituted by pyrosensitive inclusions self-adaptively ("smartly") in response to an external temperature-inducing stimulus applied as per the fed-back information on electromagnetic characteristics.

Shape-memory effects: Mechanism by which a plastically deformed object in the low-temperature martensitic condition regains its original shape when the external stress is removed and heat is applied.

Shape-memory smart materials: Materials which smartly change their elastic characteristics by virtue of their shape-restoration characteristics achieved by means of an external stimulus in proportion to the magnitude of sensed shape changes.

Smart (or) intelligent materials: A class of materials and/or composite media having inherent intelligence together with self-adaptive capabilities to external stimuli applied in proportion to a sensed material response.

Smart sensors: Sensors with inherent intelligence *via* bulit-in electronics.

Smart structural materials: Materials in which the mechanical (elastic) properties can be modified adaptively through the application of external stimulus.

Smart thermal materials: Materials which can influence their thermal states (temperature or thermal properties such as conductivity) self-adaptively by means of an external control in response to environmental demands.