ON the Functional Characterization of "Intelligent" Materials

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Abstract— ***The paper reviews possible forms of intelligence that may be incorporated in various classes of engineering materials and structures. Basic mechanisms of intelligence are described, and implementation of these, as well as pertinent algorithms and techniques are illustrated. Possible analytical approaches to the functional characterization of intelligent material systems are discussed. For this type of material, it is logical to conclude that the micromechanical approach would generally overweigh the more conventional models of macromechanics. A knowledge-based experimental system, based on a pattern-recognition methodology, is ultimately introduced as a feasible technique to determine quantitatively the mechanical response states of intelligent material systems using non-destructive stress-wave propagation testing.***

Index Terms — Characterization, intelligence material, structure, mechanical response, micromechanics, microstructure, pattern-recognition. quasi-static, dynamic.

1. *INTRODUCTION*

Engineering materials are used either for their inherent structural strength or for their functional properties. Often a feed back control loop is designed so that the mechanical response of the material is monitored and the environment that is causing such a response can be controlled. The evolution of a new kind of material termed "*Intelligent*", "*Smart*", or "*Adaptive*", e.g. [1-6], witnesses a significant development in materials science. This concept aims at creating an artificially designed material, a so-called '*tailored*' material, having several functions in itself as a sensor, a processor, an actuator and feedback functions in combination with the inherent response characteristics of the parent material substance under consideration. The typical characteristics of an intelligent material may be stated to reflect that *'its properties, structural composition, function (and/or systematized functions) can adapt to the changes required in the environment and/or operating conditions'.* Such properties can be realized if the material has some built-in intelligence such as self-diagnosis, prediction / notification, self-repair and self-learning (i.e., with an ability to recognize, discriminate and backup). The concept of an '*intelligent/smart/adaptive*' material is related to a wide area of research, i.e., interdisciplinary fields such as medicine, biomaterials, polymers, metals, semiconductors, ceramics, mechanical and electronic engineering.

An "*Intelligent*" or "*Smart*" material may be defined as "*that material which senses any environmental change and responds to it in an optimal manner"*, e.g., Rogers *et al.* [6]. From this definition and the analogy of the *bionic* system of humans and animals, it can be seen that the following mechanisms may be essential for any material to be made intelligent (see Figure 1):

- A sensing device to perceive the external stimuli (e.g., skin which senses thermal gradients, an eye that senses optical signals, etc.), termed "*sensor*" function.
- A communication network by which the sensed signal would be transmitted to a decision-making mechanism (e.g., the nervous system in humans and animals), referred to as "*memory*" function.
- A decision-making device which has the capability of reasoning (e.g., the brain), designated as "*processor*" function.
- An actuating device, which could be inherent in the parent material or externally coupled with it (e.g., stiffening of muscles in humans and animals to resist any strain due to external loading), referred to as "*actuator*" function.

All of the above mechanisms need to be active in real time applications, so that the material could respond intelligently. Another important factor in the overall process is the time of response. This is the interval between the instant when the sensor senses the stimulus and that of the actuator response. An optimum time interval is crucial in the design of an intelligent material and obviously would depend on the particular application being considered.

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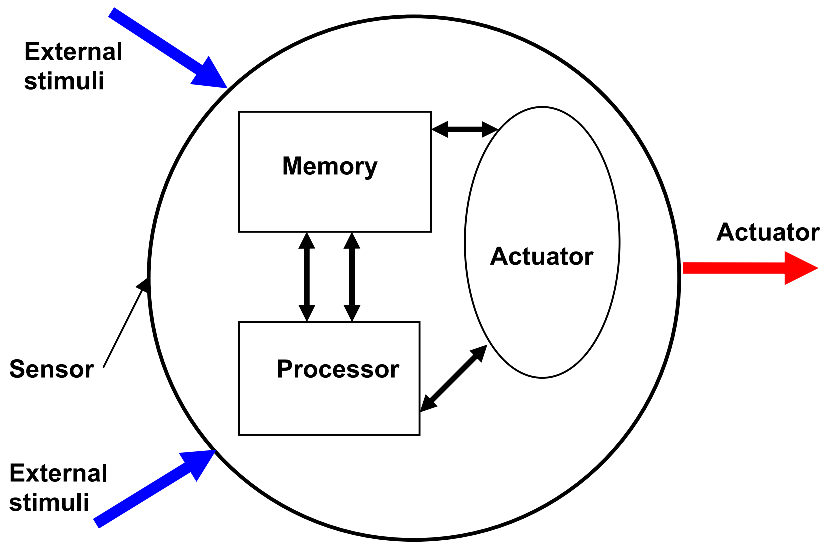

Figure 1. Concept of an "intelligent" material.

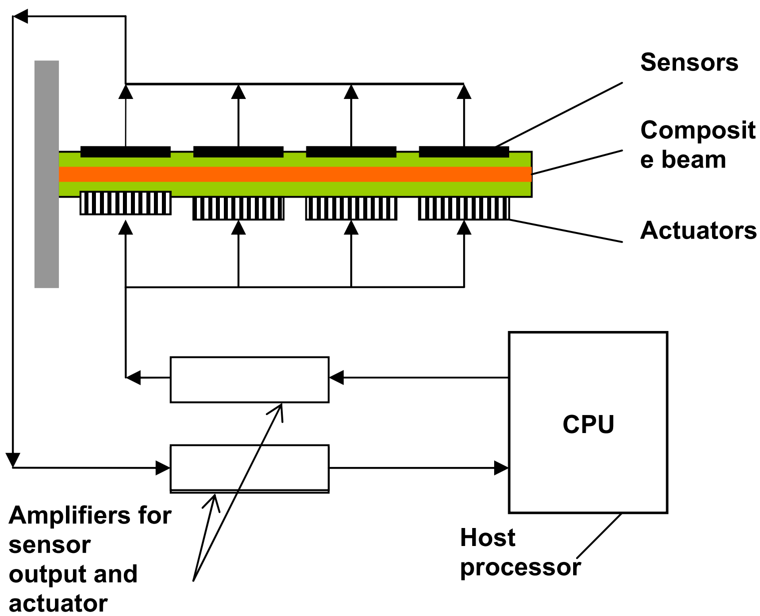

Figure 2. Incorporation of sensor, processor and actuator functions in an intelligent composite beam.

2. *INTERNAL FUNCTIONS OF AN INTELLIGENT MATERIAL*

2.1 Sensor Function

The concept of a sensor function in a smart material is defined as the ability of the material to sense the response, of self, to the externally imposed environmental factors such as mechanical loading, temperature, humidity and electrical inputs. An example of this function is that of an optical fibre sensor [7] embedded in a composite material. Such sensor diagnoses the mechanical disturbance imposed on the material by generating an output which can be further measured and analysed.

2.2 Memory and Processor Function

This mechanism stores the signals which are sensed and transmitted earlier by the sensor function. The characteristics of these signals are then compared with pre-stored acceptable values acquired during the '*training*' process of the processor. The training process may be carried out using an artificial intelligence technique, e.g., a pattern recognition method [8, 9]. Typically, this function is in the form of executable artificial intelligence software that could produce a logical output in the form of an electrical voltage that could be amplified and used to activate an actuator mechanism; see, e.g. Takagi [10].

2.3 Actuator Function

This mechanism is coupled with the material or the structure member. It produces an output corresponding to the signal received from the processor function. This output is usually in the form of a restoring stress, strain or change in temperature, or stiffness (response) of the actuator mechanism. Such change in response would be designed to neutralize the effect of the change in the environment on the material, thus enabling the material to adapt continuously to its environment. A typical intelligent composite cantilever beam which comprises of sensor, processor and actuator functions is illustrated, as a possible example, in Figure 2 above.

3. SOME CLASSES OF INTELLIGENT DEVICES

Different forms of substances that could be incorporated into the material as sensors and actuators could be designed, for instance, as piezoelectric and piezoceramic devices. Optical fibres also are often used as sensors. Shape memory alloys, shape memory polymers and electrorheological fluids, among others, can be employed as actuators

TABLE 1. Piezoelectric sensors and actuators

Type	Piezo-effect	Input	Output	Applications
Piezo ceramic (PZT)†	Direct	Stress	Voltage	Sensors for mechanical loading
	Converse	Voltage	Strain	Actuators for deformation control
Piezo electric polymer (PVDF)††	Direct	Mechanical loading (static and dynamic)	Voltage	Sensors for static and dynamic loadings. Also, as passive vibration absorbers
	Converse	Voltage	Strain	Strain rate control

† Lead zirconate titanate piezoelectric ceramics
†† Polyvinylidene fluoride

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3.1 Piezoelectric and Piezoceramic Devices

Piezoelectric and piezoceramic materials could be used as sensors and actuators in intelligent materials and structures. These devices can convert a mechanical signal to an electrical voltage, and vice versa.

A piezoelectric material is a crystal in which electricity or electric polarity is produced by pressure. Conversely, a piezoelectric material deforms when it is subjected to an electric field. The first characteristic expresses the so-called "*direct*" effect, while the second expresses the "*converse*" effect. Following the above characteristics of a piezoelectric crystal, if the pressure on the crystal is replaced by a stretch, the sign of the electric polarity would be reversed accordingly. This is determined by the crystal structural "*bias*" which establishes whether a given region on the surface is subjected to a positive or a negative mechanical effect. In the converse effect, the same unidirectional aspect determines the sign of deformation when the direction of an electric field input is reversed in the crystal. It is this reversal of sign of mechanical strain with that of the electric field that distinguishes piezoelectricity from electrostriction. Table 1 describes the utilization of direct and converse piezoelectric effects as applied to the sensor and actuator functions of such classes of intelligent materials [11-13].

3.1.1 Piezoelectric sensors and actuators

As mentioned in the foregoing, mechanical displacement and electrical voltage are the varying parameters of the intelligent material when using piezoelectric sensors and actuators. Mechanical disturbance is converted into electrical voltage by a piezoelectric sensor [14, 15]. On the other hand, a piezoelectric actuator is activated by an electrical input to produce specific mechanical effect (e.g., vibrations or strains) through properly designed control algorithms. Such mechanical effect would then be used to compensate or control undesired effects such as deflections, excessive vibrations caused by the external stimuli acting on the engineering material or structural member with which the intelligent material is incorporated.

3.1.2 Piezoelectric polymers as intelligent sensors and actuators

Polyvinylidene fluoride (PVDF), for instance, is a piezoelectric polymer that can be used for sensor/actuator functions. The piezoelectric polymer may be embedded inside a structural member to actively control the vibrations and/or strains by dissipating the elastic energy imposed on the member. Such attenuation is achieved by converting a large fraction of the elastic energy into electric energy using the piezo-electric coupling effect and then dissipating the electrical energy using a simple resistive element, e.g. [15].

3.2 Optical Fibers as Sensors

Optical fibres can be used effectively as sensors in intelligent materials. Optical fibres may be classified, in general, into the following two types:

i) An extrinsic optical fibre sensor that operates only as a transmitting medium for light but it does not perform any of the sensing functions.

ii) An intrinsic optical fibre sensor that utilizes some intrinsic property of the fibre to detect a phenomenon or to quantify a measurement.

TABLE 2. Applications of optical fibres

Variable	Methodology	Examples of applications
Stress	Photoelastic effect	Fibre composites embedded with optical fibres can detect mechanical loading & vibrations
Strain	Change in optical power due to deformation	Strain could be sensed in structures embedded with optical fibres
Temperature	Thermal change in refractive index	Thermal state of fibre composites could be monitored during manufacturing by embedded optical fibres

Glass and silica fibres form a basis for a broad range of sensors. These fibres utilize the pertinent material properties to provide signals, indicative of external stimuli such as force, temperature and strain that are to be measured. The intrinsic properties of glass and silica qualify fibre optics as smart materials. Optical fibres are capable of performing as a sensor as well as a transmitter of the sensor's signal. In this, optical wave guides may be embedded in the material composite and be used to determine the levels of dynamic strain to which the structural member is subjected to. This is carried out by using the change in the optical power transmitted in the fibre due to the induced strain in the structural member and processing the resultant signal; see e.g. [16, 17]. A list of intrinsically measurable variables associated with the use of optical fibres is given in Table 2 above.

3.3 Shape Memory Alloys (SMA's)

Shape memory alloys have emerged as an appropriate choice for situations involving dynamic control of large structures, which would often require vibration suppression and strain control. Such vibrations and strains are induced by an adverse environment.

Shape Memory Alloys possess response behaviour in dependence of the state of loading/strain they are subjected to, or the thermal environment in which they are loaded. If such alloys are deformed at one temperature, they will completely recover their original shape when their thermal state is raised to a higher temperature. On the other hand, if these alloys are constrained during recovering, they can produce a mechanical effect (a recovery response) that is in relation with their temperature of transformation. Several alloy systems exhibit the phenomenon of shape memory. A number of such alloy systems and their characteristics are given in Table 3 below.

In the case of "*one way shape memory effect*", an SMA wire, for instance, deformed below the temperature of the Martensitic end of transformation temperature can regain its original shape when heated to a temperature above that of the Austenitic transformation temperature. But when cooled again to the temperature of its Martensite start of transformation, the wire recovers its original configuration and the material does not assume any longer the earlier deformed shape. In the case of '*two way shape memory effect*', however, a deformed SMA material below its Martensitic transformation temperature would regain its undeformed configuration when heated to a temperature above the temperature of Austenite end of transformation. However, the undeformed configuration spontaneously attains its deformed configuration when cooled below its Martensitic end of transformation temperature. The specimen can, however, recover its undeformed configuration when heated to temperatures above its Austenitic end of transformation temperature. Thus, it is possible to produce two geometric configurations of the material,

TABLE 3. Alloy systems exhibiting shape memory effect

SME-alloy systems	Transportation temperature	Recovery force for 2% strain in Kg/mm^2
Nitinol[1]	373 K	17
Cu-Zn-Al[2]	350 K	9
CANTIM 75[3]	480 K	14

[1] 49.93% nickel and 50.03% titanium.
[2] 25.9% zinc, 4.04% aluminium and rest is copper
[3] 11.68% aluminium, 5.03% nickel, 2.00% Manganese, 0.96% titanium and rest is copper.

by subjecting it to thermal cycling. The latter is termed as the "*trainability of two way shape memory effect*".

Thermomechanical environment may subject materials to cyclic thermal loadings, leading to fatigue and other undesirable mechanical effects. If the shape memory material is made to alter its mechanical properties with respect to a mechanical loading, many of the induced strains, due to such loading, could be controlled. In this case, the thermal environment is sensed by an incorporated sensor and the SMA-material acts as an actuator by changing its mechanical response properties when heated (e.g., by passing an electric current through the SMA material); see, for instance [18-20].

In a multi-layered composite laminate with embedded SMA-fibres, excellent vibration suppression could be achieved when the laminate is subjected to dynamic loading. Varying the mode shapes of induced vibration could be also achieved by varying the stiffness of SMA-fibres. This is accomplished by utilizing the large force created on constraining the micromechanical phase transformation from a deformed state to an undeformed state. It is also possible to use SMA-fibres as simple thermomechanical actuators rather than integrating them into a fibre-matrix system. This is achieved by coupling the thermomechanical actuator to the structural member externally. By ensuring proper coupling between the actuator and the structural member, the effects of the SMA actuator could be transferred to the parent material. Thus, shape memory alloys can be used effectively as actuators in intelligent material systems, or structures, when coupled with proper sensor and control algorithms; e.g. [21].

3.4 Material Intelligence Using a Viscoelastic Microstructure

Polymeric materials are generally viscoelastic in response behaviour and have the capability of changing their dynamic properties (storage modulus E', loss modulus E" and loss tangent *tan* ϕ) with variations in environmental factors such as temperature, frequency and time; e.g. Haddad [22]. Thus, polymeric materials, in general, would have a smart/intelligent function capability. This is accomplished by a sensor/actuator mechanism

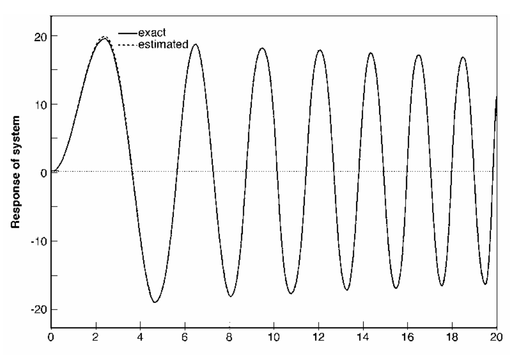

Figure 3. The exact and estimated responses from the first-order discrete time system for a particular first-order dynamic system with a first-order dynamic sinusoidal input.

that could be incorporated in a structural member so that external stimulus such as mechanical vibrations could be sensed. By incorporating a control mechanism, the dynamic moduli of the polymeric material could be made to change so that the material could adapt itself to the new environment. This could be achieved also by shifting the loss factor (*tan ϕ*) towards the frequency spectrum that matches the imposed vibrational frequency, so that the absorption of the imposed vibrations would be maximized. This shifting could be carried out by varying the loss modulus (E") or the loss factor (*tan ϕ)* of the polymeric material, which will be acting in this case as a damper, with respect to temperature or frequency.

For a linear dissipative system, it is well recognized that the behavioural functions characterizing both quasi-static and dynamic responses are interrelated, e.g. [22-24]. Quasi-static experiments, to determine such response functions, require, however, considerably long periods of time to be performed. To overcome such inconvenience, dynamic methods are recently attracting the attention of researchers. Gibson, *et al.* [25], for instance, presented a method by which experimental dynamic data are used to determine both quasi-static and dynamic response behaviour of the material. In their method, the complex moduli were obtained first from vibration measurements by employing Fast Fourier Transform technique. Then, the quasi-static time-dependent properties were calculated from the experimentally determined dynamic properties by employing a numerical integration algorithm. In this context, Haddad and Yu [24] considered that the viscoelastic material as a dynamic system, whereby a relation was established between the quasi-static response functions and corresponding frequency functions of a specifically proposed dynamic system. In the frequency domain, an analytical model was assumed for the frequency response function of the system, then, a discrete-time system analysis was developed to estimate the order and parameters of the proposed model. The proposed model was shown to be efficient and powerful; see, e.g., Figure 3 above.

3.5 Shape Memory Polymers

Shape memory polymers are unique polymeric materials which can recover their original shape before deformation at lower temperature (below the material's glass-transition temperature T_g), upon heating them to a temperature above their glass transition temperature T_g ; see e.g., Yoshiki and Shun-Ichi [27]. This is an apparent advantage over ordinary polymers. An ordinary polymer when stressed, may not recover completely to its original undeformed configuration if the stress is released (or its temperature is raised), thus, resulting in permanent deformation. In a shape memory polymer, however, the recovery loop is completed upon heating, thus, a shape memory polymer is able to revert back to its original shape without undergoing any permanent deformation.

3.6 Electro-rheological Fluids

The viscosity of certain fluids is influenced by the applied electric field. This phenomenon, termed "*Electroviscous Effect*", was first reported around the turn of the century; e.g. Duff [26]. Researchers have found, for instance, an increase in the viscosity of conducting polar liquids of up to 100%, upon application of an electric field of the order of 1-10 kV/cm. For the electroviscous effect to occur, both polar molecules and conducting impurity ions would be needed to be present. Large increases in viscosity, due to an applied electric field, for suspensions of finely divided solids in low viscosity oils was found as early as 1949. This effect, termed "*Winslow Effect*", is attributed to field induced fibre formation of the particles between the electrodes, thereby requiring additional shear stress for flow; see e.g. Conrad and Sprecher [27]. This phenomenon has recently been termed as "*Electrorheology*" and has been applied in the development of actuator mechanisms in intelligent materials. When used with suitable sensors and control algorithms, electrorheological fluids can be made to change their properties by subjecting them to an electric field.

With reference to Fig. 4, below, an engineering structural member which contains electro-rheological fluid, when not activated, has a very low composite stiffness. This state represents the undisturbed configuration. When an environmental input (e.g. mechanical loading or a difference in thermal gradient) causes, for instance, deflection in the structural member, it would be desirable to increase the stiffness to control or limit the occurring deflection. This is achieved by sensing the external mechanical loading through incorporated sensors. The sensed signal is then processed to a microprocessor, which activates an auxiliary electric input to produce a desirable voltage. This voltage, when applied to the electrorheological fluid contained in the mechanical structural member, increases the viscosity of the fluid, thus, practically converting it into a solid. As a result, the overall stiffness of the structural member is increased. The above said process could be made to take place in a matter of $1/1000^{th}$ of a second.

4. FUNCTIONAL CHARACTERIZATION OF "INTELLIGENT" MATERIALS

4.1 Macromechanics vs. Micromechanics

In assessing the mechanical response behaviour of an intelligent material system, macromechanics and micromechanics models are used.

In the *continuum mechanics* approach, the actual microstructure of the intelligent material system is disregarded and the medium is pictured as a "*continuum*" without gaps or empty spaces. Hence, the configuration of the assumed continuous medium is described by a continuous mathematical model whose geometrical points are identified with material particles of the actual physical medium. Further, when such a "continuum" changes its configuration under some boundary conditions, such change is assumed to be continuous, i.e., neighbourhoods evolve into neighbourhoods. Thus, the

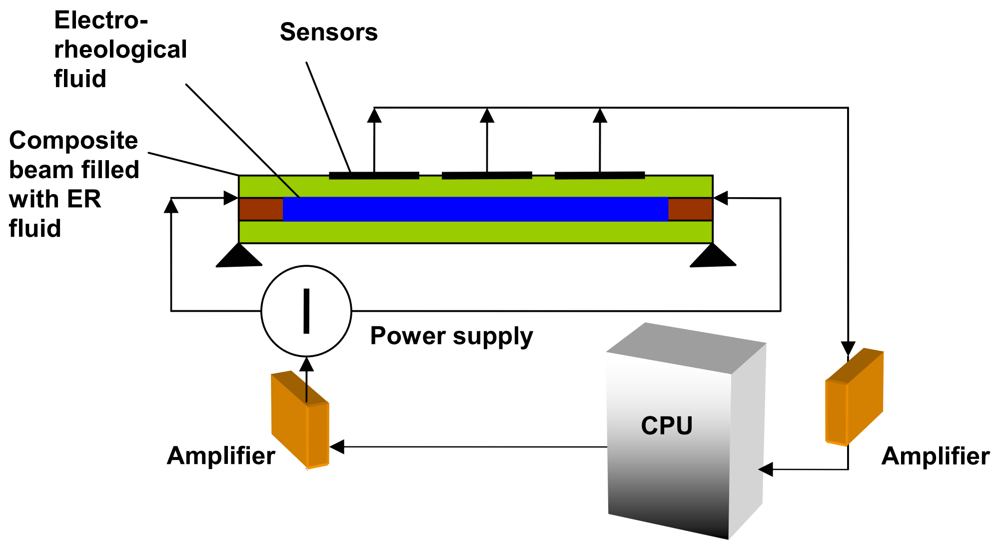

Figure 4. Electrorheological fluid as an actuator in a smart beam.

mathematical functions entering the analysis of the pertinent deformation process, are assumed to be continuous functions with continuous derivatives. Any creation of new boundary surfaces, such as those developed by interfaces between the sensor, actuator and the parent material may, then, be seen as extraordinary events that might require alternative formulations outside the realm of continuum mechanics. An example of intelligent material systems that often treated with continuum macromechanics is a cantilever beam whose response behaviour is controlled by two layers of piezoelectric material layers, e.g. [17].

In the *micromechanical* approach, however, the macroscopic medium is considered to consist of constituent structural elements. Such elements are often seen to be interacting with each other, and, hence their individual responses are considered to be mutually inter-dependent. The behaviour of an ensemble of such elements may be studied using, for instance, deterministic or statistical (stochastic) micromechanics; see, Haddad [8].

Laminated fibre composite materials, for instance, with their high specific modulus, high specific strength, and the ability to tailor them for a specific application, offer definite advantages as potential "*adaptive*", i.e. "*intelligent*" material systems. In this context, modelling of such response, from a micromechanical point of view, could provide in-depth understanding of the microstructural mechanisms that might be available for possibly controlling the mechanical performance of engineering structures made of such materials. Thus, in this context, the effects of selected microstructural parameters on the damping and stiffness of a class of "*adaptive*" viscoelastic fibre-composite systems may be examined. Subsequently, simultaneous optimisation of the adaptive material system characteristics, e.g., damping and stiffness, could be carried out; Haddad and Feng [28].

4.2 Pattern-Recognition and Classification Methodology

A knowledge-based experimental system; e.g. Haddad [8, 29], may be used to determine quantitatively the mechanical response state of an intelligent engineering material system, as based on quantitative non-destructive testing combined with "*pattern recognition" and "classification*" methodologies. In the pertaining experimental procedure, stress waves are "*simulated*" in the microstructure of the material system to resemble acoustic emission waves After propagating through the microstructure, the waveforms are captured, identified, and then classified as belonging to various classes, where each class represents one of different response states of the tested material-property. This experimental approach has been proven to be powerful in determining quantitatively numerous material response states in both homogeneous and heterogeneous classes of engineering materials that were subjected *priori* to unknown static, quasi-static and dynamic types of loading.

5. SUMMARY

Intelligent materials have the ability to control and hence improve the performance of engineering structures. Although the concepts of the techniques described in this article were discovered decades ago, only recently that such techniques have emerged as potential applications in intelligent materials methodology. The formulations for piezoelectric effect indicate the nature of direct and converse effects and their possible use in sensor and actuator technologies. Discussions relating to shape memory alloys, viscoelastic materials, shape memory polymers and electrorheological fluids, illustrate the possible usage of these materials as actuators in smart material systems. The increase in stiffness of shape memory alloys and the change in the dynamic moduli of shape memory polymers, and viscoelastic materials, in general, with temperature and/or frequency offer distinct advantages in controlling the static and dynamic states of the engineering systems and structures. In addition, the development of different feed back mechanisms, as based on control algorithms, and the increase in sophistication of microprocessor technologies and pattern recognition methodology will definitely play an important role in the advancement of processor function in this new field of science. It is emphasized that mechanical behaviour of intelligent material systems should be analysed using micromechanics. In this, an experimental quantitative approach based on pattern recognition and classification methodologies is proven to be useful.

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