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Structural Health Monitoring By Piezoelectric Sensor and Shape Memory Alloy Actuator

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Abstract:

In recent years, there has been a fast growing interest in using smart materials integrated with structural systems to form a class of smart/intelligent or adaptive structures. Smart materials have a wide range of engineering applications owing to is light weight and the ease with which these materials can be shaped and bonded to surfaces or embedded into structures. We have mainly three types of smart materials. Piezoelectric materials, the first set of materials, convert energy between the mechanical and electric domains. Shape memory alloy, the second set of materials, are thermo mechanical materials that deform when heated and cooled. The third type of materials will be electro active polymers that exhibit electromechanical coupling. In the present work, piezoelectric materials as well as shape memory alloy have been used to control the large displacements of the structure. Generally piezoelectric materials cannot be good actuators for large displacements. Whereas shape memory alloy can effectively recover strain up to 10% .So, current thesis highlights the usage of piezoelectric elements as sensors, and shape memory alloy as actuator.

1 INTRODUCTION:

1.1 Smart Material System:

A smart material system can be defined as an engineering system that utilizes the coupling properties of smart materials to provide their design function. Smartness of the material or structures describes their self-adaptability, self-sensing, memory and multiple functionality. The attribute of smartness includes the abilities to self-diagnose, repair, recover and learn. Its definition is based on its application to field of interest. While some definitions use biological technical aspects as highly integrated system of sensors, actuators and control strategies. There has not been a consensus over a unique definition of smart structures.

1.1.1 Actuator:

Actuator converts a non- mechanical input into mechanical output. Actuator materials are embedded with in a structural system or else bonded to the surface of the material. These actuators are typically exited by an external stimulus, such as electricity in order to either change their geometrical configuration or else their stiffness and energy dissipation properties in a controlled manner.

1.1.2 Sensor:

In sensing a mechanical signal is converted into non-mechanical output. They are one of the essential parts of a smart structure since they provide the ability to monitor and measure external stimuli in addition to the subsequent behaviour through the structure medium. The sensor function is typically employed to detect and monitor information.

1.2 Advantaged of Smart Structures:

Smart structures are needed, because we want our structure to be efficient, adaptive and responsive. Before venturing into any field it is very important to know the benefits or returns of its use. They are better than other because of following reasons. 10

1.2.1 Diminished cost:

For many systems the cost of purchase or manufacture is less than the cost of maintenance and operation. Continuous health monitoring the and maintenance help in minimizing the cost as compared to repairing a convention structure that has reached its distress condition.

1.2.2 Enhanced safety:

There are some systems such that they find their use after long period of their manufacturing such systems are unsafe to use.

Increased performance: This is the most important reason for need of smart structures. The changes in the system according to the changes in the eternal environments are nothing but optimization of a structure for increased efficiency and economy.

1.3 Smart materials or active material:

1.3.1 Overview:

Smart materials may be defined as those that exhibit coupling between multiple physical domains. Common examples of these materials are those that can convert thermal energy into mechanical strain or mechanical strain to thermal or electrical signals into mechanical deformation and can convert mechanical deformation into an electrical signal. So we can say that specialized subgroup of multifunctional materials that exhibit sensing and actuation capabilities is known as active or smart material.

1.3.2 Different Types of Smart Materials:

1.3.2.1 Piezoelectric Materials:

Piezoelectric materials exhibits electromechanical coupling. It produces an electric displacement when a mechanical stress is applies and can produce mechanical strain under the application of an electric field. However the relationship is linear fo low electric field values and non-linear for high electric fields and materials exhibits hysteresis. It is useful for design of devices for sensing and actuation.

1.3.2.2 Shape Memory Alloy:

The term shape memory alloy is applied to that group of metallic materials that demonstrate the ability to return to same previously defined shape and size when subjected to appropriate thermal or mechanical changes.

LITERATURE REVIEW:

The literature review in this chapter intends to present a good overview on important aspects of smart structures. It includes the structural behaviour of composite plates , mechanics of piezoelectric elements and shape memory alloy , history of smart materials ,constitutive relation of smart materials , active vibration control of structures using smart materials , buckling analysis of beams as well as beams .

2.1 Structural Behaviour of Composite Plates:

In this section a review is given on the development of the study of the structural behaviours of composite plates especially in the development of the displacement theories of laminated composites. Studies on structural behaviours of laminated composite plates has been studied since the early nineteen sixties. During the early studies, the analytical method was employed.

With the advent of computers and the development of displacement based laminated plate theories ranging from the classical lamination theory (CLT) to the higher order shear deformation theory, the approximate methods especially the finite element method has gained the most attention. It is well known that the behaviour of laminated plates can be accurately predicted if each layer is analysed by the three dimensional theory of elasticity. However due to its computational complication and cost, the equivalent single layer 2D theory was developed. In this theory, the displacements are expanded as a linear combination of the thickness co-ordinate and a laminated composite plate is represented as an equivalent single layer with anisotropic properties. This theory started with the classical lamination theory (CLT), which is the extension of the Kirchoff’s classical plate theory.

The CLT assumes the plane sections prior to deformation remain plane and normal to the deflected reference surface and the thickness does not change during deformation. This implies that it ignores transverse shear deformation, which is actually significant especially in thick laminated composites due to the high ratio between in-plane elastic modulus and transverse shear modulus. As a result, the CLT over predicts the critical loads and under predicts the stress and free vibrations compared to the exact values. This condition is improved by considering the transverse shear deformation in the shear deformation theories .The first order 14 shear deformation theories (FSDT) or Mindlin’s plate theory is based on the assumption that normal to the mid-plane remains straight during plate deformation, but not necessarily normal. However since transverse shear strains are constant throughout the thickness of the plate, this theory does not comply with the actual physical case where the shear strain at the top and bottom surfaces must be zero.

This inaccuracy of the solution can be improved by introducing the shear correction factor. Kam and Chang [1] derived the shear correction factor from the exact expression for orthotropic material for the buckling and vibration analysis of laminated plates using the FSDT and obtained results that were closed to the exact value. Another problem is that the solutions from the numerical methods can be too stiff especially for thin plates. This so called shear locking phenomenon though can be solved partly by applying selective or reduced integration; it is still a problem in many cases. With these problems in the FSDT, the higher order shear deformation theories (HSDT) that expands further the displacement in terms of the thickness direction were developed. Various theories of HSDT were proposed such as the third order theories of Reddy [2,3], Lo[5] and Zabaras and Pervez [4]. The theories of Lo [5] consider the second order displacement but the theories of Reddy and Pervez omitted that term. The third order theory of Reddy accommodates the parabolic distribution of transverse shear stress along the thickness of the plate and thus forces the transverse shear stresses on the top and bottom of the laminate to vanish which results in the omitting of the second order displacement term.

The third order theory of Zabaras and Pervez[4] however explained the third order displacement as the warping of the normal in the x and y directions and the second order displacements are omitted to meet the condition that the transverse shear stresses σxz and σyz vanish on the top and bottom surfaces of plate as in Reddy's theory. Studies on structural behaviours such as stress, deflection, vibration and buckling of laminated composite plates using several HSDT were conducted by researchers such as Lo [5], Phan and Reddy [l], Noor and Peter [7], Reddy and Khdeir [8] and Kozma and Ochoa [9]. In most cases the studies were conducted by varying the effects such as the level of anisotropy, plate thickness, the number of layers etc. Luccioni and Dong [10] conducted an intensive study on vibration and buckling of rectangular plates using the semi-analytical (Levy-type) finite element method. The extension to the geometric non-linear effect on the study of the composite plates was however studied by few researchers. Reddy [11] included the von Karman's non-linear effect in his study to calculate stresses and frequencies of composite plates while 15

Chandrashekhara and Bangera [12] used the same method for their study on beams. Understanding the post-buckling behaviour of laminated plates is important in order to know the load carrying capacity of plates after buckling. By this, the strength of the plate can be fully utilised and the weight of the plate can be reduced.

2.2 History of SMA:

The understanding of SMA started relatively late as compared to traditional materials such as metals and concrete.

The first reported SMA behaviour is the pseudo elastic behaviour of the gold-cadmium SMA that was discovered by a Swedish scientist in 1932. Chang and Read later discovered the shape memory effect behaviour of the gold-cadmium in 1951.It is however not until 1963 when Buehlers and co-workers at the Naval Ordnance Laboratory, USA discovered the shape memory effect of the nickel-titanium (Nitinol) that the understanding and the use of the SMA started to flourish. The SMA behaviours was later found in many other alloys such as CU-Zn, Cu-Zn-Al, Cu-Zn-Sn, Ni-Al and Fe-Pt.

A great deal of effort was expanded after this time to characterize the property of the SMA and to exploit those properties to the applications of the SMA. As the understanding on the subject grows, various constitutive relationship were proposed and tremendous amount of applications were suggested. SMA products has grown vastly in the field of actuators, coupling and fasteners, medical applications, smart composites, earthquake-suppression related applications, fashion, decoration and gadgets, appliances and many others. Reviews on this subjects can be obtained in books such as Funakubo [13] and papers such as C.S.Rogers [14].

2.3 SMA Constitutive Models:

This section is to give a review of some of the SMA constitutive models that are available in the literature. The aim of the constitutive model is to formulate mathematically the unified behaviours of SMA such as shape memory effect, quassi plasticity and pseudo elasticity. Several constitutive models have been and are still proposed to predict the thermo mechanical response of the SMA. One of the earliest model is the one dimensional Tanaka's model [15]. It is the macroscopic model that is derived from thermodynamic concepts and through experimental observations. The SMA behaviours in this model are constituted into two equations: constitutive equations and kinetic equations. The constitutive equation is obtained by minimization of free energy using the energy equation and the Clausius-Duhem 16 inequality. Martensitic transformation is considered progressive and this progress can be explained thru an internal variable, the volume fraction of martensite, ξ,. The evolutionary equation is determined by considering transformation micro-mechanism and it is expressed using exponential function in the form of $\xi=\xi(\sigma,T)$. Tanaka's model was found to be able to characterize most of the behaviours of the SMA. Liang and Rogers [15] improved the Tanaka's model by directly matching experimental result to get the evolutionary equation and this equation is expressed using the cosine function. The constitutive equation remains the same while parameters of the equations can be determined through experiments. A major improvement of the Tanaka's model was made by Brinson [17]. Brinson recognized that not all martensite that are converted to austenite will produce the recovery stress. Only the stress induced martensite that is responsible for the shape memory effect. As such, martensite fraction is divided into two: stress induced and temperature induced martensite. This model also does not assume constant material functions in the constitutive relationship. Furthermore Brinson's made some amendment so that the constitutive equation will be valid at any temperature. This model was found to give a better representation of the SMA behaviours than the Liang and Rogers's model [16].

1.3.2.3 Electro Rheological Fluids:

Electro rheological fluids are suspensions of extremely fine non-conducting particles in an electrically insulating fluid. In this a change in the electric field or mechanical filed can indirectly couple with the mechanical behaviour through change in the viscosity of the fluid. The normal application of ER fluids is in fast acting hydraulic valves and clutches.

1.4 Organisation of the Report:

Chapter 2 includes literature review on smart materials including piezoelectric materials and shape memory alloy. History of smart materials and their recent developments are highlight Chapter 3 includes the overview of piezoelectric elements including fundamentals of direct piezoelectric effect and converse piezoelectric effect. Details about displacement models, Van Kerman hypothesis is given. Strains are expressed in terms of midterm displacement including non-linear terms. Similarly electric potential function as well as temperature distribution across depth of the plate has been illustrated. In chapter 4, the behaviour of shape memory alloys is outlined. Phase transformation of SMA and their characteristics are discussed. Mechanism of shape memory effect and pseudo elasticity are explained

In the chapter 5, the governing equation of a composite plate having SMA wires along the neutral axis, piezo layers on the top and bottom. Stress strain relation of the composite plate has been derived. Strain recovery, stress recovery concept has been outlined. How to generate stress recovery has been explained. Temperature required to give the SMA in order to recover the stress and time of applying temperature are discussed with the useful equations.

PIEZOELECTRIC MATERIALS:

Overview:

Piezoelectricity from the Greek word "piezo" means pressure electricity. It is the property of certain crystalline substances to generate electrical charges on the application of mechanical stress. Conversely, if the crystal is placed in an electric field, it will experience a mechanical strain. The first property makes them suitable as sensors, whereas the second property makes them suitable as actuators to control structural response. Thus piezoelectric materials have the property to into mechanical energy and vice versa. When an AC voltage is applied, it will cause it to vibrate and thus generate mechanical waves at the same frequency of the input AC field. Similarly, it would sense the input mechanical vibrations and produce the proportional charge at the matching frequency of the mechanical input.

3.2 Direct Piezoelectric Effect:

When a piezoelectric materials being subjected to an applied stress. In addition to elongation like an elastic material, a piezoelectric material will produce a charge flow at electrodes placed at the two ends of the specimen. This charge flow is caused by the motion of the electric dipoles within the materials. The application of external stress causes the charged particles to move, creating an apparent charge flow that can be measured at the electrodes. The flow produced divided by the cross sectional area of the electrodes is the electrical displacement. The relation between the electrician displacement applied mechanical stress is given below.

$D = a\,\sigma$------------------------3.2.1

Where D = electrical displacement
a =piezoelectric stain coefficient
σ = mechanical stress

in addition to electrical displacement , mechanical strains will be produced. The relation between the mechanical strain and mechanical stress is given below

$\varepsilon = c\,\sigma$ ………………3.2.2
where ε = mechanical strain 21
c = compliance
σ = mechanical stress
so direct piezoelectric effect will be used in sensing application.

SHAPE MEMORY ALLOYS:

Overview :

Shape memory alloys (SMA's) are metals, which exhibit two very unique properties, pseudo-elasticity, and the shape memory effect. Arne Olander first observed these unusual properties in 1938 (Oksuta and Wayman 1998), but not until the 1960's were any serious research advances made in the field of shape memory alloys. The most effective and widely used alloys include NiTi (Nickel - Titanium), CuZnAl, and CuAlNi.

The two unique properties described above are made possible through a solid state phase change that is a molecular rearrangement, which occurs in the shape memory alloy. Typically when one thinks of a phase change a solid to liquid or liquid to gas change is the first idea that comes to mind. A solid state phase change is similar in that a molecular rearrangement is occurring, but the molecules remain closely packed so that the substance remains a solid. In most shape memory alloys, a temperature change of only about 10°C is necessary to initiate this phase change. The two phases, which occur in shape memory alloys, are Martensite, and Austenite.

After alloying and basic processing, SMAs can be formed into a shape (eg , a coil spring) and then set to that shape by a high heat treatment. When cooled, they may be bent, stretched or deformed (within limits) and then with subsequent moderate heating (well below the heat setting temperature), they can recover some or all of the deformation. Shape memory alloys have found use in everything from space missions (pathfinder and many more) to floral arrangement (animated butterflies, dragon flies and fairies), from biomedical applications, to actuators for miniature robots and cell phone antennas and even eyeglasses use SMA wires for their extreme flexibility.

4.2 General Principles:

The ability of shape memory alloy to full recover large strains is a result of a phase transformation that occur due to the application of stress and heat.

At hight temperature in stress –free state , shape memory alloys exist in the austenite phase . when the temperature of the material is decreased , the material phase transforms into martensite. The phase transformation between the martensite and 29 austenite phase induces large mechanical strains in the shape memory alloy and give rise to both shape memory effect and pseudo elastic effect.In a stress free state , the transformation between the martensite and austenite pahss is characterized by four transition temperatures. The transformation from martensite to austenite is characterized by As and Af , which are the temperatures at which phase transformation starts and finishes respectively. similarly , the transformation from austenite to martensite is characterized by the start and finish temperatures Ms and Mf. . the materials used mostly fall into the category of type I materials ,in which the transition temperatures follow the relationship

An important parameter in modelling the behaviour of shape memory alloy materials is the fraction of martensite and austenite within the material. At any value of stress or temperature, the material can be in one of the three states: fully martensite , fully austenite, or a mixure of martensite and austenite. The martensite fraction of the material can exist in multi variants which have identical crystallography but differ in orientation. These twin-related martensite variants are evenly distributed throughout the material when the shape memory alloy is in a stress free state and is fully martensite. 30

4.2 1 various form of shape memory alloy (Ref Osuka and Wayman[28])

Martensite is the relatively soft and easily deformed phase of shape memory alloys, which exists at lower temperatures. The molecular structure in this phase is twinned which the configuration is shown in the middle of Figure 4. 2.1 Upon deformation this phase takes on the second form shown in Figure 4.2, on the right. Austenite, the stronger phase of shape memory alloys, occurs at higher temperatures. The shape of the Austenite structure is cubic, the structure shown on the left side of Figure 4.2.1 The un-deformed Martensite phase is the same size and shape as the cubic Austenite phase on a macroscopic scale, so that no change in size or shape is visible in shape memory alloys until the Martensite is deformed.

4.3 Shape Memory Effect:

The shape memory effect is observed when the temperature of a piece of shape memory alloy is cooled to below the temperature Mf. At this stage the alloy is completely composed of Martensite which can be easily deformed. After distorting the SMA the original shape can be recovered simply by heating the wire above the temperature Af. The heat transferred to the wire is the power driving the molecular rearrangement of the alloy, similar to heat melting ice into water, but the alloy remains solid. The deformed Martensite is now transformed to the cubic Austenite phase, which is configured in the original shape of the wire.

4.3 1 phase transformation of SMA subjected to temperature and loading (Ref Osuka and Wayman[28])

The Shape memory effect is currently being implemented in:

- Coffepots

- The space shuttle

- Thermostats

- Vascular Stents

- Hydraulic Fittings (for Airplanes)

CONCLUDING REMARKS:

PZT has excellent sensing property, but when used as actuator, it is can recover only 0.1 % strains. Whereas shape memory alloys can recover strains up to 10 %. So to get this type of advantage, the current thesis focused on the usage of Shape memory alloy as actuator and PZT as sensor. With the help of piezoelectric elements (sensor), we need to sense the displacements / strains. These stains are needed to be put in the coupling equation to determine the required recovery stress. A rectangular plate fixed at ends is analysed and corresponding governing equations have been derived. From derived equations, recovery stress is determined and corresponding temperature is determined by using the iterative solution method. Temperature is to be given to SMA bars by supplying electric current. The equation for the time required for to get required temperature is found from the literature review.

FUTURE RESEARCH PLAN:

Constitutive relation for the composite material, consisting of PZT as well as SMA, need to be derived. Governing set of equations required to sense the deflections/vibrations of structure consisting of PZT and SMA need to be established. Coupling between deflections / strains sensed and temperature needed to recover the strains need to be derived. 45

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