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Structural Health Monitoring of Composites

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ABSTRACT

Materials are evolving today at a rate faster than any other time in the history of civilization. Composites are fast gaining attention as structural materials due to overriding advantages over conventional metallic structures. Owing to their high specific strength and stiffness and very good corrosion and fatigue properties, they are increasingly being used in the design of light weight aerospace, automobile and civil structures. This increase in usage of composites has raised the necessity for evaluating the in-service performance of such structures. Due to greater complexity of design, high operational loads and longer lifetime, composite structures are prone to unpredicted failures. Present day non-destructive evaluation (NDE) techniques, such as ultrasonic testing, acoustic emission, eddy current method, radiography and thermography etc., primarily meant for metallic materials are not always very effective for composites because of inherent micro-mechanical complexities. Anisotropy of composites, conducting properties of the fibers, isolative nature of the matrices and unintentional impact damages beneath the surface which are barely visible (BVID) make the damage prediction still more difficult and challenging in composites. These damages may cause a change in strain / stress state of the structure, and hence, its characteristics. By continuously monitoring one or more response quantities causing these changes, it is possible to assess the condition of the structure for its structural integrity. Such a monitoring of the structure is generally known as Structural Health Monitoring. Health monitoring applications have received great deal of attention all over the world due to its significant impact on safety and longevity of the structures. Real time damage detection and health monitoring in such cases have become one of the main areas of focus today.

Keywords: Composites, Non Destructive Evaluation, Anisotropy, (SHM) Structural Health Monitoring.

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I. INTRODUCTION

The emergence of new and improved materials, their processing and the development of a newer area of specialization known as Materials Design are stimulating innovation in all the walks of life making new designs for efficient systems and structures. Composite structures, beam, plates, and shellsare commonplace in many sectors of the automotive and aircraft industries. Use of such structures is now being considered for naval Applications because of the potential for improved strength to weight ratio and resistance to harsh environments. Development and exploitation of new materials like high performance composites, new engineering ceramics, high strength polymers and super alloys are providing better alternatives in terms of enhanced functionality and energy efficient systems with improved safety and reliability at a competitive price. Advent of smart and intelligent materials together with advances in processing technologies such as tape casting and screen printing, improvement in sensing and actuation technologies and their successful miniaturization and integration to composite structures along with developments in the field of real time data acquisition and information processing are likely to change the scenario in the most dramatic fashion in days to come. Composites are fast gaining attention as structural materials due to overriding advantages over conventional metallic structures. Owing to their high specific strength and stiffness and very good corrosion and fatigue properties, they are increasingly being used in the design of light weight aerospace, automobile and civil structures. Further, there is an increasing application of advanced composites in varied fields such as marine structures, turbine blades, automobile bodies etc. This increase in usage of composites has raised the necessity for evaluating the in-service performance of such structures. Due to greater complexity of design, high operational loads and longer lifetime, composite structures are prone to unpredicted failures.

In recent years efforts have been made at developing structures that can sense and control their own damage by using a network of distributed sensors and actuators. With the improvement in sensing and actuation technologies and their availability in the form of sensor patches e.g. PZT patches, PVDF films, magnetostrictive materials like Terfenol-D in the form of thick films or in particulate form and the feasibility of embedding them into or bonding those to composite structures is leading to growth of a new concept known as smart / intelligent structure. This concept is emerging to be attractive for potential high performance structural applications and other critical and advanced applications. In this paper, three different techniques for health monitoring and damage detection of composite structures have been considered. Initially, piezoelectric sensors and actuators like PVDF films bonded to composite laminate are considered for active vibration control and damage detection. Later, magnetostrictive (MS) material like Terfenol-D in particulate form embedded in one of the layers of composite laminate is considered for damage detection. Lastly, experimental modal analysis of composite laminate is carried out on Laser Doppler Scanning Vibrometer to record vibration signatures of the structure which is used in noncontact sensing of structural damages.

II. STRUCTURAL HEALTH MONITORING

Structural Health Monitoring has been defined in a number of ways by different groups of researchers such as"SHM denotes a system with the ability to detect and interpret adverse ‘changes’ in a structure in order to improve reliability and reduce life-cycle costs. The greatest challenge in designing a SHM system is knowing what ‘changes’ to look for and how to identifythem. The process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure is referred to as SHM. Damage is defined as changes to the material and/or geometric properties of these systems including changes to the boundary conditions and system connectivity which adversely affect the performance of the system.

III.ORGANIZATION OF A SHM SYSTEM

SHM is a new and improved way of making a non-destructive evaluation. It involves the integration of sensors-probably made of smart materials, data transmission, and computational power and processing ability inside the structure. It makes it possible to reconsider the design of the structure and the full management of the structure as a single unit and of the structure considered as a part of wider systems. The safety and performance of all commercial, civil and military structural systems deteriorate with time. It is very important to know the state of the structure immediately by non-destructive inspection or by other methods when the structure receives any foreign object impact. Structural damage detection at the earliest possible stage is very important in critical areas such as in the aerospace industry to prevent major failures. With the advances in sensor systems, data acquisition, data communication andcomputational methodologies, instrumentation based monitoring has been a widely accepted technology to monitor and diagnose structural health and conditions for civil, aerospace and mechanical structural systems. A schematic arrangement of sub-systems in a health management system is shown in figure 1

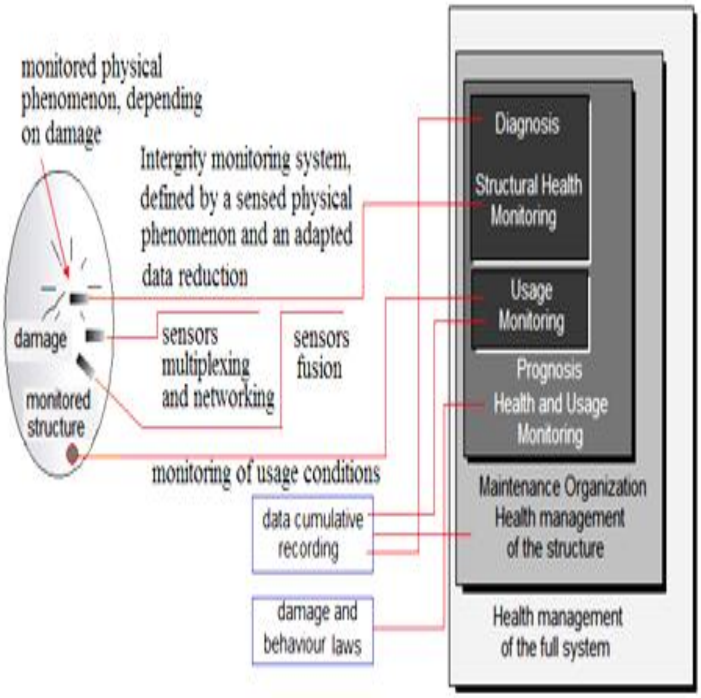

Figure 1: Organization of a SHM system

Some of the general attributes of SHM as noted from literature are listed below:

i) SHM is the whole process of the design, development and implementation of techniques for the detection, localization and estimation of damages for monitoring the integrity of structures and machines.
ii) Since the manual inspection and maintenance scheduling procedures are time consuming, costly, prone to error and insensitive to small variations in structural health, there is an urgent economic and technological need to

deploy SHM systems for seamless evaluation of structural integrity and reliability.

iii) SHM offers a shift from schedule driven maintenance to condition based maintenance / predictive maintenance of structures.

iv) The concept of SHM is a technology that automatically monitors structural conditions from sensor information in real time by equipping sensor network and diagnosis algorithms into structures.

v) The key requirements of a health monitoring system are that it should be able to detect damaging events, characterize the nature, extent and seriousness of the damage and respond intelligently within a reasonable time period to mitigate the ill effect of the damage or to repair the damage.

IV. STRUCTURAL HEALTH MONITORING VERSUS NON DESTRUCTIVE EVALUATION

Due to greater complexity of design, high operational loads and longer designed life time, composite structures are prone to unpredicted failures. Present day non-destructive evaluation (NDE) technologies such as ultrasonic testing, acoustic emission, eddy current method, radiography and thermography etc; primarily developed for metallic materials are not always very effective for composites due to their micro-mechanical complexities such as:

- Anisotropy of composites
- Conducting properties of the fibers
- Isolative nature of the matrices
- Impact damages beneath the surface, BVID

Limitations of present day NDE techniques

- Require specialized equipment and skilled man power
- In-situ evaluation and evaluation on real time basis is not always possible
- Longer downtime
- Bigger structures may not be kept out of are for longer period.

Many of the existing NDE techniques have been customized for specific SHM uses by integrating sensors and actuators inside

The structure to be monitored, Following are the perceptible advantages of SHM over NDE:

- Reduced inspection down time.
- Elimination of component tear down and human involvement.
- Potential prevention of failure during operation.
- Enabling new possibilities for maintenance concepts influencing design and assembly technologies leading to both maintenance and weight saving benefits.

V. SHM METHODOLOGY

There are three different techniques for health monitoring and damage detection of composite structures have been considered. They are as follows

1) Piezoelectric sensors and actuators like PVDF films bonded to composite laminate are considered for active vibration control and damage detection.

2) Magnetostrictive (MS) material like Terfenol-D in particulate form embedded in one of the layers of composite laminate is considered for damage detection.

3) Experimental modal analysis of composite laminate is carried out on Laser Doppler Scanning Vibrometer to record vibration signatures of the structure which is used in noncontact sensing of structural damages.

Composite: Two or more chemically different constituents combined macroscopically to yield a useful material. Composite materials are lighter, stronger, wear resistance, rust free, temperature resistance.

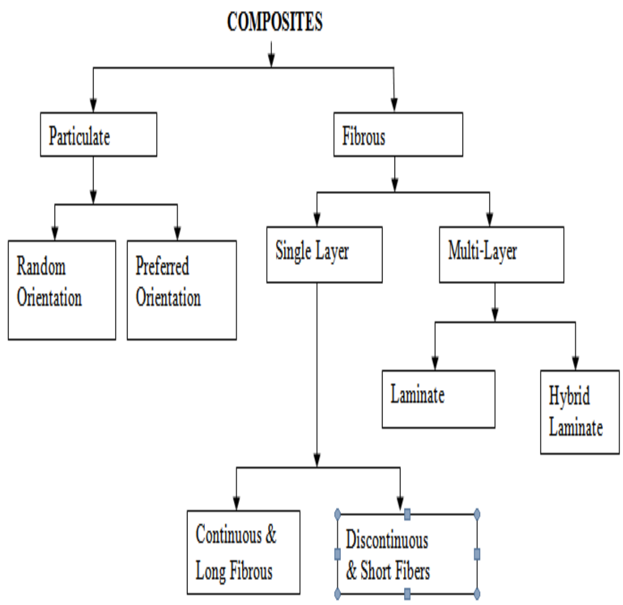

Figure 2: Classification of composites

1. Structural Health Monitoring By Piezoelectric Sensors:-Piezoelectric materials are materials that physically deform in the presence of an electric field, or conversely, produce an electrical charge when mechanically deformed. This effect is due to the spontaneous separation of charge within certain crystals structures producing an electrical dipole.Piezoelectric materials develop electric charge on application of mechanical stress (the direct effect) and get strained due to the application of an electric potential The very basis of SHM is its ability to monitor structures using embedded / attached sensors and to utilize the data to assess the state of the structure. Non-destructive evaluation sensors for SHM purposes have attained a modest degree of maturity and are able to monitor significantly large areas of structures. Following are the important SHM technologies:

- Piezoelectric sensors
- Magnetostrictive sensors
- Optical fiber sensors
- Dynamic response analysis using Laser Doppler Vibrometer.

➢ **Piezoelectric sensors:-** Piezoelectric sensors convert mechanical energy into

electrical energy and vice versa. This phenomenon enables them to detect impacts and deformations in a structure. Lead ZirconateTitanate (PZT) is the most commonly used piezoelectric material. It is used in the form of patches. Since it is a hard ceramic which is weak in tension it is not always possible to embed it into a structure. The most common piezo-polymer for sensing dynamic strain is PVDF. PVDF sensors are not likely to modify the stiffness of the host structure due to their own low stiffness. Being a polymer PVDF film can be shaped as desired according to intended application and can be formed into very thin films making it attractive for sensing purposes.

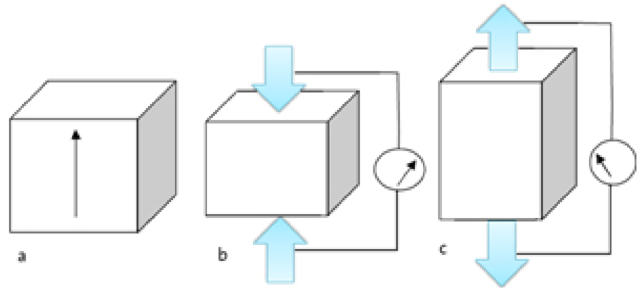

Figure 3: Piezoelectric materials (a) in original state with poling direction
(b) voltage generation under compression (c) under tension

There are two types of test for this piezoelectric SHM method they are as follows:

Acoustic emission (AE) method:- Acoustic emission (AE) is elastic radiation generated by the rapid release of energy from inside the material. These elastic waves are detected and converted to electrical signals by piezoelectric transducers bonded to the material surface. Fracture, impact, corrosive film rupture and other similar deformation processes may cause acoustic emission. Acoustic emission is fairly sensitive to detect newly formed crack surfaces of micron level. AE is a proven and reliable structural health monitoring tool for predictive maintenance and detects the cracks and damages well before they may endanger the wellbeing of the structure.

Acousto-ultrasonics (AU):-Acousto-ultrasonics uses pulser and receivers with resonant frequencies in low ultrasonic range to detect damages. Ultrasonic waves are reflected by surfaces and interfaces, attenuated by dispersion and absorption and undergo mode changes during reflection and transmission. The technique is able to detect and characterize differences in the structure of single and multilayer metallic and composite structures. When damage has occurred to a structure, changes in the signal indicate the type of damage.

2. Structural Health Monitoring ByMagnetostrictive (MS) material: Magnetostriction is mostly found in

- Magnetic transition materials like iron, cobalt, nickel and
- The rare earth materials like lanthanum and terbium.

The grains of these materials consist of numerous small randomly oriented domains which can rotate and align under the influence of an external magnetic field. The magnetic orientation or alignment causes internal strain in the material which is known as magnetostriction shown in figure 4.

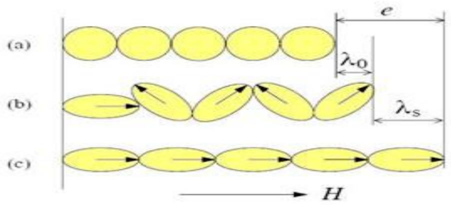

Figure.4 Magnetostriction

Magnetostriction in a ferromagnetic material (a) paramagnetic state above Tc;(b) after it has cooled through Tc; and (c) after it has been brought to saturation by a field H.

Electro-Mechanical Phenomenon: Electro-mechanical phenomenon is quite different from the piezoelectricity as it is essentially non-linear in nature and the response is always unidirectional under unbiased field i.e. the material can only expand irrespective of the direction of voltage or magnetic field applied to it.

Main advantage of magnetostrictive sensing: The fundamental technology is non-contact in nature so that the sensors can last indefinitely and can be inserted/embedded inside the composite layers.

Disadvantage of MS materials:-Need for delivery of a controlled magnetic field to an embedded actuator.
A typical magnetostrictive transducer is shown in figure 5.

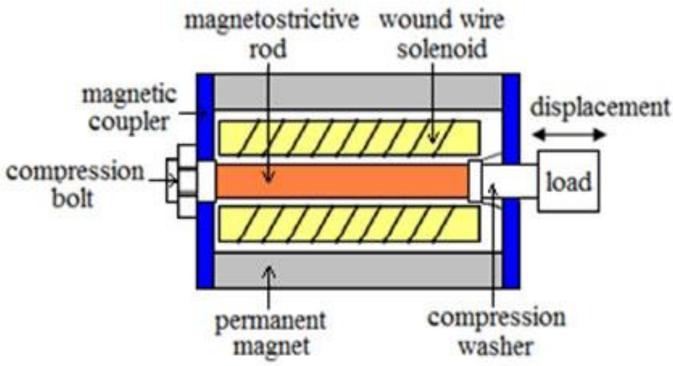

Figure 5:A typical magnetostrictive transducer

3. Optical Fibers

Fiber optic sensors are probably the most used sensors in practical situations. They are further gaining rapid attention in the field of SHM. They are most prominently being used in civil structures. The recent advances in the development of fibre optic technology are likely to replace some present day electrical sensors. It is important that the sensors and actuators embedded to the parent structure should not affect the integrity of the structure.

VI. SOLUTION DOMAINS OF SHM

We can obtain the solution by SHM in following domains:

- Static Domain
- Modal Domain
- Frequency Domain

Static Domain:

One can detect the faults in static system by the displacement, stiffness matrices for the different loading of structures.

Modal domain:

Since modal parameters depend on the material property and geometry, the change in natural frequencies, mode shapes andmodal curvature etc. can be used to locate the damage in structures without the knowledge of excitation force.

When compared to frequencies and mode shapes, damping properties have not been used as extensively as frequencies andmode shapes for damage diagnosis. Crack detection in a structure based on damping, however, has the advantage over otherdetection schemes based on frequencies and mode shapes. This is due to the fact that the damping changes have the ability todetect the nonlinear, dissipative effects that cracks produce.

Frequency domain:

In the frequency domain method, most important part is to calculate the dynamic stiffness matrix at each frequency either fromstiffness and mass matrix or directly from spectral formulation. The applied load vector is transformed in the frequency domain byFourier Transform and solved for structural response at each frequency. After getting responses for each frequency, inverseFourier Transform provides the time domain responses.

Benefits of Implementation of SHM:

Traditional systems are designed for a set of service parameters such as load, speed or life span and are unable to modify itsresponse mechanism in changed circumstances leading to loss of reliability, utility and increase in cost of maintenance.

VII. CONCLUSION

An attempt has been made to evaluate the performance of smart structures in the field of Structural Health Monitoring. This paper also shows that the SHM is better in testing compared to NDT. SHM covers almost every engineering field. SHM is very effective tool to find out the faults in vibrating structures. Faults in the structural components can easily find outby applying piezoelectric patches and results can easily obtained by the displacement and stiffness matrices.

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