Structural Health Monitoring of Composite Structures using Magnetostrictive Sensors and Actuators.

A Thesis
Submitted for the Degree of
Doctor of Philosophy
in the Faculty of Engineering

By
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Declaration

I declare that the thesis entitled **Structural Health Monitoring of Composite Structures Using Magnetostrictive Sensors and Actuators** submitted by me for the degree of Doctor of Philosophy in the Faculty of Engineering of Indian Institute of Science, Bangalore did not form the subject matter of any other thesis submitted by me for any outside degree, and the original work done by me and incorporated in this thesis is entirely done at the Indian Institute of Science, Bangalore.

Bangalore

Debiprasad Ghosh

July 2006

Dedicated to

My Extended Family Members

and

My Teachers

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SYNOPSIS

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Fiber reinforced composite materials are widely used in aerospace, mechanical, civil and other industries because of their high strength-to-weight and stiffness-to-weight ratios. However, composite structures are highly prone to impact damage. Possible types of defect or damage in composite include matrix cracking, fiber breakage, and delamination between plies. In addition, delamination in a laminated composite is usually invisible. It is very difficult to detect it while the component is in service and this will eventually lead to catastrophic failure of the structure. Such damages may be caused by dropped tools and ground handling equipments. Damage in a composite structure normally starts as a tiny speckle and gradually grows with the increase in load to some degree. However, when such damage reaches a threshold level, serious accident can occur. Hence, it is important to have up-to-date information on the integrity of the structure to ensure the safety and reliability of composite components, which require frequent inspections to identify and quantify damage that might have occurred even during manufacturing, transportation or storage.

How to identify a damage using the obtained information from a damaged composite structure is one of the most pivotal research objectives. Various forms of structural damage cause variations in structural mechanical characteristics, and this property is extensively employed for damage detection. Existing traditional non-destructive inspection techniques utilize a variety of methods such as acoustic emission, C-scan, thermography, shearography and Moir interferometry etc. Each of these techniques is limited in accuracy and applicability. Most of these methods require access to the structure. They also require a significant amount of equipment and expertise to perform inspection. The inspections are typically based on a schedule rather than based on the condition of the structure. Furthermore, the cost associated with these traditional non-destructive techniques can be rather prohibitive. Therefore, there is a need to develop a cost-effective, in-service, diagnostic system for monitoring structural integrity in composite structures.

Structural health monitoring techniques based on dynamic response is being used for several years. Changes in lower natural frequencies and mode shapes with their special derivatives or stiffness/flexibility calculation from the measured displacement mode shapes are the most common parameters used in identification of damage. But the sensitivity of these parameters for incipient damage is not satisfactory. On the other hand, for in service structural health monitoring, direct use of structural response histories are more suitable. However, they are very few works reported in the literature on these aspects, especially for composite structures, where higher order modes are the ones that get normally excited due to the presence of flaws.

Due to the absence of suitable direct procedure, damage identification from response histories needs inverse mapping; like artificial neural network. But, the main difficulty in such mapping using whole response histories is its high dimensionality. Different general purpose dimension reduction procedures; like principle component analysis or independent component analysis are available in the literature. As these dimensionally reduced spaces may loose the output uniqueness, which is an essential requirement for neural network mapping, suitable algorithms for extraction of damage signature from these response histories are not available. Alternatively, fusion of trained networks for different partitioning of the damage space or different number of dimension reduction technique, can overcome this issue efficiently. In addition, coordination of different networks trained with different partitioning for training and testing samples, training algorithms, initial conditions, learning and momentum rates, architectures and sequence of training etc., are some of the factors that improves the mapping efficiency of the networks.

The applications of smart materials have drawn much attention in aerospace, civil, mechanical and even bioengineering. The emerging field of smart composite structures offers the promise of truly integrated health and usage monitoring, where a structure can sense and adapt to their environment, loading conditions and operational requirements, and materials can self-repair when damaged. The concept of structural health monitoring using smart materials relies on a network of sensors and actuators integrated with the structure. This area shows great promise as it will be possible to monitor the structural condition of a structure, throughout its service lifetime. Integrating intelligence into the structures using such networks is an interesting field of research in recent years. Some materials that are being used for this purpose include piezoelectric, magnetostrictive and fiber-optic sensors. Structural health monitoring using, piezoelectric or fiber-optic sensors are available in the literature. However, very few works have been reported in the literature on the use of magnetostrictive materials, especially for composite structures.

Non contact sensing and actuation with high coupling factor, along with other properties such as large bandwidth and less voltage requirement, make magnetostrictive materials increasingly popular as potential candidates for sensors and actuators in structural health monitoring. Constitutive relationships of magnetostrictive material are represented through two equations, one for actuation and other for sensing, both of which are coupled through magneto-mechanical coefficient. In existing finite element formulation, both the equations are decoupled assuming magnetic field as proportional to the applied current. This assumption neglects the stiffness contribution coming from the coupling between mechanical and magnetic domains, which can cause the response to deviate from the time response. In addition, due to different fabrication and curing difficulties, the actual properties of this material such as magneto-mechanical coupling coefficient or elastic modulus, may differ from results measured at laboratory conditions. Hence, identification of the material properties of these embedded sensor and actuator are essential at their in-situ condition.

Although, finite element method still remains most versatile, accurate and generally applicable technique for numerical analysis, the method is computationally expensive for wave propagation analysis of large structures. This is because for accurate prediction, the finite element size should be of the order of the wavelength, which is very small due to high frequency loading. Even in health monitoring studies, when the flaw sizes are very small (of the order of few hundred microns), only higher order modes will get affected. This essentially leads to wave propagation problem. The requirement of cost-effective computation of wave propagation brings us to the necessity of spectral finite element method, which is suitable for the study of wave propagation problems. By virtue of its domain transfer formulation, it bypasses the large system size of finite element method. Further, inverse problem such as force identification problem can be performed most conveniently and efficiently, compared to any other existing methods. In addition, spectral element approach helps us to perform force identification directly from the response histories measured in the sensor. The spectral finite element is used widely for both elementary and higher order one or two dimensional waveguides. Higher order waveguides, normally gives a behavior, where a damping mode (evanescent) will start propagating beyond a certain frequency called the cut-off frequency. Hence, when the loading frequencies are much beyond their corresponding cut-off frequencies, higher order modes start propagating along the structure and should be considered in the analysis of wave propagations.

Based on these considerations, three main goals are identified to be pursued in this thesis. The first is to develop the constitutive relationship for magnetostrictive sensor and actuator suitable for structural analysis. The second is the development of different numerical tools for the modelling the damages. The third is the application of these developed elements towards solving inverse problems such as, material property identification, impact force identification, detection and identification of delamination in composite structure.

The thesis consists of four parts spread over six chapters. In the first part, linear, nonlinear, coupled and uncoupled constitutive relationships of magnetostrictive materials are studied and the elastic modulus and magnetostrictive constant are evaluated from the experimental results reported in the literature. In uncoupled model, magnetic field for actuator is considered as coil constant times coil current. The coupled model is studied without assuming any explicit direct relationship with magnetic field. In linear coupled model, the elastic modulus, the permeability and magnetostrictive coupling are assumed as constant. In nonlinear-coupled model, the nonlinearity is decoupled and solved separately for the magnetic domain and mechanical domain using two nonlinear curves, namely the stress vs. strain curve and magnetic flux density vs. magnetic field curve. This is done by two different methods. In the first, the magnetic flux density is computed iteratively, while in the second, artificial neural network is used, where a trained network gives the necessary strain and magnetic flux density for a given magnetic field and stress level.

In the second part, different finite element formulations for composite structures with embedded magnetostrictive patches, which can act both as sensors and actuators, is studied. Both mechanical and magnetic degrees of freedoms are considered in the formulation. One, two and three-dimensional finite element formulations for both coupled and uncoupled analysis is developed. These developed elements are then used to identify the errors in the overall response of the structure due to uncoupled assumption of the magnetostrictive patches and shown that this error is comparable with the sensitivity of the response due to different damage scenarios. These studies clearly bring out the requirement of coupled analysis for structural health monitoring when magnetostrictive sensor and actuator are used.

For the specific cases of beam elements, super convergent finite element formulation for composite beam with embedded magnetostrictive patches is introduced for their specific advantages in having superior convergence and in addition, these elements are free from shear locking. A refined 2-node beam element is derived based on classical and first order shear deformation theory for axial-flexural-shear coupled deformation in asymmetrically stacked laminated composite beams with magnetostrictive patches. The element has an exact shape function matrix, which is derived by exactly solving the static part of the governing equations of motion, where a general ply stacking is considered. This makes the element super convergent for static analysis. The formulated consistent mass matrix, however, is approximate. Since the stiffness is exactly represented, the formulated element predicts natural frequency to greater level of accuracy with smaller discretization compared to other conventional finite elements. Finally, these elements are used for material property identification in conjunction with artificial neural network.

In the third part, frequency domain analysis is performed using spectrally formulated beam elements. The formulated elements consider deformation due to both shear and lateral contraction, and numerical experiments are performed to highlight the higher order effects, especially at high frequencies. Spectral element is developed for modelling wave propagation in composite laminate in the presence of magnetostrictive patches. The element, by virtue of its frequency domain formulation, can analyze very large domain with nominal cost of computation and is suitable for studying wave propagation through composite materials. Further more, identification of impact force is performed form the magnetostrictive sensor response histories using these spectral elements.

In the last part, different numerical examples for structural health monitoring are directed towards studying the responses due to the presence of the delamination in the structure; and the identification of the delamination from these responses using artificial neural network. Neural network is applied to get structural damage status from the finite element response using its mapping feature, which requires output uniqueness. To overcome the loss of output uniqueness due to the dimension reduction, damage space is divided into different overlapped zones and then different networks are trained for these zones. Committee machine is used to coordinate among these networks. Next, a five-stage hierarchy of networks is used to consider partitioning of damage space, where different dimension reduction algorithms and different partitioning between training and testing samples are used for better mapping for the identification procedure. The results of delamination detection for composite laminate show that the method developed in this thesis can be applied to structural damage detection and health monitoring for various industrial structures.

This thesis collectively addresses all aspects pertaining to the solution of inverse problem and specially the health monitoring of composite structures using magnetostrictive sensor and actuator. In addition, the thesis discusses the necessity of higher order theory in the high frequency analysis of wave propagation. The thesis ends with brief summary of the tasks accomplished, significant contribution made to the literature and the future applications where the proposed methods addressed in this thesis can be applied.

List of Publications

Journal papers

1. Ghosh D. P. and Gopalakrishnan S.; Role of Coupling in constitutive relationships of magnetostrictive material. "Computers, Materials & Continua, Vol.-1, No. 3, pp. 213-228"

2. Ghosh D. P. and Gopalakrishnan S.; Coupled analysis of composite laminate with embedded magnetostrictive patches. Smart Materials and Structures 14 (2005) 1462-1473.

3. Ghosh D. P. and Gopalakrishnan S.; Super convergent finite element analysis of composite beam with embedded magnetostrictive patches. Composite Structures [in press].

4. Ghosh D. P. and Gopalakrishnan S.; Spectral finite element analysis of composite beam with embedded magnetostrictive patches considering arbitrary order of shear deformation and arbitrary order of poisson contraction. will be communicated

Conference papers

1. Ghosh D. P. and Gopalakrishnan S.; "Structural health monitoring in a composite beam using magnetostrictive material through a new FE formulation." In Proceedings of SPIE vol. 5062 Smart Materials, Structures and Systems, edited by Sangeneni Mohan, B. Dattaguru, S. Gopalakrishnan, (SPIE, Bellingham, WA, 2003) and page number 704-711. ; Dec'12-14, 2002, Indian Institute of Science, Bangalore, India.

2. Ghosh D. P. and Gopalakrishnan S.; Time Domain Structural Health Monitoring for Composite Laminate Using Magnetostrictive Material with ANN Modeling for

Nonlinear Actuation Properties. Proceedings of INCCOM-2 & XII NASAS Second ISAMPE national conference on composites and twelfth national seminar on aerospace structures Sep' 05-06, 2003, Bangalore, Karnataka, India

3. Ghosh D. P. and Gopalakrishnan S.; Identification of delamination size and location of composite laminate from time domain data of magnetostrictive sensor and actuator using artificial neural network. Proceeding of the SEC 2003, December 12-14, structural engineering convention an international meet.

4. Ghosh D. P. and Gopalakrishnan S.; Time domain Structural Health Monitoring with magnetostrictive patches using five-stage hierarchical neural network. Proceeding of the ICASI-2004, July 14-17,International Conference on Advances in Structural Integrity.

5. Chakraborty A.; Ghosh D. P. and Gopalakrishnan S.; Damage Modelling And Detection Using Spectral Plate Element, International Congress on Computational Mechanics and Simulation (ICCSM-2004). 9-12 December, 2004 at Indian Institute of Technology Kanpur.

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