

# Chapter 8

## Summary and Future Scope of Research

The work presented in the last six chapters gives a comprehensive account of the current status of the structural health monitoring (SHM) of composite structures using magnetostrictive sensor and actuator. In this chapter, an overview of the whole thesis is provided along with an outline of the possible future works on SHM using magnetostrictive sensors and actuators.

The main objective of this thesis was to develop the necessary numerical tools for the structural health monitoring of composite structures. The focus here was in the use of magnetostrictive material as sensor/actuator materials to trigger the required interrogatory signal for the active SHM. Hence, the first part of this thesis was developed to the numerical material characterization of the highly nonlinear magnetostrictive material, Terfenol-D. This was dealt in Chapter-2, where in two approaches, namely the polynomial approach and ANN were employed to completely characterize both sensing and actuation law of the magnetostrictive material. It is seen that ANN approach gives 5 to 10 times more accurate prediction than polynomial approach. The necessary features of coupled and uncoupled model were highlighted in this chapter.

Chapter-3 discussed a new finite element formulation for structures with in-built magnetostrictive patches that can also handle coupled analysis. Here, both magnetic and mechanical degrees are considered as unknown degrees of freedom. The developed FE model can handle smart patches embedded in the laminates, which are required to induce actuation strains on the application of magnetic field. This changes the state of stress in the sensing patch and hence the magnetic flux density through the enclosed magnetic coil changes, resulting in a voltage across the sensing coil. These developed elements are used to study the effect of coupling in the overall performance of the structure. The response

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difference between healthy and damaged structure is 2 to 5 times less sensitive than the difference between coupled and uncoupled formulations. Comparing the error due to uncoupled analysis with the sensitivity of the damage in structural response, it is shown that the coupled analysis is very essential for structural health monitoring applications.

In Chapter-4 of the thesis, two super convergent beam elements with embedded magnetostrictive patches were developed, one for Euler-Bernoulli beam and the other for first order shear deformable beam. As a result, in most cases, only a single element is adequate to capture the superconvergent static behavior irrespective of boundary conditions and ply-stacking configuration. For static tip deflection, single such element is within 0.05 to 0.4% error from 2D FE results. Also, its superconvergent behavior for vibration and wave propagation problem was demonstrated. Dynamic Responses and natural frequencies with 10 superconvergent elements shows better results than with 20 conventional elements. Next, these developed elements were used for material property identification from sensor response with the help of mapping properties of artificial neural network and shown that it is identifying within 1% accuracy.

Chapter-5 deals with a new higher order spectral element, which is developed for wave propagation analysis of a magnetostrictive embedded composite beam in the presence of thermal, magnetic and mechanical loading. The element is based on Higher order Shear deformation with Higher order Poisson's contraction Theory (HSPT) that is, the formulated element can handle  $n^{th}$  order shear deformation and  $n^{th}$  order Poisson's contraction. Numerical examples are directed towards highlighting the effect of the requirement of higher order theories on the structural and magnetic responses. For excitation of 100kHz, third order contraction and fourth order shear deformable assumption is required. The spectrum and the dispersion relations were studied in detail. Developed elements were then used for force identification from the sensor response of the structure and shown that 4 mili-sec sensor response can reconstruct 25 kHz broadband force excitation exactly.

Delamination is the most important mode of damage on composite laminate. In Chapter-6, numerical simulation were carried out for a delaminated composite laminate with or without magnetostrictive patches as sensors and actuators using anhysteretic, coupled, linear properties of magnetostrictive materials. Effect of delamination on the cantilever tip velocity and the sensor open circuit voltages are studied. Single and multiple delaminations are considered with tip vertical impact load and biased sinusoidal current in the actuator coil. Amplitudes of reflections for 100mm delamination is similar to the

reflection from the support of healthy beam, which can be identified easily. Although, the reflection for 10mm single delamination is undetectable, 10 mm symmetric delaminations can be identified. Next, the sensitivities of the delamination on the location of the sensors were studied for a portal frame and shown that the sensor near the delamination have maximum sensitivity.

Chapter-7 illustrated a methodology for automatic damage identification and localization in composite structural components using various ANN. Responses for delaminated and healthy beam was calculated as per Chapter-6. These responses and the corresponding damage configurations were used to train ANN as input and output of the network, respectively. The Feed-forward back-propagation neural network, the committee machine and the Hierarchical Neural Network (HNN) were designed, trained, tested and to predict the delamination location using the structural response as inputs. Single ANN can identify length of the delamination with in 50mm accuracy. Committee machine can predict delaminated layer exactly. Five stage HNN shows quite accurate identification in both location and length the of delamination, simultaneously.

## 8.1 Contribution of the Thesis

The main contribution of this thesis is outlined as:

1. One, two and three dimensional finite element formulation for both coupled and uncoupled analysis was developed using developed constitutive relationships of magnetostrictive materials.
2. Developed superconvergent finite element formulation for analysis of beam with magnetostrictive materials.
3. Higher order spectral finite elements are formulated and developed considering  $n^{th}$  order of shear and contraction effects.
4. Force and material property identification from the magnetostrictive sensor response procedure were established.
5. The effects of the delamination and the multiple delaminations on the structural and magnetostrictive sensor responses were studied due to known force actuation and current excitation in the magnetostrictive actuator embedded in the composite structure.

Table 8.1: Comparison with existing state-of-the-art

	Present Study	State-of-the-art
Degrees of freedom in FE Formulation	Both mechanical and smart dof, Coupled	Mechanical [326, 216] dof, Uncoupled
Elements with magnetostrictive sensor/actuator	Rod, Beam, Plate, 3D and Plane stress/strain	Beam [326], Plate [216], Uncoupled
Modelling of delamination	Equivalent single layer, Beam and Plate	Layer wise plate theory [29], Spectral [284, 285],
Superconvergent Element	Magnetostrictive actuator/sensor	FGM [63], Higher order beam [114] Thin walled composite beam [268]
Spectral Element formulation	$n^{th}$ order (Poisson's and shear) Beam with magnetostrictive sensor/actuator	Rod [109], Elementary beam [110, 111], Timoshenko beam [140], Poisson's contraction [64] FGM beam and plate [59], Composite beam [249] tube [250]
Force Identification Technique	Magnetostrictive sensor response, FFT based Spectral finite element	Layered system [330], PZT [82], Velocity [159], Wavelet [271], Greens's function [373], Kalman Filter [239], Multiple location [405], ANN [228], Moving force [211], FGM [61], Least square [413],
Delamination Study	Time domain study with Single and multiple delamination, magnetostrictive sensor/actuator	Natural frequency [127, 213, 251, 371], Lamb wave [332, 350], Layer wise delamination [29, 72, 212], Damage spectral element [284, 285], multiple delamination [191, 247], Fiber optic [234, 410]
In-situ sensor/material property identification	Magnetostrictive sensor response, ANN	FGM beam and plate [59]
Geometric Inverse problem	Delamination study using ANN, Committee machine, Five stage hierarchical neural network	Mode shape [158], Modal damping [176], Curvature mode shape [143], Crack [125, 206, 287], Fuzzy logic [359], Dynamic residual force [126], Prestress concrete [243], Embedded Flaw [319], ANN [328, 350], PZT [352, 391]

6. Location of the sensors on the structural response were studied for a critical location of delamination in a composite portal frame.
7. Developed five stage hierarchical neural network for automatic damage detection from measured responses.

### 8.1.1 Limitation of the Approach

Weights of magnetostrictive sensor/actuator with corresponding coils are high. Hence, SHM in this approach in aerospace application may be limited. For an array, the density of sensors certainly depends on the particular physical mechanism of the sensing material. For example, because of the prestress requirement, and because coils are usually required to generate magnetic fields, magnetostrictive actuators are generally physically more cumbersome to construct than piezoceramic actuators. Therefore, for array applications with high sensor/actuator density, piezoceramics or piezopolymers would be preferred. Although such strains are larger than those achievable in piezoceramic materials, optimum performance requires that a stress be applied to the magnetostrictive prior to actuation, which renders certain applications impractical.

## 8.2 Future Scope of Research

This section will highlight the direction where the research can be extended.

- Multi-scale modelling of magnetostrictive patches is essential to get the exact features of the patches. Two different scales one for the macro features and others for the micro features can be used in the analysis.
- In Chapter-2, the thesis studied the anhysteretic coupled and uncoupled constitutive relationships. In future, hysteretic coupled and uncoupled model of magnetostrictive materials can be studied, which can be used in structural application.
- More recently, mesh less finite element is gaining popularity among the finite element community. Mesh less formulation with magnetostrictive sensor and actuator can be studied.
- As the magneto-mechanical coupling coefficient of magnetostrictive material is highly nonlinear and hysteretic, some nonlinear finite element analysis can be done.

- In Chapter-4 super convergent formulation of only Euler-Bernoulli and FSDT were studied, this can be extend to higher order beam formulation also.
- In Chapter-5 spectral analysis is done through FFT, which has in-built difficulties to give boundary condition in time. These difficulties can be removed using some time-frequency transformation like wavelet transformation.
- Structural response in frequency domain for delaminated beam requires the formulation and development of damaged spectral element with magnetostrictive sensor and actuator in-built. In addition, thus developed spectral element can be compared with superconvergent element with same case study of SHM.
- Recently modelling carbon nano-tube (CNT) is gaining importance due to their superb electrical and mechanical properties. Dynamic responses on single wall CNT for Tera Hz loading is studied by many researchers in both spectral and as well as conventional finite element. Research in modelling of multi wall CNT is still in primitive stage due to its radial Van der Waals forces (a particular class of intermolecular forces) and breathing mode of vibration. Present higher order spectral element can be extended to semi-infinite curve plate, which can model multi wall CNT easily with a pair of cylindrical elements. Researchers are already trying to insert different chemicals inside the carbon nano-tube. Similarly, if any magnetostrictive material is inserted inside CNT, it can be used as non contact nano sensor or actuator. This nano sensor can be modelled using the above approach.
- In this thesis, other than delamination, simplified modelling of matrix cracking and fiber breakage is addressed. More sophisticated models are possible to be formulated under this SHM environment.
- Numerical study of optimum location of sensor is performed for time domain analysis. Study of optimum location of sensor in other domain, like frequency domain or wavelet domain may give more information on SHM study.
- Gradually SHM community is moving from smart structural era to wireless communication with MEMs and Nano sensors era. The main advantages and features of this wireless based SHM will be:
  - Multiple and heterogeneous sensors and actuator integration

- Optimal location of actuator and excitation frequency selection
- Wireless communication with MEMs and Nano sensors
- Optimization of noise to signal ratio
- Million Wireless MEMS Communication hub with billion Nano-sensor in each structural component
- Hierarchical decomposition of sensor networks
- Software and Hardware development
- Simultaneous SHM with vibration suppression

Thus in this line, the magnetostrictive thinfilm can be used as MEMS and modelled with existing formulation. Similarly magnetostrictive-nano sensor can also be made and used in SHM.

- Recent interest of artificial neural network is moving from multi layer perceptron to support vector machine (SVM), which can be used for both identification and estimation (support vector regression) of the damages.
- As every analysis in finite element is computationally costly, Response Surface Method (RSM) can be used to map the response features of the structure from damage configuration. For this, some initial finite element simulation is required for a particular set of damage configuration dictated by Design Of Experiment (DOE). Once the response surface is generated, Evolutionary Algorithm (EA) can be used to search the damage configuration without doing any further finite element simulation.
- Fuzzy Logic (FL) is one of the powerful tool in soft computing, which can be used independently or combined with ANN or EA for SHM.