Chapter 1

Introduction

1.1 Motivation and Scope

Composites have revolutionized structural construction. They are extensively used in aerospace, civil, mechanical and other industries. Present day aerospace vehicles have composites upto 60 % or more of the total material used. More recently, materials, which can give rise to mechanical response when subjected to non-mechanical loads such as PZTs, magnetostrictive, SMAs, have become available. Such materials may broadly refer to as functional materials. With the availability of functional materials and the feasibility of embedding those into or bonding those to composite structures, smart structural concepts are emerging to be attractive for potential high performance structural applications [236]. A smart structure may be generally defined as one which has the ability to determine its current state, decides in a rational manner on a set of actions that would change its state to a more desirable state and carries out these actions in a controlled manner in a short period of time. With such features incorporated in a structure by embedding functional materials, it is feasible to achieve technological advances such as vibration and noise reduction, high pointing accuracy of antennae, damage detection, damage mitigation etc. [128, 45].

Various damages like crack or delamination in composite structures are unavoidable during service time due to the impact or continual load, chemical corrosion and aging, change of ambient conditions, etc. These damages will cause a change in the strain/stress state of the structure and hence its vibration characteristics. By continuously monitoring one or more of these response quantities, it is possible to assess the condition of the structure for its structural integrity. Such a monitoring of the structure is called structural health monitoring. Health monitoring application has received great deal of attention all over the world, due to its significant impact on safety and longevity of the structure.

To implement health monitoring concept, it is necessary to have a number of sensors to measure response parameters. These response will then be post-processed to asses the condition of structure. Such a system was built by Lin and Chang [232], when they developed a built-in monitoring system for composite structures using a network of actuators or sensors. The engineering community has great interest in the development of new real-time, in-service health monitoring techniques to reduce cost and improve safety. With the current NDE techniques, the complex mechanical systems need to be taken out of service for an extended period of time for the inspection. The inspection becomes even more lengthy and expensive for inaccessible locations. Also, on the same preventive basis, structures are often withdrawn from service early, even if the structure is still capable of performing its task. It is estimated that nearly 27 percent of an aircraft's life cycle cost is spent on inspections and repairs (Kessler et al. [178]). With an on-line, self actuated system, such costs can be dramatically reduced. Furthermore, the impact of such an in-situ SHM system is that it not only increases safety and performance, but also enables converting schedule based into condition based maintenance, thus reducing both down time and costs (Bray and Roderick [46]).

The overall objective of this thesis is how magnetostrictive sensor responses can be used to identify the health condition of the composite structures. So, the central question is how responses can be obtained for both healthy or damaged structures, which is forward analysis; and how these obtained responses can be mapped with the damage state of the structure, which is inverse problem. Hence, different 1D, 2D and 3D finite element is formulated to get magnetostrictive sensor responses for healthy and damaged structures with mapping of different artificial neural networks for identification of damages. Sensing and actuation properties are characterized using available experimental results. Optimal location of sensors are studied in structural health monitoring framework. In addition, in-situ sensor properties and applied forces on structures are identified from truncated sensor responses.

1.2 Background: Structural Health Monitoring

The safety and performance of all commercial, civil, and military structural systems deteriorate with time. Further more, it is very important to confirm the structural condition immediately by nondestructive inspection or other method when the structure receives the foreign object collision. Structural damage detection at the earliest possible stage is very important in the aerospace industry to prevent major failures and for this reason it has attracted a lot of interest. However, it is not practical to assume experts are always available to explain the measured data. With the advances in sensor systems, data acquisition, data communication and computational 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. The process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering infrastructure is referred to as Structural Health Monitoring (SHM). Followings are some of the facts attributed to SHM:

- 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.

- Because of current manual inspection and maintenance scheduling procedures are time consuming, costly, insensitive to small variations in structural health, and prone to error in severe and mild operating environments, there is an urgent economic and technological need to deploy automated structural diagnostic instrumentation for seamless evaluation of structural integrity and reliability.

- SHM offers the promise of a paradigm shift from schedule-driven maintenance to condition-based maintenance of structures.

- 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.

- 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 on whatever timescale is required, either to mitigate the effects of the damage or to effect its repair.

Doebling et al. [100, 101] provide one of the most comprehensive reviews of the technical literature concerning the detection, location, and characterization of structural damage through techniques that examine changes in measured structural-vibration response.

1.2.1 Application Areas

1.2.1.1 Aerospace Application

SHM for Aerospace structures are studied by many researchers. Qing et al. [317] had developed a hybrid piezoelectric/fiber optic diagnostic system for quick non-destructive evaluation and long term health monitoring of aerospace vehicles and structures. The SHM system for the Eurofighter Typhoon had been reported by Hunt and Hebden [164]. Fujimoto and Sekine [125] presented a method for identification of the locations and shapes of crack and disbond fronts in aircraft structural panels repaired with bonded FRP composite patches for extension of the service life of aging aircrafts. Zingoni [428] had stated the essentiality of SHM, damage detection and long-term performance of aging structures. Tessler and Spangler [366] formulated a variational principle for reconstruction of three-dimensional shell deformations from experimentally measured surface strains, which could be used for real-time SHM systems of aerospace vehicles. Epureanu and Yin [115] had explored nonlinear dynamics of aeroelastic system and increased the sensitivity of the vibration based SHM system. Baker et al. [26] reported the development of life extension strategies for Australian military aircraft, using SHM of composite repairs and joints. Balageas [27] had reported research and development in SHM at the European Research Establishments in Aeronautics.

1.2.1.2 Wind Turbine Blade Application

Ghoshal et al. [133] had tested transmittance function, resonant comparison, operational deflection shape, and wave propagation methods for detecting damage on wind turbine blades.

1.2.1.3 Bridge Structures

Structural health monitoring of bridge had been studied by various researcher [66, 67, 68, 185, 223, 224, 225, 226, 227, 242, 276, 290, 298, 308, 359, 365, 411, 412]. DeWolf et al. [97] had reported their experience in non-destructive field monitoring to evaluate the health of a variety of existing bridges and shown the need and benefits in using non-destructive evaluation to determine the state of structural health. Moyo and Brownjohn [277] had analyzed in-service civil infrastructure based on strain data recorded by a SHM system installed in the bridge at construction stage. Bridge instrumentation and monitoring for structural diagnostics is been done by Farhey [118]. The strain-time histories at critical locations of long-span bridges during a typhoon passing the bridge area were investigated by Li et al. [223, 224, 225] using on-line strain data acquired from the SHM system permanently installed on the bridge. Ko and Ni [185] had explored the technology developments in the field of long term SHM and their application to large-scale bridge projects, in order to secure structural and operational safety and issue early warnings on damage or deterioration prior to costly repair or even catastrophic collapse. Patjawit and Nukulchai [308] conducted laboratory tests to demonstrate the sensitivity of Global Flexibility Index for SHM of highway bridges. Li et al. [226] had studied the reliability assessment of the fatigue life of a bridge-deck section based on the statistical analysis of the strain-time histories measured by the SHM system permanently installed on the long-span steel bridge. Li et al. [223, 224, 225] had determined the effective stress range and its application on fatigue stress assessment of existing bridges. Tennyson et al. [365] had described the design and development and application of fiber optic sensors for monitoring of bridge structures.

1.2.1.4 Under Ground Structure

A low-cost fracture monitoring system for underground sewer pipelines had been reported by Todoroki et al. [367] using sensors made of fabric glass and carbon black-epoxy composite materials. Bhalla et al. [42] had addressed technology associated with SHM of underground structures. An experimental program was carried out by Mooney et al. [274] to explore the efficacy of vibration based SHM of earth structures, e.g., foundations, dams, embankments, and tunnels, to improve design, construction, and performance.

1.2.1.5 Concrete Structure

SHM of concrete structure is performed by many researchers [41, 292, 359]. Corrosion of the reinforcing bars in concrete beams was monitored by Maalej et al. [241] using fiber optic sensor. Both semi-empirical and experimental results for one-way reinforced concrete slab were studied by Koh et al. [187] using Fast Fourier Transform and the Hilbert Huang Transform. Chen et al. [75] used coaxial cables as distributed sensors to detect cracks in reinforced concrete structures from the change in topology of the outer conductor under strain conditions. Bhalla and Soh [41] discuss the feasibility of employing mechatronic conductance signatures of surface bonded piezoelectric-ceramic (PZT) patches in monitoring the conditions of reinforced concrete structures subjected to base vibrations, such as those caused by earthquakes and underground blasts. Nojavan and Yuan [292] have proposed SHM systems using electromagnetic migration technique to image the damages in reinforced concrete structures. Taha and Lucero [359] examined fuzzy pattern recognition techniques to provide damage identification using the data simulated from finite element analysis of a prestressed concrete bridge without a priori known levels of damage.

1.2.1.6 Composite Structure

Fibre reinforced laminate composites are widely used nowadays in load-bearing structures due to their light weight, high specific strength and stiffness, good corrosion resistance and superb fatigue strength limit. While composite materials enjoy different advantages, they are also prone to a wide range of defects and damage which may significantly reduce their structural integrity. Internal damages such as delamination, fiber breakage and matrix cracks are caused easily in the composite laminates under external force such as foreign object collision. Such damages induced by transverse impact can cause reductions in the strength and stiffness of the materials, even if the damages are tiny. Hence, there is a need to detect and locate damage as it occurs.

Wang et al. [387] investigated the interaction between a crack of a cantilevered composite panel and aerodynamic characteristics by employing Galerkins method for one-dimensional beam vibrating in coupled bending and torsion modes. Prasad et al. [312] used Lamb wave tomography for SHM of composite structures. Iwasaki et al. [167] had implemented unsupervised statistical damage detection method for SHM delaminated composite beam. Dong and Wang [103] had presented the influences of large deformation for geometric non-linearity, rotary inertia and thermal load on wave propagation in a cylindrically laminated piezoelectric shell. Verijenko and Verijenko [380] had studied smart composite panels with embedded peak strain sensors for SHM. Takeda [362] had presented a methodology for observation and modelling of microscopic damage evolution in quasi-isotropic composite laminates. Kuang et al. [195] used polymer-based sensors for monitoring the static and dynamic response of a cantilever composite beam. Chung [88] had reviewed the use of smart materials in composite. Takeda [360] reported the summary of the structural health-monitoring project for smart composite structure systems as a university-industry collaboration program.

1.2.2 Sensors and Actuators

1.2.2.1 Piezoelectric Material

Piezoelectric are class of sensor/actuator materials, which are available in various forms. It is available in the form of crystals, polymers or ceramics. Polymer form is normally called PVDF (PolyVinylidine DiFluoride) and is available as very thin films, which are extensively used as sensor material. In ceramic form, it is called PZT (Lead Zirconate Titanate), which is used both as sensor and actuator.

PZT has been used by many researchers [41, 72, 130, 103, 131, 317, 329, 350, 385] for SHM. Koh et al. [186] reported an experimental study for in situ detection of disbond growth in a bonded composite repair patch in which an array of surface-mounted lead zirconate titanate elements (PZT) had been used. Bonding piezoelectric wafers to either end of the fasteners, Barke et al. [30] had shown a technique capable of detecting in situ damage in structural grades of fasteners. Han et al. [145] had presented a vibration-based method of detection of the crack in the structures by using piezoelectric sensors and actuators glued to the surface of the structure. Wang and Huang [391] reported a theoretical study of elastic wave propagation in a cracked elastic medium induced by an embedded piezoelectric actuator. Wang and Huang [390] provided a theoretical study of crack identification by piezoelectric actuator. Gex et al. [131] presented low frequency bending piezoelectric actuator for fatigue tests and damage detection. Qualitative experimental results of fatigue tests and damage detection were presented and low frequency bending piezoelectric actuator was used by Gex et al. [130] for SHM. Ritdumrongkul et al. [329] used PZT actuator-sensor in conjunction with numerical model-based methodology in SHM to quantitatively detect damage of bolted joints.

1.2.2.2 Optical Fiber

Fiber-optic sensors are gaining rapid attention in the field of SHM [68, 94, 154, 173, 210, 219, 234, 278, 357]. Tsuda et al. [374] studied damage detection of CFRP using fiber Bragg gratings sensors. Murayama et al. [280] studied SHM of a full-scale composite structure using fiber optic sensors. High-speed dense channel fiber optic sensors based on Fiber Bragg Grating (FBG) technology was used by Cheng [74] for SHM. Xu et al. [410] introduced an approach for delamination detection using fiber-optic interferometric technique. Long gage and acoustic sensors types of optical fibers were used for SHM of large civil structural systems by Ansari [20]. Suresh et al. [357] had presented fiber

Bragg grating based shear force sensor in SHM. Tennyson et al. [365] had described the development and application of fiber optic sensors for monitoring bridge structures. Chan et al. [68] investigated the feasibility of SHM using FBG sensors, via monitoring the strain of different parts of a suspension bridge. Fiber bragg grating strain sensors was developed by Moyo et al. [278] for SHM of large scale civil infrastructure. Kang et al. [173] had studied the embedding technique of fiber Bragg grating sensors into filament wound pressure tanks used for SHM. Embedded optical fiber Bragg grating sensors was used by Herszberg et al. [154] for SHM. Ling et al. [234] had studied the dynamic strain measurement and delamination detection of composite structures using embedded multiplexed FBG sensors through experimental and theoretical approaches and revealed that the use of the embedded FBG sensors is able to actually measure the dynamic strain and identify the existence of delamination of the structures. Li et al. [227] had presented an overview of research and development in the field of fiber optical sensor SHM for civil engineering applications, including buildings, piles, bridges, pipelines, tunnels, and dams. Cusano et al. [94] described the design of a fiber Bragg grating sensing system for static and dynamic strain measurements leading to the possibility to perform high frequency detection for on-line SHM in civil, aeronautic, and aerospace applications. Fluorescent fiber optic sensors were used by McAdam et al. [262] for preventing and controlling corrosion in aging aircraft.

1.2.2.3 Vibrometer

Scanning laser vibrometer [221, 345, 356] are used for SHM mainly for their non-contact, distributed sensing.

1.2.2.4 Magnetostrictive Material

Sensing of delamination in composite laminates using embedded magnetostrictive material was studied by Krishna Murty, A. V. et al. [192]. Saidha et al. [335] presented an experimental investigation of a smart laminated composite beam with embedded/surface-bonded magnetostrictive patches for health monitoring applications. Theoretical and experimental investigation had been done by Giurgiutiu et al. [134] for SHM of magnetostrictive composite beams. Hison et al. [156] reported magnetoelastic sensor prototype for on-line elastic deformation monitoring and fracture alarm in civil engineering structures.

1.2.2.5 Nano sensor

Watkins et al. [392] had studied on single wall carbon nanotube-based SHM sensing materials. Collette et al. [91] had developed nano-scale electrically conductive strain measurement device potential for SHM. This nano-sensor based SHM has great potential in the coming years.

1.2.2.6 Comparisons of different sensors

In high frequency structural application like, SHM, frequency bandwidth of the material is most important criteria for both sensing and actuation mechanism. Although shape memory alloy gives high strain of 2-8%, its bandwidth limitation is one of the main disadvantages for SHM application.

Actuator: The maximum force exerted by any material is necessarily limited by its maximum stress. In order to maximize the actuation force, it is generally desirable to employ a material with a large maximum stress capable of large actuation strains. It seems unlikely that both parameters can be optimized in the same materials. As a result, the maximum actuation force of future materials may not be vastly greater than the forces achievable at present. Low-stiffness materials with large actuation strains can provide an effective source of actuation for certain type of structural applications. Ferromagnetic Shape-Memory Alloys can produce relatively large strains, limited mainly by the yield strength of the metal. Given the trade-off between stiffness and strain, perhaps the more important physical limit to consider in SHM application is the maximum actuation stress that is achievable by a material. PZT actuators typically provide displacements of 0.13% strains. Their large bandwidth is another great advantage; operation in the gigahertz frequency range is even possible. They have good linearity, and since they are electrically driven, can be directly integrated with the composite structures. The devices and material are moderately priced compared to other actuators. Piezoceramics specific weigh near 7.5-7.8 and have a maximum operating temperature near $300°C$. The main disadvantage of piezoelectric actuators is the high voltage requirements, typically from 1 to 2 kV. Further, as the size of the actuators increases, so does the required voltage, making them favorable only for small-scale devices. Being ceramic, PZT actuators are also brittle, requiring special packaging and protection. Other disadvantages are the high hysteresis and creep, both at levels from 15-20%. Electrostrictive materials can provide 0.1% strain and operate from 20 to 100 kHz. They have specific weigh near 7.8 with operating temperatures near $300°C$. Finally, their low hysteresis (<1%) makes them unique among most smart material

Table 1.1: Comparison of different smart materials for SHM application.

	PZT 5H	PVDF	PMN	Terfenol-D	Nitinol
Actuation mechanism	Piezoceramic (31)	Piezo film	electro-strictive	magneto-strictive	SMA
Maximum strain (%)	0.13	0.07	0.1	0.2	8
Modulus (GPa)	60	2	64	30	28/90
Specific Weight	7.5	1.78	7.8	9.25	7.1
Hysteresis (%)	10	>10	<1	2	high
Bandwidth (kHz)	1000	100	100	30	0.005

actuators. The main disadvantage of electrostrictors is their inherent nonlinearity. From their constitutive equations, elongation follows a square law function of applied electric field (V/m). To compensate for this, voltage biasing is used to attain regions of nominal linearity. Magnetostrictive material, Terfenol-D gives maximum strain of 0.2%, with operating frequencies from 0 to 30 kHz. In addition, Terfenol-D has better power-handling capability. Not only do they exhibit good linearity (after adding bias), but a moderate level of hysteresis at 2%. The material specific weighs about 9.25 and has a maximum operating temperature near $380°C$. A primary disadvantage of magnetostrictive material is the need for delivery of a controlled magnetic field to an embedded actuator.

Sensor: The limit of the smallest force that can be sensed depends on the sensing mechanism involved. The technical and commercial success of Atomic Force Microscopy and related scanning probe technologies demonstrate that there are certainly clever ways to sense even atomic-scale forces. The simplest example of a sensitive force measurement is perhaps a resonant circuit employing a parallel-plate capacitor with a squeezable dielectric: As a force is applied on the capacitor plate, the capacitance changes, producing a shift in the resonant frequency that can be measured with very high precision. But these techniques are not suitable for SHM application. However, an issue that is more salient to SHM is to consider the response of the intrinsic material itself. In the case of a smart material, such as a piezoelectric or magnetostrictive material, an applied force will produce a change in some measurable electrical property of the material. The magnitude of the electromagnetic response generally depends on the amount of strain produced from the applied stress and how the magnitude of the response depends on this strain. Generally, the material modulus determines the amount of strain, and the electromagnetic coupling coefficient determines how much the electronic properties change in response to a given strain. Maximum sensitivity would thus be achieved by choosing a material with a low modulus but with a high coupling coefficient. For those applications that can tolerate low mechanical stiffness, PVDF is generally chosen over a piezoceramic material because of its low modulus and relatively low cost, despite its relatively low electromechanical coupling coefficient. Flexibility and manufacturability of PVDF sensor has made them popular for use as thin-film contact sensors and acoustic transducers. The main advantage of magnetostrictive sensing is that the fundamental technology is non-contact in nature so that the sensors can last indefinitely and can be inserted inside the composite layers.

1.2.3 Solution Domain

Literature for SHM can be divided according to their solution domain. These are the following:

1.2.3.1 Static Domain

In the presence of damage, stiffness matrix of the structure changes. Due to this change, displacement of the structure due to static load changes. This change is one of the criteria used for the detection of damage. Jenkins et al. [169] introduced a static deflection based damage detection method. They mention that the other methods are relatively insensitive to many instances of localized damage such as fatigue crack or notch, which results in very little changes in the system mass or inertia. Zhao and Shenton [235] presented a novel damage detection method based on best approximation of dead load stress redistribution due to damage.

For self-equilibrating static load (usually generated from smart actuator), the effect of load far away from the actuator has negligible effect on the static response, even in the presence of damage. Hence, the change of structural properties distant from the actuator cannot be sensed through static self-equilibrating load. Hence, the use of smart actuator for SHM in static domain is limited to the proximity of actuator only.

1.2.3.2 Modal domain

Since modal parameters depend on the material property and geometry, the change in natural frequencies, mode shape curvature etc. can be used to locate the damage in structures without the knowledge of excitation force, when linear analysis is adequate. The amount of the literature pertaining to the various methods for SHM based on modal domain is quite large [58, 66, 177, 197, 197, 221, 242, 290, 342, 378, 379]. New and sophisticated strategies for damage identification using modal parameters is studied extensively (e.g. [Ratcliffe, [320]; Lam *et al.*, [208]; Ratcliffe and Bagaria, [321]; Ratcliffe [322]; Chinchalkar, [77]). Lakshminarayana and Jebaraj, [206] used the first four bending and torsional modes and corresponding changes in natural frequencies to estimate the location of a crack in a beam. It is reported that if the crack is located at the peak/trough positions of the strain mode shapes, then percentage change in frequency would be higher for corresponding modes. It is also found that if the crack is located at the nodal points of the strain mode shapes, then the percentage change in frequency values would be lower for corresponding modes. Uhl [376] presented different approaches for identification of modal parameters for model-based SHM. Khoo et al. [182] presented modal analysis techniques for locating damage in a wooden wall structure. Ching and Beck [78] used modal identification for probabilistic SHM. Verboven et al. [378] applied total least-squares algorithms for the estimation of modal parameters in the frequency-domain. Caccese et al. [58] studied the detection of bolt load loss in hybrid composite/metal bolted connections using low frequency modal analysis. Sodano et al. [342] used macro-fiber composites sensor to find modal parameters for SHM of an inflatable structure. Chan et al. [66] updated finite element model of a large suspension steel bridge using modal characteristics for SHM of the bridge. Laser vibrometer, designed for modal analysis was used for crack detection in metallic structures by Leong et al. [221].

The presence of delamination changes the structural dynamic characteristics and can be traced in natural frequencies, mode shapes, phase, dynamic strain and stress wave patterns etc. Significant research has been reported on the effect of delamination on natural frequencies and mode shapes and strategies have been developed to identify location of delamination using changes in these modal parameters (Tracy and Pardoen, [371]; Gadelrab, [127]; Schulz *at al.*, [338]; Zou *et al.*, [430]; Chinchalkar, [77]). Tracy and Pardoen, [371] found that if the delamination is in a region of mode shape where the shear force is very high, there will be considerable degradation in natural frequency, which is otherwise not significant. Hence, by studying the mode shapes and the corresponding natural frequencies, estimation on the location of delamination can be made.

Resonant Frequencies / Natural Frequencies: The resonant frequencies are defined as the frequencies at which the magnitude of the frequency response at a measured degrees of freedom approaches infinity, which is also called as natural frequency. Adams, et al. [4] illustrated a method to detect damage from changes in resonant frequencies. Wang and Zhang [389] estimate the sensitivity of modal frequencies to changes in the structural stiffness parameters. Zak et al. [420] examined the changes in resonant frequencies produced by closing delamination in a composite plate. In particular, the effects of delamination length and position on changes in resonant frequencies were investigated. Williams and Messina [396] formulate a correlation coefficient that compares changes in a structure's resonant frequencies with predictions based on a frequency-sensitivity model derived from a finite element model. Hearn and Testa [152] developed a damage detection method from ratio of changes in natural frequency for various modes.

Antiresonance frequencies: The antiresonance frequencies are defined as the frequencies at which the magnitude of the frequency response at measured degrees of freedom approaches zero [310]. To calculate antiresonance frequencies of a dynamic system, He and Li [151] developed an accurate and efficient method for undamped systems. The reasons for looking to the antiresonance frequencies are that these antiresonance frequencies can be easily and accurately measured in a similar way as for the natural frequencies. Furthermore, a system can have much greater number of antiresonance frequencies than natural frequencies because every different FRF between an actuator and a sensor contains another set of antiresonance frequencies. Williams and Messina [396] considered anti-resonance frequencies for their damage detection technique. Lallement and Cogan [207] introduced the concept of using antiresonance frequencies to update FE models. Mottershead [275] showed that the antiresonance sensitivities to structural parameters can be expressed as a linear combination of natural frequency and mode shape sensitivities, and furthermore that the dominating contributors to the antiresonance sensitivities are the sensitivities of the nearest frequencies and corresponding mode shapes. It is concluded that the antiresonance frequencies can be a preferred alternative to mode shape data.

Mode Shapes: Doebling and Farrar [99] examine changes in the frequencies and mode shapes of a bridge as a function of damage. This study focuses on estimating the statistics of the modal parameters using Monte Carlo procedures to determine if damage has produced a statistically significant change in the mode shapes. Stanbridge, et al. [343] also use mode shape changes to detect saw-cut and fatigue crack damage in flat plates. They also discuss methods of extracting those mode shapes using laser-based vibrometers. Another application of SHM using changes in mode shapes can be found in (Ahmadian et al. [13]). West [393] used mode shape information (Modal Assurance Criteria) for the location of structural damage. Ettouney et al. [116] discuss a comparison of three different SHM techniques applied to a complex structure, which are based on the information of mode shapes and natural frequencies of the damaged and undamaged structure.

Mode Shape Curvatures / Modal Strain Energy: Pandey, et al. [303] identified the absolute changes in mode shape curvature as an indicator of damage. An experimental damage detection investigation of fiber-reinforced polymer honeycomb sandwich beams was performed by Lestari and Qiao [222] based on the curvature mode shapes. Different damage detection algorithms were studied by Hamey et al. [143] using curvature modes of structures with piezoelectric sensors or actuators. Ho and Ewins [157] present a Damage Index method, which is defined as the quotient squared of a structure's modal curvature in the undamaged state to the structure's corresponding modal curvature in its damaged state. In another paper by Ho and Ewins [158], the authors state that higher derivatives of mode shapes are more sensitive to damage, but the differentiation process enhances the experimental variations inherent in those mode shapes. Zhang et al. [425] propose a structural damage identification method based on element modal strain energy, which uses measured mode shapes and modal frequencies from both damaged and undamaged structures as well as a finite element model to locate damage. Worden et al. [403] present another strain energy study using a damage index approach. Carrasco et al. [55] discuss using changes in modal strain energy to locate and quantify damage within a space truss model. Choi and Stubbs [83] used changes in local modal strain energy to develop a method for detecting damage in two-dimensional plates.

Modal Damping: When compared to frequencies and mode shapes, damping properties have not been used as extensively as frequencies and mode shapes for damage diagnosis. Crack detection in a structure based on damping, however, has the advantage over other detection schemes based on frequencies and mode shapes. This is due to the fact that the damping changes have the ability to detect the nonlinear, dissipative effects that cracks produce. Modena et al. [272] show that the visually undetectable cracks cause very little change in resonant frequencies and require higher mode shapes to be detected, while the same cracks cause larger changes in the damping. Zonta et al. [429] observe that crack creates a non-viscous dissipative mechanism for making damping more sensitive to damage. Kawiecki [176, 177] notes that damping can be a useful damage-sensitive feature particularly suitable for SHM of lightweight and micro-structures. Author has described the application of arrays of surface-bonded piezo-elements to determine modal damping characteristics for structural healthy monitoring of light-weight and micro-structures.

Dynamic Stiffness from Mode shape: Many structural health-monitoring techniques rely on the fact that structural damage can be expressed by a reduction in stiffness. Maeck and Roeck [243] apply a direct stiffness approach to damage detection, localization, and quantification for a bridge structure, which uses experimental frequencies and mode shapes in deriving the dynamic stiffness of a structure.

*Dynamic Flexibility from Mode shape:*A reduction in stiffness corresponds to an increase in structural flexibility. Dynamically measured flexibility matrix $[G]$ of the damaged structure can be estimated from the natural frequencies $[\Lambda]$ and normalized mode shapes $[\Phi]$ as:

$$[G] \approx [\Phi][\Lambda]^{-1}[\Phi]^T$$

Pandey and Biswas [302] present a damage-detection and damage localization method based on changes in the flexibility of the structure. Mayes [261] uses measured flexibility to locate damage from the results of a modal test on a bridge. Aoki and Byon [21] presented modal-based structural damage detection using localized flexibility properties that can be deduced from the experimentally determined global flexibility matrix. Bernal [39] mentions that changes in the flexibility matrix are sometimes more desirable to monitor than changes in the stiffness matrix. Because the flexibility matrix is dominated by the lower modes, good approximations can be obtained even when only a few lower modes are employed. Reich and Park [327] focus on the use of localized flexibility properties for structural damage detection. The authors choose flexibility over stiffness for several reasons, including the facts that (1) flexibility matrices are directly attainable through the modes and mode shapes determined by the system identification process, (2) iterative algorithms usually converge the fastest to high eigenvalues, and (3) in flexibility-based methods, these eigenvalues correspond to the dominant low-frequency components in structural vibrations. A structural flexibility partitioning technique is used because when the global flexibility matrix is used, there is an inability to uniquely model elemental changes in flexibility. The strain-based sub-structural flexibility matrices measured before and after a damage event, are compared to identify the location and relative degree of damage. Topole [368] discusses the use of the flexibility of structural elements to identify damage. Author indicates that there are certain instances where it is advantageous to use changes in flexibility as an indicator of damage rather than using stiffness perturbations. Topole develops a sensitivity matrix that describes how modal parameters are affected by changes in the flexibility of structural elements. From this information, he develops a scalar quantity for each structural element, which indicates the relative level of damage within the element.

Unity Check Method: In unity check method, the product of an undamaged stiffness matrix K^u and dynamically measured flexibility matrix $[G]$ from a unity matrix at any stage of damage are checked using following relation.

$$[E] = [G][K^u] - I$$

The unity check method, proposed by Lin [230, 231] is useful for locating and quantifying damage using modal parameters.

Best Achievable Eigen Vectors: Lim and Kashangaki, [229] located damage in space truss structures by computing Euclidian distances between the measured mode shapes and best achievable eigenvectors. The best achievable eigenvectors are the projection of the measured mode shapes onto the subspace defined by the refined analytical model of structure and measured frequencies.

Limitation of Modal Domain in SHM: However modal methods are not very sensitive to the small size of delaminations which are of practical interest, and can be very cumbersome as well as computationally expensive while implementing in practice for online health monitoring. In most of the methods based on modal parameters, it is assumed that the modes under consideration are affected by damages. As pointed out by Ratcliffe, [322], the change in individual natural frequencies due to small damage may become insignificant and may fall within measurement error. In practical situation, this can considerably reduce the effectiveness of the prediction. The main limitation of modal domain approach is that the lower modes are less sensitive to damage, particularly becomes a significant problem when only a few lower modes are used in SHM. Change of structural dynamic performance caused by structural damage that is less than 1% of the total structural size is unnoticeable. Yan and Yam [415] pointed out that when the crack length in a composite plate equals 1% of the plate length, the relative variation of structural natural frequency is only about 0.01 to 0.1%. Therefore, using vibration modal parameters, e.g., natural frequencies, displacement or strain mode shapes, and modal damping are generally ineffective in identifying small and incipient structural damage.

1.2.3.3 Frequency Domain

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

Frequency Response Function (FRF): Although the majority of investigations into structures under dynamic loading are concerned with obtaining the natural frequencies, and possibly mode shapes, of the structure, a much more valuable description of the dynamic behavior of the structure is the FRF, which describes the relationship between a local excitation force applied at one location on the structure and the resulting response at another location. Essentially, the FRF returns information about the behavior of the structure over a range of frequencies. The response at a particular frequency for some forcing and response locations will simply be a single complex number, which is often plotted in terms of real and imaginary parts or in terms of amplitude and phase. The frequency response of a system can be measured by: (1) applying an impulse to the system and measuring its response. (2) sweeping a constant-amplitude pure tone through the bandwidth of interest and measuring the output level and phase shift relative to the input.

Mal et al. [252] presented a methodology for automatic damage identification and localization using FRF of the structure. Agneni, et al. [12] use the measured FRFs for damage detection. Lopes, et al. [237] relate the electrical impedance of the piezoelectric material to the FRFs of a structure. The FRFs are extracted from the measured electric impedance through the electromechanical interaction of the piezoceramic and the structure. Trendafilova [372] use the FRFs as damage-sensitive features.

Spectral finite element (SFE): SFE gives exact dynamic stiffness matrix for two noded elements for frequency domain solution. Sreekanth et al. [198] had modeled transverse crack in SFE formulation to simulate the diagnostic wave scattering in composite beams for SHM technique. Mahapatra and Gopalakrishnan [247] had studied the effect of wave scattering and power flow through multiple delaminations and strip inclusions in composite beams with distributed friction at the inter-laminar region using SFE formulation. Nag et al. [285] had proposed a SFE method for modeling of wave scattering in laminated composite beam with delamination.

1.2.3.4 Time-Frequency Domain

In contrast to the Fourier analysis, the time-frequency analysis can be used to analyze any nonstationary events localized in time domain. Vill [381] notes that there are two basic approaches to time-frequency analysis. The first is to divide the signal into slices in time and to analyze the frequency content of each of these slices separately. The second approach is to first filter the signal at different frequency bands and then cut the frequency bands into slices in time to analyze their energy content as a function of time and frequency. The first approach is the basic short term Fourier transform, also known as spectrogram, and the second one is the Wigner-Wille Transform. Other time-frequency analysis techniques include, but are not limited to, wavelet analysis and empirical mode decomposition combined with Hilbert transform. Bonato et al. [44] extract modal parameters from structures in non-stationary conditions or subjected to unknown excitations using time-frequency and cross-time-frequency techniques. Mitra and Gopalakrishnan [269, 270, 271] have developed wavelet transform based spectral finite element formulation, which they used to identify the delamination of composite laminates.

1.2.3.5 Impedance Domain

The basic concept of impedance method is to use high-frequency structural excitations to monitor the local area of a structure for changes in structural impedance that would indicate imminent damage. The impedance domain technique successfully detects damage that is located near the sensor/actuator.

Electro-mechanical impedance (EMI): Electro-mechanical impedance is a technique for SHM that uses a collocated piezoelectric actuator/sensor to measure the variations of mechanical impedance of a structural component or assembly. This technique relies on the electromechanical coupling between the electrical impedance of the piezoelectric materials and the local mechanical impedance of the structure adjacent to the PZT materials. The PZT materials are used both to actuate the structure and to monitor the response. From the input and output relationship of the PZT materials, the electrical impedance is computed. When the PZT sensor actuator is bonded to a structure, the electrical impedance is coupled with the local mechanical impedance. Small flaws in the early stages of damage are often undetectable through global vibration signature methods, but these flaws can be detected using the PZT sensor-actuator, provided that the PZT sensor actuators are near the incipient damage. By inspecting the differences between the impedance spectrum of a reference baseline of the structure in an undamaged condition and the impedance spectrum of the same structure with damage, incipient anomalies of the structural integrity can be detected. This health monitoring technique can also be implemented in an on-line fashion to provide a real-time assessment to detect the presence of structural damage.

Giurgiutiu and Zagrai [137] used high-frequency electro-mechanical impedance spectra for health monitoring of thin plates. Park et al. [305] summarized the hardware and software issues of impedance-based SHM, where high-frequency structural excitations are used to monitor the local area of a structure from changes in structural impedance. Piezoelectric-wafer active sensors SHM and damage detection based on elastic wave propagation and the Electro-Mechanical (E/M) impedance technique is reviewed by Giurgiutiu et al. [138]. Giurgiutiu et al. [136] apply this method for health monitoring of aging aerospace structures. Giurgiutiu and Rogers [135] discussed the use of an Electro-Mechanical Impedance (EMI) technique to detect incipient damage within a structure.

Limitation of Impedance Domain: Although, Impedance technique is suitable for the detection of very small damage, it cannot identify damage from the far field measurement. This is due to very high frequency solution domain, which is suitable for local identification of damage.

1.2.3.6 Time Domain

In time domain SHM, damage is estimated using time histories of the input and vibration responses of the structure. The structure is excited by multiple actuators across a desired frequency range. Then, the structure's dynamics are characterized by measuring the response between each actuator/sensor pair. Using these time response over a long period while at the same time taking into account the information on several modes so that the damage evaluation is not dependent on any one particular mode, the presence of damage is assessed. The big advantage of this method is that it can detect damage situations both globally and locally by monitoring the input frequencies. In industry, using the time domain measured structural vibration responses to identify and monitor structural damage is one of the important ways to ensure reliable operation and reduced maintenance cost for in-service structures. One of the main advantages of this solution domain is, it can handle nonlinearity and hysteresis easily.

1.2.4 Levels of SHM

The major tasks in structural health monitoring and damage identification can be categorized under different levels as given below:

1.2.4.1 Unsupervised SHM

Unsupervised SHM is defined as the one, where the structural model of damage state is not available for computation.

NDE: Different nondestructive testing (Visual Inspection, Thermograph, Electrical resistance, Magnetic particle, Eddy current, Die penetration, Acoustic Emission etc.) are used for structural health monitoring.

Novelty detection: In this level of SHM, sensor responses of both damaged and undamaged structure are required (for same actuation) to compare healthy and damaged structural response for identification of the existence of damage.

Material Property identification: Different material property identification (damping, elasticity, density, magneto-mechanical coupling etc.) is performed from sensor response and actuation.

Force Identification: Actuation or Impact force identification (bird strike, space debris or foam impact in space craft, aerodynamic forces etc.) requires both sensor response, and undamaged structural model.

Damage localization: Basic idea behind damage localization is some unbalanced forces exist near the damage. That is, if damage occurs, the damage vector will have nonzero entities only at the DOFs connected to the damaged elements. Fukunaga et al. [126] showed a damage identification method based on dynamic residual forces which can be evaluated using an analytical model of undamaged structures and measured vibration data of damaged structures. Schulz *et al.*, [338] used *damage force* to identify the elements having damage. Nag et al. [284] have used damage force indicator for identification of delaminations in laminated composite beams with spectral finite element model based on the Fast Fourier Transform.

1.2.4.2 Supervised SHM

Supervised SHM is defined as where structural model of damaged state is also available for computation.

Damage confirmation: This is referred as forward problem in structural health monitoring. Damage location and extent are assumed and modelled in finite element to get the response of damaged structure. If this response dose not matches with experimentally measured response, damage properties are changed. So, this is an iterative process. As the finite element computation is costly, good prediction of damage is always required, which can be obtained from inverse mapping between damage to its responses.

Damage estimation: This is refereed to as inverse problem in structural health monitoring. It identifies the magnitude, location and type of the damage from response of damaged structure directly using artificial neural network, which are trained by some responses of different assumed damage configuration.

1.2.5 Damage Modelling in Composite Laminate

Composite structures provide opportunities for weight reduction, tailoring the material, integrating control surfaces in the form of embedded transducers etc., which are not possible with conventional metallic structures. Therefore, a potential barrier at present is that the composite structures can have internal defects and they are difficult to be detected but need frequent monitoring to asses their vulnerability. Although, matrix cracking, fiber breakage, fiber debonding etc. initiate the damage that occurs in laminated composites, inter-laminar crack or delamination is most vulnerable and can grow, thus reducing the life of the structure. This is because of the fact that in contrast to their in-plane properties, transverse tensile and inter-laminar shear strengths are quite low.

Damage states in composite and their evolution is a complex process. They depend on the geometric scale and the micro-structural properties of the material system at the interfaces. The matrix phase of the composite shows micro-cracks in it, which are characterized by matrix crack density. In laminated composite, such micro-cracks appear due to fiber separation in an angle plies. Under in-plane tensile load, as well as under bending load, these transverse micro-cracks first grow through the thickness of the layer and reach the upper and the lower interfaces with the neighboring layers. Similar but more complex growth occurs in inhomogeneous composite having array of cells and interfaces in three dimensions. The micro-cracks increase in number under increasing deformation. Due to mismatch in the elastic moduli between the neighboring layers, possibility of having delamination is very high. As the critical value of the strain energy release rate is reached, the delaminations start growing rapidly. As a result, under the condition of matrix crack density being very high, which results in angle plies not able to take any tensile load, this tensile load is then transferred through the 0° fibers. With further increase of tensile loading, the 0° fibers break. This is the final stage of failure. Similarly, under compressive load, the laminates start buckling at the delaminated zone and may fail instantaneously.

1.2.5.1 Matrix cracking

Matrix cracking has long been recognized as the first damage mode observed in composite laminates under static and fatigue tensile loading. It does not necessarily result in the immediate catastrophic failure of the laminate and therefore can be tolerated. However, its presence causes stiffness reduction and can be detrimental to the strength of the laminate.

It also triggers the development of delaminations, which can cause fiber-breakage in the primary load-bearing plies. A number of theories have appeared in an attempt to predict the initiation of transverse cracking and describe its effect on the stiffness properties of the laminate. Following are the methods on which these theories are based: the self-consistent method, variational principles, continuum damage mechanics, shear lag, approximate elasticity theory solutions and stress transfer mechanics.

Modelling of cracked beams can be performed by 2-D or 3-D FEM. Alternatively; simplified procedures are available with less computational effort. Among these simplified methods are those proposed by Christides and Barr [86] and Shen and Pierre [339, 340]. In both cases, a crack function representing the perturbation in the stress field induced by the crack is considered. Chondros et al. [84] have developed a continuous cracked beam vibration theory. They considered that the crack introduces a continuous change in the flexibility in its neighborhood and models it by incorporating a displacement field consistent with the singularity. In other cases, the cracked beam is modelled as two segments connected by means of massless rotational springs [4], whose stiffness may be related to the crack length by the fracture mechanics theory [172]. Thus, at the cracked section, a discontinuity in the rotation due to bending must be considered. These kinds of models have been successfully applied to Euler-Bernoulli cracked beams with different support conditions [287, 218, 28, 43, 121, 120].

Dvorak et al. [113] evaluated overall stiffnesses and compliances, for a composite lamina which contains a given density of matrix cracks and subjected to uniform mechanical loads. The evaluation procedure is based on the self-consistent method and is similar, to that used in finding elastic constants of unidirectional composites. Hashin [147] analyzed cross-ply laminates by variational methods for tensile and for shear membrane loading, which contain distributions of intralaminar cracks within the 90 degree ply. In another paper, Hashin [148] treated the problem of stiffness reduction and stress analysis of orthogonally cracked cross-ply laminates under uniaxial tension by the variational method based on the principle of minimum complementary energy. Talreja [363] predicted the stiffness reductions due to transverse cracking in composite laminates from crack initiation to crack saturation using the stiffness-damage relationships of continuum damage model. Later, Talreja et al. [364] tested cross ply laminate under longitudinal tensile loading for the behavior of transverse cracking and the associated mechanical response. Shear-lag-based models [423, 424, 155, 297, 146, 217, 409, 40, 422] remain the most commonly used ones for calculating the reduced stiffness properties of transversally cracked composites.

They are being modified and generalized to enable better description of wider classes of laminates. Nuismer and Tan [293] gave an approximate elasticity theory solution for the stress-strain relations of a cracked composite lamina. McCartney [263, 264] estimated the dependence of the longitudinal values of Young's modulus, Poisson's ratio, and thermal expansion coefficient on the density of transverse cracks. Recently, Kumar et al. [198, 199] modelled cracked composite laminate using spectral finite element formulation for wave based structural diagnostics.

1.2.5.2 Techniques for Modelling of Delamination

Delaminations in composites are usually modelled using beams, plates or shells with appropriate kinematics. The technique used by Majumdar and Suryanarayana [251] to model a through-width delamination subdivides the beam into a delamination region (sub-laminates) and two integral regions (base-laminates) on either side of the delamination region. Each of these sub-laminates and base-laminates are modelled as Euler beam and the whole structure is solved satisfying global boundary conditions. For one dimensional beam elements, additional axial forces give rise to a net resultant internal bending moment which creates differential stretching of the sub-laminates above and below the plane of delamination. The model used by Tracy and Pardoen [371] to study the effect of delamination on natural frequency is also based on the engineering beam theory. This model uses 2-D beam elements and includes the effect of contact between the delaminated surfaces and can allow independent extensional and bending stiffness.

Gadelrab [127] in his work has taken two different types of finite elements for the undelaminated and delaminated elements. For undelaminated elements, all the lamina assumed to have the same transverse and longitudinal displacements at a typical cross-section, but each lamina can rotate by different amount from the others depending on its material and geometrical properties. This is also called "layer-wise constant shear kinematics". The delaminated element has the same transverse and axial displacement at both ends of the element. Only the rotation is different along the element length of each lamina. In the same direction, Barbero and Reddy [29] used layer-wise plate theory for modelling delamination in plates where delaminations were simulated by step discontinuity at the interfaces.

Modelling performed by Luo and Hanagud [238] assumes opening and closing action at the region of delamination. Here it is considered that after delamination, partially intact matrix and fibers still fill the delamination gap. The contact effect between the delaminated sub-laminates is modelled as a distributed nonlinear soft spring between them. The spring is taken as nonlinear because when the delamination opens beyond some small amplitude constraints, the spring effect becomes zero; on the other hand, when the vibration mode does not tend to open the delamination, the delaminated sub-laminates have the same flexural displacements and slopes. This nonlinear spring is then simplified as a combination of few linear springs. Such modelling provides better representation of the practical problem. In many mechanical components under fatigue loading, such delamination can induce non-linear modes in vibration characteristics. Related measurements in metal beam with fatigue crack can be found in Léonard *et al.* [220].

Williams [398] has proposed a generalized theory of delaminated plates using a global / local variation approach. This theory uses unique coupling between the global and local displacement fields in two different length scales and is a generalization of the earlier proposed theories based on "layer-wise constant shear kinematics". However, these above global/local analysis are based on semi-analytic approach and difficult to incorporate for transient dynamic and wave-based diagnostic problems.

In continuum mechanics, formulation for damage, one can use a mixed variational formulation in the local coordinates to capture the localized stress field accurately. An assumed stress field for the local damage region and assumed displacement for the global region can generally be used (Pagano [300]). Here, one can consider an appropriate damage dependent constitutive model (Coats and Harris [90]) based on continuum damage mechanics for the local region, and equivalent fiber-matrix mixture constitutive model (Reddy [324]) for the global region. However, such detailed model becomes computationally intensive in the context of structural health monitoring and identification of damage.

Neglecting the relative rotation of the damaged and undamaged sections and treating the structures with Euler-Bernoulli or Kirchhoff type kinematics delamination models have been verified experimentally by Purekar and Pines [315] in the context of wave propagation in delaminated isotropic helicopter flexbeams, and by Luo and Hanagud [238] in the context of natural frequency change in first order shear deformable composite beam with delamination and the associated contact non-linearity in the low frequency dynamics. Also, such simplified model can be found useful while modelling advanced composite with stitching (Sankar and Zhu [337]) and various other types of material interfaces.

Considering axial-flexural-shear coupled wave propagation in composite beams, a delaminated spectral element has been developed by Mahapatra [245], where the exact dynamics of internal debonded sub-laminates was taken into account. In this formulation, the internal FE nodal informations are condensed out leaving the delamination in between the end nodes.

The restriction due to constant shear kinematics can be eliminated using the approach reported by Barbero and Reddy [29], where the layer-wise kinematics allows individual sub-laminates to rotate by different amount. Similar approach has been used by Kouchakzadeh and Sekine [191], where the formulation uses penalty function to impose appropriate constraints at the interface between base-laminates and multiple sub-laminates. In the works of Lee *et al.*, [212] and Lee [213], the interface is assumed to translate and rotate in a rigid-body mode. Thus, the normal plane is assumed continuous across the base laminate thickness and is hence not affected by the stress discontinuity in the two delaminated faces at the tip due to Mode-I and Mode-II stable delaminations. However, this assumption may not be adequate, since strong coupling between the displacement components may exist in case of asymmetric ply stacking, asymmetry among the sub-laminates (due to inclusions of different material) and discontinuity in the stiffness and inertia by foreign inclusions such as MEMS devices and integrated electronics.

Mahapatra [245] used spectral finite elements to model the individual sub-laminates, base-laminates and strip inclusions. A layer-wise constant shear kinematics was imposed by him at the interfaces of sub-laminates and base-laminates. Equilibrium of the system was then obtained using multi-point constraints in Fourier domain associated with the nodal displacement components and the force components at these interfaces allows to model small local rotations of the individual sub-laminates and the base-laminates at the interface in an average sense. Also, the model is a general one, where the length-wise multiple delaminations of debonding between strip inclusions can be modelled easily. Another advantage of the model is that both the frequency domain changes in phase and amplitude of scattered waves in presence of delaminations or strip inclusions as well as the time domain change in the response can be computed efficiently with the help of FFT (Mahapatra *et al.*, [244]).

1.2.5.3 Multiple Delaminations

The delaminations usually appear in several interfaces through the thickness of the laminate (multiple delaminations), between plies of different fiber angles, and are oblong in the direction of the fibers in the lower ply interface. The area of the delaminations increases through the thickness away from the point of impact. Multiple delamination damage identification in a composite plate using migration technique was proposed by Wang and

Yuan [388]. Chattopadhyay et al. [72] had studied time domain nonlinear dynamic response of composite laminates using a refined layer-wise theory with piezoelectric sensors and multiple delaminations, where the contact problem of delaminated interfacial surfaces was modelled in terms of fictitious linear springs to provide an accurate description of the transient behavior.

Mahapatra and Gopalakrishnan [247] had studied the effect of wave scattering and power flow through multiple delaminations and strip inclusions in composite beams with distributed friction at the inter-laminar region using spectral finite element formulation. In this model [247], the multiple delaminated beams are divided into several sound beams at the front of the delamination tip and the beam kinematics are then imposed. Each beam is constrained to contact each other but a free mode assumption is generally considered for linear analysis of the structure. Hence, each beam segment freely vibrates without touching each other. The effect of bending-extension coupling induced from the presence of delaminations can also be considered in the formulation.

1.2.6 Effective SHM Methodology

With the conventional NDE techniques, the complex mechanical system needs to be taken out of service for inspection. Where as, modal domain approaches are less sensitive to the small size damages. Small damages is sensitive to higher modes. To extract information from higher modes smart actuator/sensor based SHM techniques are used. In very high frequency (> 30kHz), global nature of the structure is remain unidentified. Approach in frequency domain is suitable for linear system. Time domain approach can detect damage with nonlinearity and hysteresis.

1.3 Background: Magnetostrictive Materials

Some magnetic materials (magnetostrictive) show elongation and contraction in the magnetization direction (Figure-1.1) due to an induced magnetic field. This is called the magnetostriction, which is due to the switching of a large amount of magnetic domains caused by spontaneous magnetization, below the Curie point of temperature. Thus magnetostrictive materials have the ability to convert magnetic energy into mechanical energy and vice versa. This coupling between magnetic and mechanical energies is the transudation capability that allows a magnetostrictive material to be used in both actuation and sensing devices. Due to magnetostriction and its inverse effect (also called Villery

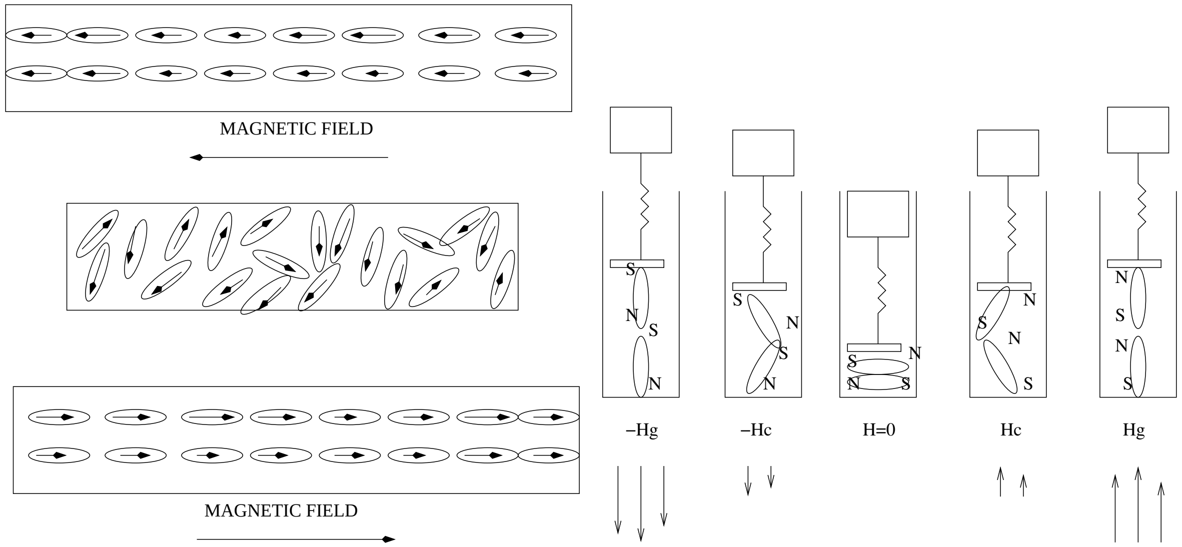

Figure 1.1: Magnetostriction due to switching of magnetic domains.

effect)[382], magnetostrictive materials can be used both as an actuator and as well as a sensor. References [369] and [260] performed extensive work related to electrostrictive and piezoelectric phenomena which have similarities in form with the magnetostriction phenomena.

1.3.1 Initial History

The first positive identification of a magnetostrictive effect was in 1842 [171] when James Joule observed that a sample of nickel changed in length when it was magnetized. Subsequently, cobalt, iron and alloys of these materials were found to show a significant magnetostrictive properties with strains of about 50 parts per million (ppm). Apart from magnetostriction and its inverse effect, other similar phenomenon known as the Wiedemann effect is present in such material, which is the twisting of the material when a helical magnetic field is applied. Its inverse effect is called the Matteuci effect [258], which is the creation of a helical field when the same material is subjected to a torque. One of the first practical applications of magnetostriction was its use in SONAR devices in echo location during the Second World War. Another early application was in torque sensing and these applications are as important today as they were then. The nickel based materials used in these devices had saturation magnetostriction values of 50 ppm. These strains are quite low and hence have limited applications.

1.3.2 Rare Earth Material Era

In the 1960s, the rare-earth elements terbium (Tb) and dysprosium (Dy) were found to have 100 times the magnetostrictive strains found in nickel alloys. However, because this property occurs only at low temperatures, applications of these materials above ambient temperature were not possible. The addition of iron to terbium and dysprosium to form the compounds $TbFe_2$ and $DyFe_2$ brought the magnetostrictive properties to room temperature. These materials individually required very large magnetic fields to generate a considerable strain, which means magnetomechanical coupling coefficient is very small.

1.3.2.1 Giant Magnetostrictive Materials

The theoretical and experimental study of magnetostrictive materials has been the focus of considerable research for many years. However, only the recent development of giant magnetostrictive materials (e.g. Terfenol-D) has enabled to produce sufficiently large strains and forces to facilitate the use of these materials in actuators and sensors. This has led to the application of magnetostrictive materials to such devices as micro-positioners, vibration controller, sonar projectors and insulators, etc. Giant magnetostrictive material has the ability to operate at high temperatures, and they give large strain for low magnetic field intensity and hence have very high coupling coefficient. By alloying the two compounds $TbFe_2$ and $DyFe_2$, it was found that the magnetic field required to produce saturated strains were considerably reduced. The resulting alloy $Tb_{.27}Dy_{.73}Fe_{1.95}$ (commercially known as Terfenol-D) is at present the most widely used giant magnetostrictive material. Terfenol-D is capable of strains as high as 1500ppm and, since the 1980's, it is commercially available for applications in many fields of science and engineering. Terfenol-D is known to have high magnetostriction and low anisotropy energy. Therefore, comparatively high strain amplitudes, approaching 1000ppm, can be obtained at low field (<100kA/m).

1.3.3 Applications

Due to its capacity to sense and actuate, giant magnetostrictive materials is used in wide varieties of applications. Choudhary and Meydan [85] designed accelerometer using inverse effect of magnetostrictive material. Oduncu and Meydan [296] performed Biochemical monitoring using magnetostrictive material. They determined the stress and strain in bone and bone implant to assess fracture healing. Hattori et al. [149] studied low frequency elastic wave measurement using magnetostrictive material in the concrete structure. Customary piezoelectric devices cannot produce such a low frequency elastic wave efficiently. The magnetostrictive sensors have a unique characteristic such that one can monitor stress waves without any direct physical contact. Because of this non-contact measurement property of the sensors, these have been used in various applications [397, 375, 184, 14, 299, 200, 201, 202, 203, 204, 205, 281, 282]. The measurement principle of this sensor is based on the Villari effect [382]. Cho et al. [79] investigated the design of an optimal configuration of the bias magnet assembly to maximize the voltage output of a magnetostrictive sensor. Visone and Serpico [383] proposed a black box type hysteresis model for magnetostrictive materials that is constituted by suitable composition of Preisach-like operators.

Hristoforou [161] given a review on the use of amorphous magnetostrictive wires in delay lines for sensing applications. Christos et al. [253] developed an optimized distributed field sensor based on magnetostrictive delay line response, suitable for NDT purposes. Hristoforou et al. [162] demonstrated the application of magnetostrictive delay line arrangement in thin film thickness determination, during film production.

1.3.3.1 Thin Film and MEMS

Magnetostrictive materials are very attractive for the production of microelectromechanical systems (MEMS), such as micro robots, micro motors, etc. [22, 233]. Wetherhold and Guerrero [394] studied the effects of the stress and magnetic states of magnetostrictive multi-layered thin films for the case in which a bending strain was applied to the substrate during film deposition and then released. Jain et al. [168] used the free standing magnetostrictive thick or thin film sensor for remote query of temperature and humidity for time-varying external magnetic field. From the oscillations at resonant frequency of the sensor, an acoustic wave is generated, which was detected remotely from the test area by a microphone. Gehring et al. [129] calculated the deflection for a magnetoelastic cantilever for an arbitrary ratio of thickness of film and substrate. Grimes et al. [141] considered magnetoelastic thin film sensors as the magnetic analog of surface acoustic wave sensors, with the characteristic resonant frequency of the magnetoelastic sensor to monitor the change in the response with different environmental parameters. Pasquale et al. [307] measured the magnetic properties of a set of (Tb_xFe_{1-x}) magnetostrictive thin films under applied stress in a cantilever configuration with complementary flux metric and magneto-optic Kerr effect methods.

1.3.3.2 Thick Film, Magnetostrictive Particle Composite

Kouzoudis and Grimes [98] studied the response mechanism of magnetoelastic thick-film sensors and have shown that the characteristic resonant frequency is a function of both pressure and the mechanical stress. Armstrong [23] presented nonlinear magnetoelastic behavior of magnetically dilute magnetostrictive particulate composites. To get this relationship, he assumed a uniform external magnetic field, which was operated over a large number of well-distributed, crystallographically and globally parallel ellipsoidal magnetostrictive particles encased in an elastic, non-magnetic composite matrix. Saito et al. [336] investigated the decrease of magnetization in positive magnetostrictive materials. Giurgiutiu et al. [134] presented theoretical and experimental result from the study of a MS-tagged fiber-reinforced composite beam under bending. Lanotte et al. [209] studied the potentiality of composite elastic magnets as novel materials for sensors and actuators.

1.3.4 Structural Applications

Subramanian [353] presented an analytical model for a simply supported symmetric laminated beams embedded with magnetostrictive layers based on the higher order shear deformation theory. Chakraborty and Tomlinson [65] investigated the suitability of transferring appreciable amounts of magnetic energy to external media using the property of change of magnetization of a Terfenol-D rod due to an applied force under a defined prestress level. Experimental investigations was also conducted on a Terfenol-D monolithic rod under different levels of constant pre-stress to quantitatively estimate the change in magnetic induction and measured that the change in magnetic induction is very small compared with that for a permanent magnet. Pan and Heyliger [301] derived analytical solutions for the cylindrical bending of multilayered, linear, and anisotropic magneto-electro-elastic plates under simple-supported edge conditions. Magnetostrictive material has found its way in many structural applications such as vibration control, noise control and structural health monitoring (see Section-1.2.2.4).

1.3.4.1 Vibration and Noise Suppression

Reddy and Barbosa [326] investigated laminated composite beams containing magnetostrictive layers modelled as distributed parameter systems to control the vibration suppression. The effect of material properties, lamination scheme and placement of the magnetostrictive layers on vibration suppression was investigated. Nakamura et al. [286]

developed an active six degrees-of-freedom micro-vibration control system using giant magnetostrictive actuators. Pelinescu and Balachandran [309] presented analytical investigations conducted into active control of longitudinal and flexural vibrations transmitted through a cylindrical strut fitted with piezoelectric and magnetostrictive actuators. Fenn et al. [119] developed a vibration reduction system for the UH-60A helicopter using magnetostrictive actuators drive with four trailing edge flaps on each blade. Anjanappa and Bi [19] developed an integrated model to analyze the vibration suppression capability of a cantilever beam embedded with magnetostrictive mini actuator using the Euler-Bernoulli beam theory and strain energy conservation principle. Anjanappa and Bi [18] also investigated the magnetostrictive mini actuator for distributed applications and further developed theoretical framework based on two-dimensional thermal analysis modifying the general form of constitutive equation for a magnetostrictive material to include thermal effects coming from resistive heating of a coil. Qian et al. [316] investigated vibration control for simply supported laminated composite shells with smart plies acting as sensor and actuator layers through magnetostrictive actuation. Pradhan et al. [311] formulated a theory for a laminated plate with embedded magnetostrictive layers based on the first order shear deformation theory (FSDT) and developed its analytical solution for simply-supported boundary conditions based on the FSDT, and the analytical solution for simply-supported plates is based on the Navier solution approach.

The effects of the material properties of the lamina, lamination scheme, and placement of the magnetostrictive layers on the vibration suppression time have been examined by many researchers. Brennan et al. [47] demonstrated the practical viability of a non-intrusive magnetostrictive actuator and sensor for the active control of fluid-waves in a pipe. Zheng et al. [426] presented active and passive magnetic constrained layer damping treatment for controlling vibration of three-layer clamped clamped beams. Mahapatra et al. [246] used this material to suppress all the frequency gear box noise components for active noise control in helicopter passenger cabin.

1.4 Artificial Neural Network

Studies of Artificial Neural Network (ANN) have been motivated to imitate the way that the brain operates. Neural networks learn by example, which gathers representative data, and then invokes training algorithms to automatically learn the structure of the data. Neural networks, with their remarkable ability to derive meaning from complicated or imprecise data, can be used to extract patterns and detect trends that are too complex to be noticed by either humans or other computer techniques. A trained neural network can be thought of as an "expert" in the category of information it has been given to analyze. This expert can then be used to provide projections for new situations.

1.4.1 The Biological Inspiration

The brain is principally composed of a very large number (100,000,000,000) of neurons, massively interconnected. Each neuron is a specialized cell which can propagate an electrochemical signal. The neuron has a branching input structure (the dendrites), a cell body, and a branching output structure (the axon). The axons of one cell connect to the dendrites of another via a synapse. When a neuron is activated, it fires an electrochemical signal along the axon. This signal crosses the synapses to other neurons, which may in turn fire. A neuron fires only if the total signal received at the cell body from the dendrites exceeds a certain level (the firing threshold). The strength of the signal received by a neuron (and therefore its chances of firing) critically depends on the efficacy of the synapses. Each synapse actually contains a gap, with neurotransmitter chemicals poised to transmit a signal across the gap. Learning occurs by changing the effectiveness of the synapses so that the influence of one neuron on another changes. A biological neuron may have as many as 10,000 different inputs, and may send its output (the presence or absence of a short-duration spike) to many other neurons. Neurons are wired up in a 3-dimensional pattern. Real brains, however, are orders of magnitude more complex than any artificial neural network so far considered. Thus, from a very large number of extremely simple processing units (each performing a weighted sum of its inputs, and then firing a binary signal if the total input exceeds a certain level) the brain manages to perform extremely complex tasks. Of course, there is a great deal of complexity in the brain, but it is interesting that the artificial neural networks can achieve some remarkable results using a model not much more complex than this.

1.4.2 The Basic Artificial Model

Neuron receives a number of inputs (either from original data, or from the output of other neurons in the neural network). Each input comes via a connection that has a strength (or weight); these weights correspond to synaptic efficacy in a biological neuron. Each neuron also has a single threshold value. The weighted sum of the inputs is formed, and the threshold subtracted, to compose the activation of the neuron. The activation signal is passed through an activation function (also known as a transfer function) to produce the output of the neuron. If the step activation function is used (i.e., the neuron's output is 0 if the input is less than zero, and the output is 1 if the input is greater than or equal to 0) then the neuron acts just like the biological neuron described earlier (subtracting the threshold from the weighted sum and comparing with zero is equivalent to comparing the weighted sum to the threshold). Actually, the step function is rarely used in artificial neural networks.

1.4.3 Historical Background

McCulloch and Pitts [265] developed models of neural networks based on their understanding of neurology in 1943 and shown that an artificial neural network, in theory, could compute any mathematical or logical function. Neural network research was then continued by Hebb [153], who proposed a mechanism for learning in biological neurons. These models made several assumptions about how neurons worked. In 1958 Rosenblatt [333] designed and developed the perceptron and demonstrated the ability of a perceptron network to recognize different patterns. The perceptron had three layers with the middle layer known as the association layer. This system could learn to connect or associate a given input to a random output unit. Another system was the ADALINE (ADAptive LINear Element), which was developed in 1960 by Widrow and Hoff [395]. The method used for learning was different to that of the Perceptron; it employed the Least-Mean-Squares (LMS) learning rule. Widrow-Hoff learning algorithm is that of gradient descent algorithm, aimed at minimizing the error of the network.

Though, between 1960 and 1980 interest in neural networks dropped because of lack of new ideas and computational power, in 1972 Kohonen [188, 189] and Anderson [15] independently and separately developed new neural networks, which were able to act as memories. In 1982, Hopfield [160] introduced a new type of network. Since the 1980s, with the help of new personal computers and workstations, neural network development and research has dramatically increased. One of the most important developments during this time was the introduction of the backpropagation algorithm developed by Rumelhart et al. [334].

1.4.4 Neural Network Types

Neural Network types can be classified based on following attributes:

1.4.4.1 Topology

1. Single layer: A single layer network is a simple structure consisting of m neurons each having n inputs. The system performs a mapping from the n-dimensional input space to the m-dimensional output space. To train the network, the same learning algorithms as for a single neuron can be used. This type of network is widely used for linear separable problems, but like a neuron, single layer network are not capable of classifying non linear separable data sets. One way to tackle this problem is to use a multi-layer network architecture.

2. Multi layer: Multi-layer networks solve the classification problem for non linear sets by employing hidden layers, whose neurons are not directly connected to the output. The additional hidden layers can be interpreted geometrically as additional hyper-planes, which enhance the separation capacity of the network. Figure-1.2 shows a typical multi-layer network architecture. This new architecture introduces a new question: how to train the hidden units for which the desired output is not known? The Back-propagation algorithm offers a solution to this problem, which is discussed in Section-1.4.6.

1.4.4.2 Connection Type

1. Feed-forward: In computing, feed-forward normally refers to a multi-layer perceptron network in which the outputs from all neurons go to following but not preceding layers, so there are no feedback loops.

2. Feedback: A feedback network is a system where the outputs are fed back into the system as inputs, increasing or decreasing effects.

1.4.4.3 Learning Methods

There are three major learning paradigms, each corresponding to a particular abstract learning task.

1. Supervised: In supervised training, both the inputs and the outputs are provided. The network then processes the inputs and compares its resulting outputs against

the desired outputs. Errors are then calculated, causing the system to adjust the weights which control the network.

2. Unsupervised: In unsupervised training, the network is provided with inputs but not with the desired outputs. The system itself must then decide what features it will use to group the input data. This is often referred to as self-organization or adaption.

3. Reinforcement learning: In the reinforcement learning model, an agent is connected to its environment via perception and action.

1.4.4.4 Applications

1. Classification: Neural networks can be used successfully for pattern recognition and classification on data sets of realistic size. Commercially important examples are classification of fingerprints and hand printed characters.

2. Clustering: Clustering could be defined as "the process of organizing objects into groups whose members are similar in some way." Clustering can be considered the most important unsupervised learning problem

3. Function approximation: ANN can be used to approximate a function.

4. Prediction: Different series predictions can be performed by ANN.

1.4.5 Multi Layer Perceptrons (MLP)

The Multi-layer perceptron (MLP) is the most widely used type of neural network. It is both simple and based on solid mathematical grounds. An MLP is a network of simple neurons called perceptrons. The basic concept of a single perceptron was introduced by Rosenblatt [333] in 1958. The perceptron computes a single output from multiple real-valued inputs by forming a linear combination according to its input weights and then possibly putting the output through some nonlinear activation function. Mathematically this can be written as

$$y = \varphi(\sum_{i=1}^{n} w_i x_i + b) = \varphi(\mathbf{w}^{\mathbf{T}}\mathbf{x} + \mathbf{b})$$

where $\mathbf{w}$ denotes the vector of weights, $\mathbf{x}$ is the vector of inputs, b is the bias and φ is the activation function. The original Rosenblatt's perceptron used a Heaviside step function as the activation function φ. Nowadays, and especially in multilayer networks, the activation function is often chosen to be the logistic sigmoid $1/(1+e^{-x})$ or the hyperbolic tangent $\tanh(x)$. These functions are used because they are mathematically convenient and are close to linear near origin while saturating rather quickly when getting away from the origin. This allows MLP networks to model well both strongly and mildly nonlinear mappings.

A single perceptron is not very useful because of its limited mapping ability. No matter what the activation function is used, the perceptron is only able to represent a simple function. The perceptrons can, however, be used as building blocks of a larger, much more practical structure. A typical MLP network consists of a set of source nodes forming the input layer, one or more hidden layers of computation nodes, and an output layer of nodes. The input signal propagates through the network layer-by-layer. It maps an input vector from one space to another. The mapping is not specified, but is learned. The learning process is used to determine proper interconnection weights and the network is trained to make proper associations between the inputs and their corresponding outputs. The signal-flow of such a network with one hidden layer is shown in Figure-1.2. Mathematically this can be written as

$$\mathbf{y} = \varphi_{\mathbf{3}}\left(\mathbf{W_3}^{\mathbf{T}}\varphi_{\mathbf{2}}\left(\mathbf{W_2}^{\mathbf{T}}\varphi_{\mathbf{1}}\left(\mathbf{W_1}^{\mathbf{T}}\mathbf{x}+\mathbf{b_1}\right)+\mathbf{b_2}\right)+\mathbf{b_3}\right) \tag{1.1}$$

where $\mathbf{W_i}$, $\mathbf{b_i}$ and $\varphi_{\mathbf{i}}$ are weight matrices, bias vectors and the activation functions for i^{th} layer, respectively. Through this simple structure, MLP have been shown to be able to approximate most continuous functions to very high degrees of accuracy, by choice of an appropriate number of units and connection structure. A three-layer network (Figure-1.2) with the sigmoidal activation functions can approximate any smooth mapping.

The MLP network can also be used for unsupervised learning by using the so called auto-associative structure. This is done by setting the same values for both the inputs and the outputs of the network. The extracted sources emerge from the values of the hidden neurons. This approach is computationally rather intensive. The MLP network needs to have at least three hidden layers for any reasonable representation and training such a network is a time consuming process.

1.4.5.1 Transfer / Activation Function

The behavior of an MLP depends on both the weights (bias included) and the input-output function (transfer function) that is specified for the units. This function typically falls into one of four categories:

1. Linear (or ramp): For linear units, the output activity is proportional to the total weighted output.

2. Threshold: For threshold units, the output are set at one of the two levels, depending on whether the total input is greater than or less than some threshold value.

3. Logistic sigmoid ($1/(1 + e^{-x})$): For sigmoid units, the output varies continuously but not linearly as the input changes.

4. Hyperbolic tangent ($\tanh(x)$): Logistic sigmoid and hyperbolic tangent are related by $(\tanh(x) + 1)/2 = 1/(1 + e^{-2x})$.

1.4.6 The Back-propagation Algorithm

The supervised learning problem of the MLP can be solved with the Back-Propagation (BP) algorithm. While, there are a large number of ANN types and architectures, neural mapping is generally been associated with the so-called back propagation network (Rumelhart et al. [334]). This network, in general, is organized in three types of layers: an input layer, some hidden layers and an output layer. The algorithm consists of two steps. In the forward pass, the predicted outputs corresponding to the given inputs are evaluated as in Equation-(1.1). In the backward pass, partial derivatives of the error with respect to the different parameters are propagated back through the network. The chain rule of differentiation gives very similar computational rules for the backward pass as the ones in the forward pass. The network weights can then be adapted using any gradient-based optimization algorithm. The whole process is iterated until the weights have converged. The structure of a network is determined by a number of factors including the nature of the data to be mapped. For instance, there is usually an input unit for each input variable and an output for each output variable of the data. The number of hidden units (and layers) is typically determined experimentally on the basis of training results.

1.4.6.1 Training of BP ANN

The training of a BP neural network is a two-step procedure [334]. In the first step, the network propagates input through each layer until an output is generated. The error between the output and the target output is then computed. In the second step, the

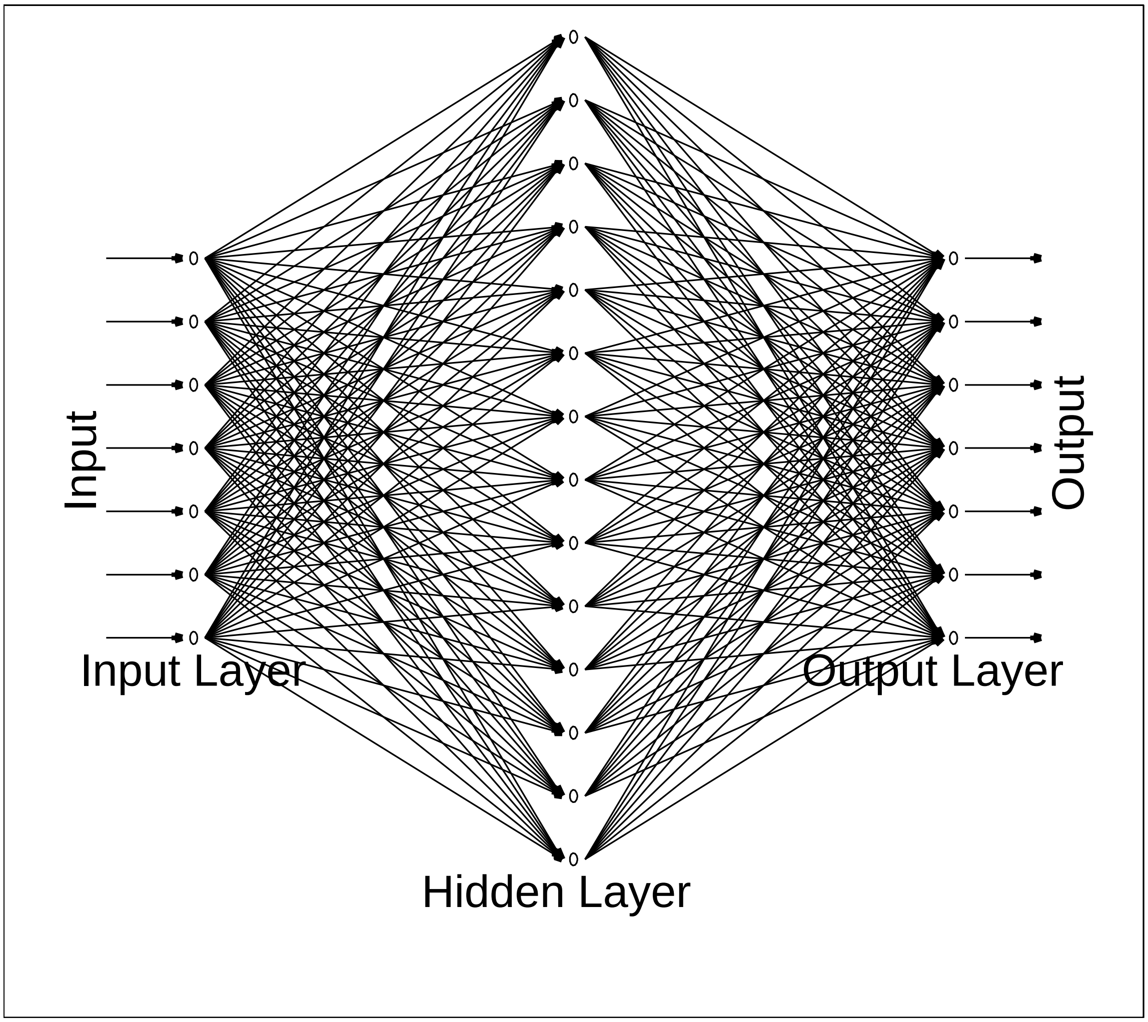

Figure 1.2: Artificial Neural Network of 7-14-7 Architecture.

calculated error is transmitted backwards from the output layer and the weights are adjusted to minimize the error. The training process is terminated when the error is sufficiently small for all training samples. In practical applications of the back-propagation algorithm, learning is the result from many presentations of these training examples to the multi-layer perceptron. One complete presentation of the entire training set during the learning process is called an *epoch*. The learning process is maintained on an epoch-by-epoch basic until the synaptic weights and bias levels of the network stabilizes and the averaged squared error over the entire training set converges to some minimum value. For a given training set, back-propagation learning can be done in sequential or batch modes, which are explained below.

1.4.6.2 Sequential Mode

The sequential mode of back-propagation learning is also referred to as on-line, pattern, or stochastic mode. In this mode of operation, weight updating is performed after the presentation of each training examples. To be specific, the first example in the epoch is presented to the network, and the sequence of forward and backward computation is performed, resulting in a certain adjustments to the synaptic weights and the bias levels of the network. Then the second example in the epoch is presented, and the sequence of forward and backward computation is repeated, resulting in further adjustments to the synaptic weights and bias levels. This process is continued until the last example in the epoch is accounted for. It is a good practice to randomize the order of presentation of training examples from one epoch to the next. This randomization tends to make the search in weight space stochastic over the learning cycles, thus avoiding the possibility of limit cycles in the evolution of the synaptic weight vectors.

1.4.6.3 Batch Mode

In this mode of back-propagation learning, weight updating is performed after the presentation of all the training examples that constitute an epoch, so that the randomization of the training examples is of no use in this training mode. It requires local storage of the each synaptic connection. Moreover, the network may trap in a local minimum. One advantage of batch mode over sequential mode is that it is easier to parallelize the entire operation.

1.4.6.4 Validation of Trained Network

To test the trained network, the data set is separated into two parts, one for training and the other for testing the network performance. The network will be trained using training sample and the trained network will be validated with the test sample. A network is said to generalize well when the input-output mapping computed by the network, is corrected with the test data that was never used in creating or training the network. Although the network performs useful interpolation, because of multilayered perceptrons with continuous activation functions, it leads to output functions that are also continuous.

1.4.6.5 Execution of Trained Network

Once the network is trained and validated with sample set, it can execute rapidly to map any point in input space to the corresponding point of output space.

1.4.7 Applications for Neural Networks

Neural networks have seen an explosion of interest over the last few years, and are being successfully applied across an extraordinary long range of problem domains, in areas as diverse as finance, medicine, engineering, geology and physics. Indeed, anywhere, where there are problems of prediction, classification or control, neural networks are being introduced. Since neural networks are best at identifying patterns or trends in data, they are well suited for

- sales forecasting, industrial process control, customer research, data validation, risk management, target marketing, resource allocation and scheduling, credit evaluation (mortgage screening), investment analysis (to attempt to predict the movement of stocks currencies etc., from previous data);
- signature analysis (as a mechanism for comparing signatures made with those stored); recognition of speakers in communications, interpretation of multi-meaning Chinese words, three-dimensional object recognition, hand-written word recognition, and facial recognition;
- diagnosis of hepatitis, modelling parts of the human body and recognizing diseases from various scans (e.g. cardiograms, scans, etc.), sensor fusion, implementation of electronic noses (potential applications in telemedicine), instant physician (an auto-associative memory neural network to store a large number of medical records, each of which includes information on symptoms, diagnosis, and treatment for a particular case);
- recovery of telecommunications from faulty software, undersea mine detection; texture analysis, monitoring the state of aircraft and diesel engines, etc.

In this thesis, the use of ANN will be explored for damage detection in composite structures, where these networks are trained using the surrogate experimental data obtained through finite element simulation.

1.5 Objectives and Organization of the Thesis

Based on the literature survey in the previous sections, the requirements in the computational aspects of structural health monitoring using magnetostrictive materials and the current status of the SHM, the main objectives of this thesis are

1. Develop linear and non-linear constitutive relationships of magnetostrictive materials useful for structural applications.
2. Using the above developed constitutive relationships, formulate finite elements for both coupled and uncoupled analysis.
3. Develop superconvergent and spectral finite element formulation for analysis of beam with magnetostrictive materials.
4. Develop artificial neural network as a tool to solve inverse problem.
5. Develop higher order beams finite element with magnetostrictive sensor and actuator.
6. Demonstrate the ability of the developed finite element and spectral element methods for the solution of inverse problems, such as, force and material property identification using magnetostrictive sensors.
7. Development of 2-D and 3-D elements for analysis of structure with magnetostrictive patches.
8. Study the effect of delamination or multiple delaminations on the sensor response due to known actuation in the beam and plate like structure.
9. Study the geometric inverse problem like delamination identification using artificial neural network.

Thus, we have three main goals to pursue in this study. The first one is to obtain the coupled, uncoupled, linear and nonlinear properties of the magnetostrictive material, applicable to structural applications. The second one is to develop 1D, 2D and 3D finite element formulation to get sensor response from known material properties and actuation current. The third one is identification of the material properties, impact force and size and location of delamination from magnetostrictive sensor response.

We proceed to our study by dividing it into following three parts. In the first part, we begin by formulating linear, nonlinear, coupled and uncoupled constitutive relationships from published experimental results. All the details of formulation and numerical examples are given in Chapter 2.

In the second part, we develop the 1D, 2D and 3D finite element formulation to model elastic coupled and uncoupled thermo-magneto-elastic analysis (Chapter 3, Chapter 4 and Chapter 5).

In the third part, structural health monitoring using magnetostrictive material as sensors and actuators are addressed (Chapter 6 and Chapter 7). Impact force identification from sensor response is demonstrated using spectral finite element formulation (Chapter 5). Sensor responses are used to train the artificial neural network for material properties identification (Chapter 4) and identification of the location and size of delamination in a structure.