Chapter 2

Literature Review

The previous chapter discussed the importance of advance structural health monitoring systems. The detailed literature review regarding methodologies related to structural health monitoring based on fiber optic technology and diffuse wave analysis will be discussed in this chapter.

2.1. Structural Health Monitoring

The condition of a structure can be predicted well by analyzing the response received from the structure under test signals. SHM helps in revealing the real-time state of the structure. SHM is an excellent research area in the field of engineering, especially related to mechanical, civil, and architecture. SHM lays a systematic inspection and maintenance procedure of structures. SHM is a continuous process of measurement and analysis of structural parameters under different operational conditions. Civil structures in specific play a very important role in the running economy of a country. Periodic inspection and systematic measurement with proper data processing provide a reliable assessment of the serviceability of the structure under consideration. Effective physical parameters like applied load, vibration, existence of damage affect the serviceability of a structure. The potential of advance sensing provides an improved methodology of SHM. Structures like bridges, dams, towers, and spacecraft parts are some of the most complex designs for which advancement in the SHM method is essential.

Daniel Cortázar et al. proposes a new SHM technique for the failure detection of the breakage of individual wire in a rope employing commercial optical fiber [1]. Hong-Nan Li et al. presented an overview of current research and development in the field of structural health monitoring with civil engineering applications based on fiber optic sensors [2]. J.M.Ko et al. studied the critical technological issues concerning structural health monitoring of large scale bridges. The focus of the study includes the current status of and recent trends in the specific area of bridge health monitoring [3].

A. Panopoulou et al. investigated a new system for structural health monitoring of composites aerospace structures under the dynamic state of measurement. Signal processing techniques, e.g., the wavelet transform (WT), were used for the analysis of the dynamic response for feature extraction [4].

T. H. T. Chan et al. presented an FBG sensor for structural health monitoring of Tsing Ma bridge, which is the world's longest suspension bridge. This study aims to inspect the probability of using FBG sensors for successful health monitoring of bridge under rail and road dynamic loading [5]. Paulo Roriz et al. presented a review related to the application of fiber optic sensors in the field of biomechanics. Strain and force detection on biomaterials is provided in this article [6]. Mousumi Majumder et al. reviewed recent developments in the area of FBG based structural health monitoring. The conclusion of the study includes that for better strain transfer thin layer of adhesive should be used, the adhesive must have a high modulus of elasticity, and a sufficient embedding length is required [7].

R. Maaskant et al. briefly discussed along with its application in long-gauge measurements [8]. Fang Cheng and Kuang-Chao Fan proposed a high-resolution angle measurement using the Michelson interferometer [9]. Muneesh Maheshwari et al. introduced a new design of fiber optic polarimetric sensor (FOPS) in which only the central part of FOPS is sensitive, leading-in, and leading-out parts are insensitive which help in the monitoring of a specific area of interest within a long structural member [10]. T.H. Loutas, P. Charlaftis et al. investigated the structural durability of fiber optic ribbon tapes (FORTs) concept comparing two ways of mounting the FORT(co-bonding and secondary bonding) under fatigue loading conditions [11].

Sun et al. have presented the use of PZT transducers for structural health monitoring. The current, in terms of electrical admittance, is measured by an impedance analyzer. Any changes caused to the structure by damage can be measured by analyzing the admittance signature [12]. Liang et al. proposed a 1D model by considering the PZT patch to be a thin bar undergoing axial vibrations [13]. Zhou et al. extended the 1D impedance method to model a two-dimensional (2D) PZT transducer element coupled to a 2D monitored structure [14]. By considering the concept of effective impedance, Bhalla, and Soh improved Zhou's model for PZT based SHM [15-16]. Yang proposed a generic model for predicting the electromechanical impedance of one-dimensional and two-dimensional PZT-structure interaction systems [17]. Ong et al. introduce an EMI model that considered the shear lag effect of the bond layer between the host and sensor [18]. Bhalla et al. improved the shear lag effect into the existing 1D and 2D EMI models [19]. Yan et al. considered the adhesive layer and presented an EMI model for Timoshenko beams and Mindlin-Herrmann rods [20-

21]. Pietrzakowski studied the inertial terms of PZT patches and studied the influence of the bonding layer on the beam response, but this method is not suitable for high-frequency EMI techniques due to the use of Euler beams [22].

Recently, attention has been paid to the effects of adhesives on the performance of piezoelectric elements. The contact between PZT transducer patches and host structure is achieved through interfacial shear stress based on the shear lag model [23-24-25]. Giurgiutiu et al. proposed that the EMI and the lamb wave techniques applied with a piezoelectric patch active sensor can detect both the presence and the propagation of a crack under mixed-mode fatigue loading. Increment in damage index is observed along with damage increment [26]. Ihn and Chang successfully used the wave propagation technique with PZT transducer patches for damage detection using changes in the received signal. The method was proved to be effective in detecting de-bonding and delamination and as well as in monitoring fatigue crack growth [27]. Soh and Lim investigated the feasibility of fatigue-induced damage detection and characterization using the EMI technique. The experiments on aluminum beam with a pre-induced circular notch indicated that the EMI technique is excellent at detecting incipient crack through changes in the admittance signature [28].

2.2. Fiber Optic Sensors

The working of optical fiber is based on total internal reflection. It is a phenomenon that occurs when a propagating wave strikes a medium boundary at an angle greater than the critical angle. If the refractive index is lower on the other side of the boundary and the incident angle is greater than the critical angle, the wave cannot pass through and is entirely reflected. This is especially normal as an optical singularity, where light waves are included, yet it happens with numerous sorts of waves, for example, electromagnetic waves as a rule or sound waves. At the point when a wave crosses a periphery between various materials with various types of refractive indices, the wave will be halfway refracted at the peripheral surface, and in part reflected. In any case, if the edge of frequency is more noteworthy (i.e., the heading of spread or beam is nearer to being corresponding to the peripheral limit) than the basic point – the edge of occurrence at which light is refracted with the end goal that it goes along the limit – at that point, the wave won't cross the limit and rather be completely reflected back inside. This can possibly happen when the wave in a medium with a higher refractive file (n_1) hits its surface that is in contact with a surface of lower refractive record (n_2). The critical angle $\emptyset_c$ is given by Snell's law.

$$n_1 \sin \emptyset_1 = n_2 \sin \emptyset_2 \tag{2.1}$$

For the fiber optic cable, the mediums are silica core and silica with a different composition and slightly lower reflective index around it. Most fiber is in addition to the cladding, coated with a coating suited for the application for which the cable is going to be used. The coating will, for example, give it the color, protect it against chemicals, enhance bonding, etc. Fiber coatings are required to protect the fiber from abrasion, concrete, and moisture.

Fiber optic sensors can be classified under different categories. Based on the location of sensor FOS are of two types as follows:

1) **Intrinsic optical sensor:** In inherent detecting, the inside property of optical fiber itself changes over the external changes into an adjustment of the light signal. This adjustment of the light signal might be as intensity, phase, and frequency or possibly polarization.
2) **Extrinsic optical fiber:** In extraneous detecting, the fiber might be utilized as data transporters that lead to a black box, and that will create a light signal contingent upon the data received at the black box. This black box might be made of mirrors, gas, fluid cell, or numerous different systems.

Udd E. Early efforts to initiate the field of fiber optic smart structures at Mcdonnell Douglas. The first fiber optic sensor, a closed-loop fiber gyro, was invented to replace mechanical spinning gyros on the Delta Rocket in 1978 [29]. Optical fiber experiences the geometrical (size and shape) and optical (refractive index and mode conversion) change due to various environmental perturbations while transmitting light from one place to another. However, it is found that such optical change can be employed to measure the external environment parameters [30-31].

In general, an FOS is characterized by its high sensitivity when compared to other types of sensors. It is also passive in nature due to its dielectric construction. Specially prepared fibers can withstand high temperatures and other harsh environments. With many signal processing devices (splitter, combiner, multiplexer, filter, delay line, etc.) being made of fiber elements, an all-fiber measuring system can be realized.

2.2.1. Local Fiber Optic Sensors

Numerous intensity-based sensors, such as micro bend sensors, and most of the interferometric FOSs are local sensors, which can quantify changes at determined nearby focuses in a structure. Interferometric FOSs are by a long shot the most regularly utilized local sensors since they offer the best affectability. This detecting strategy depends basically on identifying the optical phase change instigated in the light as it proliferates along with the optical fiber. Light from a source is similarly partitioned into two fiber-guided paths (out of these two, one is a reference). The light rays are then recombined to blend lucidly and a fringe pattern is generated. This pattern directly correlates with the optical phase difference between initial rays. The most widely recognized designs of such interferometric sensors are the Mach-Zehnder, Michelson, and Fabry–Perot FOSs [32-33]. Among them, the Fabry–Perot (F-P cavity) FOS and the supposed long gauge FOS (LGFOSs) are the two local sensors normally used in SHM. Fabry-Perot FOSs, which can give supreme Fabry–Perot depression length estimations with prevalent precision, depends on the white-light cross-connection rule.

2.2.2. Quasi-distributed sensors

Fiber Bragg grating (FBG) sensor, which can be easily multiplexed to measure strains at many locations, is a kind of typical quasi-distributed sensor. A Bragg grating is a permanent periodic modulation of the refractive index in the core of a single-mode optical fiber. The change of the core refraction index is between 10^{-5} and 10^{-3}, and the length of a Bragg grating is usually around 10 mm, which is much shorter than that of a long period grating (LPG) [34]. This technology originated from the discovery of photosensitivity of germanium doped silica by Hill et al. in 1978 [35]. Later Meltz et al. devised a more efficient transverse holographic method, which enormously increased the scope of FBGs applications [36]. Now the phase mask technique supersedes the above two methods and is commonly used to form the in-core gratings [37]. Techniques such as hydrogen loading and flame brushing can be adopted to enhance the germanium doped single-mode optical fiber's photosensitivity prior to laser irradiation [38].

The standard of an FBG is portrayed as follows: When light inside a fiber encroaches upon Bragg gratings, the useful impedance between the forward wave and the contra-proliferating light wave prompts narrowband back-impression of light when the Bragg (or stage coordinate) condition is fulfilled. Along these lines, a fiber Bragg gating can fill in as an intrinsic sensor. Any local strain or temperature changes modify the file of center refraction and the grinding time frame, trailed by changes in the frequency of the reflected light. Frequency changes can be distinguished by an interrogator, which utilizes edge channels, tunable narrowband channels, or CCD spectrometers [39-40]. Tunable narrowband channels are financially well-known cross-examination established frameworks. There are a few significant worries in choosing FBGs and the related cross-examination frameworks. For example, the overly cover of the gratings changes nearby attractive frequency [41]. For another occasion, sidebands in the deliberate frequency, the cross-examination channel, and the tunable light source additionally present faults in the framework.

2.2.3. Distributed Fiber Optic Sensors

Distributed sensors are generally appropriate for enormous auxiliary applications since all the sections of an optical fiber go about as sensors. Along these lines, the distresses inside different sections of the structure can be detected. These types of sensors depend on the variations of light intensity in the fiber. Fracture and local damages produce changes in light intensity. Two significant distributed sensor philosophies are the optical time-space reflectometry (OTDR) and the Brillouin dissipating. In the OTDR, Rayleigh and Fresnel's scatterings are utilized for detecting basic structural irregularities. Then again, Brillouin dissipating identifies the Doppler shift in light recurrence, which is identified with the estimations.

In the recent past, optical fibers have been successfully used in area of telecommunication industries because of their special transmission characteristics. Recent research investigates the feasibility of using FBG sensors for health conditioning measurement by monitoring the strain of different parts of the structure under transportation loads [42]. A recent investigation successfully employed Mach-Zehnder interferometric sensors to measure the dynamic strain. Successful assessment of low strain measurement was performed for structural health monitoring using a fiber optic sensor [43]. FBG sensors are used for strain measurement, thus measuring the reliability of the civil structures.

2.3. Neural Network Based Structural Health Monitoring

Methodologies involved in damage detection can be divided into two basic categories, namely model-based and model-free. Model-based approach includes the development of an accurate finite element model for required structural analysis. FEA model development became difficult in the case of complex structures. Model-free analysis overcomes the problem of developing a detailed model by using artificial intelligence. But to give a physical interpretation to a structural phenomenon like damage detection is still a complicated task to accomplish using artificial intelligence. A systematic approach to SHM using neural network includes training an algorithm with a data set obtained under undamaged condition. This training helps the developed algorithm to understand the future behavior of the system. On providing a new set of data as input to the neural network for validation and testing, the system successfully predicts the variation in the physical state of the structure. As a result, initial damage identification uses qualitative analysis for the identifying the presence of damage in the structure. Algorithms used in novelty detection, focus on the analysis of measured target values which are deviated from its normal pre-existing condition. Deviation in the pre-existing condition is considered as the probability of occurrence of damage. Working of artificial neural networks falls in the category of novelty detection methodology based on machine learning and reconstruction. Some areas of ANN application include structural health monitoring, speech recognition, pattern recognition, chemical optimization production process control, etc.

ANN is one of the mathematical model inspired by understanding the working of a biological neural network system. Neurons are processing units of the nervous system, which actively participate in receiving, analyzing, and transmission processes. The biological structure of a nerve cell has three basic parts-dendrites, which act as a receiver for the information in the form of signals. The cell body performs the processing part of the received signals. Axon is the end part of the cell, which helps in transmitting the processed signals to the next level. The basic components of a neuron are shown in fig. 2.1.

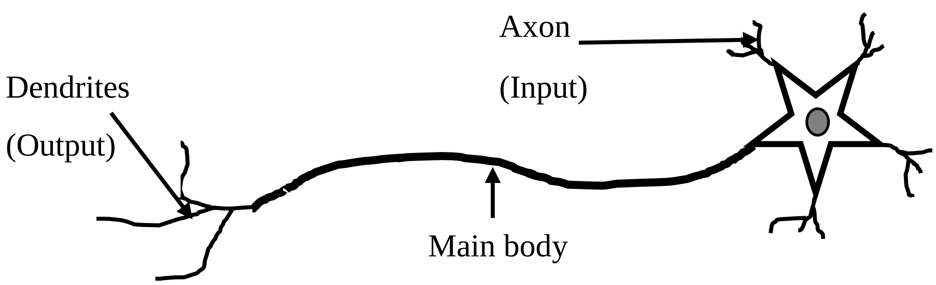

Fig. 2.1.Schematic diagram of nerve cell

Valuable information is encoded in the connection strength between the neurons. Learning is a process of gradual development and modification as a result of brain interaction with the environment. As defined, the development and modification depend on the connection strength and stimulus-based response. ANN is the outcome of the rigorous search for a mechanism analogous to the biological nervous system used for computation. This possibility of programming a system by interaction with a sequence of stimuli responses so that the system perfectly identifies the correct relationship.

Warren McCulloch et al. studied analogous characteristics of biological neurons with an artificial neuron unit which receives a set of stimuli (input data) and provide a response as a signal (output) [44]. The working of an artificial neuron unit is shown in fig. 2.2.

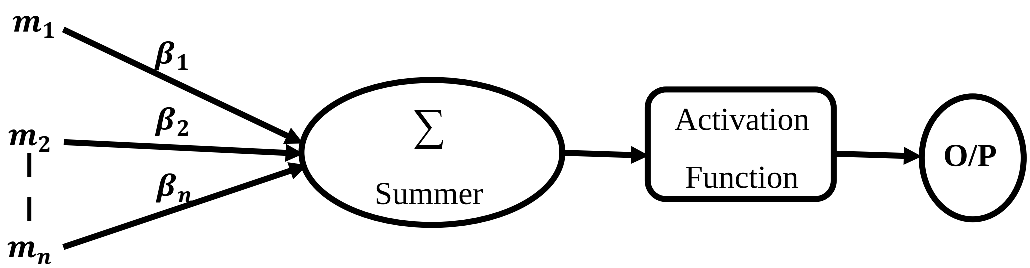

Fig. 2.2. Basic working of artificial neural network

Resenblatt developed the first multilayer neuron network model. The developed neural architecture was non-homogeneous in nature based on a three-layered network structure. The first layer takes input data and transfers it to the next processing layer. The function of the middle layer is to process the data and analyses for decision making. Information in the sequence gets transferred to the third layer, which is the output layer. The main aim of developing this perceptron model was for image analysis based on pattern recognition with input as a black and white data base [45]. Minsky et al. identified some of the major problems associated with the initial machine learning process. One of the major problems was computational power and time [46]. In a study, FEA strain data is successfully used in the neural network to predict the defect present in the structure [47]. The recent research shows advancement in approximating the hidden layers in neural network back-propagation architecture [48]. Lu et al. effectively used the neural network in the identification of damage in the aluminum plate [49]. A scaled conjugate gradient-based back-propagation algorithm is developed with two hidden layers for identifying the damage location. Review of different artificial intelligence techniques like a neural network, fuzzy logic, and genetic algorithm, which are used in damage detection prove acceptability of new technique in SHM [50]. Thatoi et al. described a cascade forward back-propagation neural network for damage detection using natural frequency as input parameters [51]. Lam et al. used a Bayesian probabilistic framework on structures based on dynamic response for fault detection [52]. Gordan et al. discussed different fault measurement techniques based on the data mining process. The focus of the study is based on artificial intelligence area [53]. Cha et al. used a convolution neural network approach for identifying the damage in structures [54]. Xie et al. studied the performance of the dynamic neural model of fatigue crack growth in aluminum alloy specimens [55]. Elshafey et al. proposed a practical equation for analyzing the crack spacing. Using a neural network approach it was shown that concrete compressive strength and element thickness have minimal effect on crack spacing [56]. Recent comparative study for output convergence is successfully analyzed using static parameters [57]. A neural network is a machine learning process which can be successfully used in the area of structural health monitoring. The investigation provides a damage assessment method using neural network analysis for composite structures [58]. Performance of a neural network is based on the number of neurons present in the hidden layer and the number of hidden layers in network architecture. Concepts are developed to set selection criteria for the number of neurons in a network [59]. Over and underfitting is an important criterion which plays an important role in developing a neural network model. Some studies used a feed-forward back-propagation neural network model for strain approximation using airspeed and angle of attack as input parameters in the aerodynamic analysis [60]. In any neural network, weights play an important role in optimizing network performance [61]. For minimizing computational cost, optimization is obtained using the Levenberg-Marquardt algorithm for training [62].

Hopefield studied the neural network problem, which was based on the dynamic behavior of the system. The output of the neuron is a time-dependent parameter. A learning rule for a multilayer structure can be derived by replacing the threshold with a continuous function [63]. These functions include sigmoidal or hyperbolic tangential as defined below:

$$y = \frac{1}{1 + e^{-z}} \qquad (2.2)$$

$$y = \tanh(z) \qquad (2.3)$$

Selecting of activation function as continuous; the whole problem gets transformed as a problem based on the partial differential equation. Rumelhat et al. get the credit of introducing the back-propagation learning rule in ANN area. This method is integrated with optimization methods using the delta rule for finding a local minimum of the linear system of networks [64]. Bishop introduced supervised and unsupervised network learning for specified problems. At each training step, a set of input values is transferred using a feed-forward mechanism into the network [65]. Haykin developed the concept of algorithm learning by defining the updating rule [66]. Mullar studied the first-order algorithm along with a second-order algorithm and concluded that second-order algorithms are computationally more expensive but have a high convergence rate compared to the first-order algorithm [67]. Press et al. performed a comparative study for two second-order algorithms, namely the scaled conjugate gradient and Levenberg Marquardt algorithms [68].

The ANN is a area of artificial intelligence which is used for SHM in the area of sensor data processing that requires computation and optimization due to high convolution of variable variations. Different dimensions of problems in which ANN can be applied are given below:

1) Auto association- Capacity of the trained network to restore pattern under a distorted input signal due to noise.
2) Regression- Provide an output characteristic based on a given input.
3) Classification- Defining group for the specific input data type.
4) Novelty detection- Study of statistical abnormalities related to input data.

Integrated ANN-based SHM is a recent advancement in which signal data is obtained from the reference structure. These data set are used as input parameters for the network analysis. The training of the network is based on the input of the reference structure. This data analysis is considered as unsupervised learning. In this concept, a reference state of normal condition is established, and then a new data set is used for comparison. If the variation between reference and new data exist, this indicates that structure has deviated from its normal conditions. This novelty detection method can be made advanced for multilevel classification for the severity and extent of the damage. Advancement in novelty increases the complexity of ANN, and also increases the computational cost and time.

2.4. Diffuse wave sensors

Diffuse ultrasonic waves can be used to interrogate a large volume of complex structures with high sensitivity using a small number of sensors, but it is difficult to correlate changes in diffuse ultrasonic signals with the health of the structure being interrogated. This research provides a wavelet-based comprehensive damage detection strategy for diffuse ultrasonic waves. They are generated by an impulse and tone burst and received by broadband piezoelectric transducers. The potential of the technique is examined, and laboratory examples are presented. It is shown that the wavelet carries information about the material damage. The strategy includes a systematic feature extraction method for the declaration of the structural status as "damaged" or "undamaged."

Elastic waves and ultrasonic waves are frequently used for in situ monitoring of the health of the structure. For inspection of large structures such as plates and pipes, narrowband guided waves are preferred, but the method is unsuitable for a large class of small and complex shape structures because of the noise generated from the boundary reflected waves [69-72].

Some researchers found the diffuse ultrasonic waves as a good alternative for complex structures. The diffuse field concept was used for the analysis of acoustic signals in a room where the wall reflects the sound. It is observed that energy distribution depends on the structure, and a new defect changes the energy distribution. The sensitivity of diffuse ultrasonic signal to environmental changes further obscure response from the damage [73-75]. Recently, some researchers have used various techniques to observe the change in energy distribution and analyzed it to detect the defects. Lu and Michaels have used the waveform of the diffuse field for the detection of defects at various working temperatures [76]. Sabra el al. suggested the potential of passive ultrasound imaging reconstructed from diffuse fields [77]. Schurr et al. have utilized coda wave interferometry to observe the change in velocity of diffuse fields in defective and healthy concrete structures [78]. Concrete structures are tested using diffuse ultrasound by Fröjd and Ulriksen [79]. Hayashi has used a scanning laser source for diffuse field imaging in a plate-like structure for the detection of defects [80].

For the success of a structural health monitoring method (SHM), it is necessary that the testing method should apply to a wide range of structural components, and non-expert personnel must be able to implement it with ease. It is easy to generate the diffuse field by exciting broadband waves, but the complex nature of the received signals is difficult to analyze.