Chapter – 1

Introduction

1.1 General

Condition evaluation and damage assessment of the engineering systems is needed while decision making to ensure their regular safe operation as well as before and after disasters. The process of implementing a damage detection strategy for civil, mechanical and aerospace engineering structures is referred to as Structural Health Monitoring (SHM). Structural Health Monitoring (SHM) methodology provides an interesting approach for the continuous monitoring of technical structures. The application of SHM methods offers opportunities for prolonging the useful life of a structure by early detection of damage. Beside this, the increased knowledge about the state of health of the structure can lead to an improved design of structures.

The modern history of structural damage detection traces its roots in the 1960s when the aerospace industry began to validate finite element models with the measured vibration data. The offshore oil industries led to develop practical damage detection and health monitoring of offshore oil platforms during the 1970s and 1980s.

The improvement of safety is a strong motivation for Structural Health Monitoring (SHM). Knowing the integrity of in-service structures on a continuous real-time basis is a very important objective for manufacturers, end-users and maintenance people. In the boarder scope, the SHM systems aim:

- To allow an optimal use of the structure; minimize the downtime and the avoidance of catastrophic failures.
- To allow the constructor for an improvement over his products.
- To drastically change the maintenance philosophy (a) by replacing the scheduled and periodic maintenance inspection with performance-based (or condition-based)

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- maintenance; (b) by minimizing the human involvement and consequently reducing labor, downtime and human errors, and thus improving safety and reliability.

The economic motivation for SHM is even stronger, principally for end-users. For structures with SHM systems, the envisaged benefits are constant maintenance costs and reliability. It is difficult to evaluate the economic impact of the introduction of SHM. It depends on the usage conditions of the structure. The time saved by the new performance-based maintenance, as reported in the literature, can be as high as 40% or more for a modern fighter aircraft featuring both metal and composite structure, through the use of smart monitoring systems. However, the cost of SHM systems must not be so high as to cancel out the expected maintenance cost savings.

The field of SHM and damage detection is quite broad and encompasses various local and global methods. Local methods are either visual or localized experimental techniques which inspect the structure in a relatively small area by the acoustic or ultrasound waves, radiography, eddy-current, magnetic or thermal field methods. These methods require that the vicinity of damage is to be known a priori. In cases where the sensors and actuators cannot be embedded in the structure, the portion to be inspected has to be readily accessible. These methods are usually time consuming and expensive. However, the local methods are very sensitive and are able to find small defects.

On the other hand, the global methods try to utilize the fact that the local damage changes the local stiffness, mass and damping properties and has an influence on the global behavior of the whole structure. However, global methods are less sensitive and usually have a lower spatial resolution compared to local methods.

Vibration based damage detection methods that examine the changes in the dynamic characteristics, such as mode shapes, modal frequencies and damping, of a structure has received considerable attention from the research community because they allow global damage detection at a relatively low cost. These methods, based on low-frequency dynamics, operate by examining the deviations between the actual dynamic properties and that of the undamaged state of the structure to detect damage and diagnose its location and extent.

In most general terms, damage is defined as *changes occurred in a structure that significantly affects its current or future performance*. The definition of damage is limited to

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the changes in material or geometric properties, including changes in the boundary conditions and system connectivity, which significantly affect the current or future performance of the structure.

The overall problem of structural health monitoring can be divided into four levels as shown in Fig 1.1.

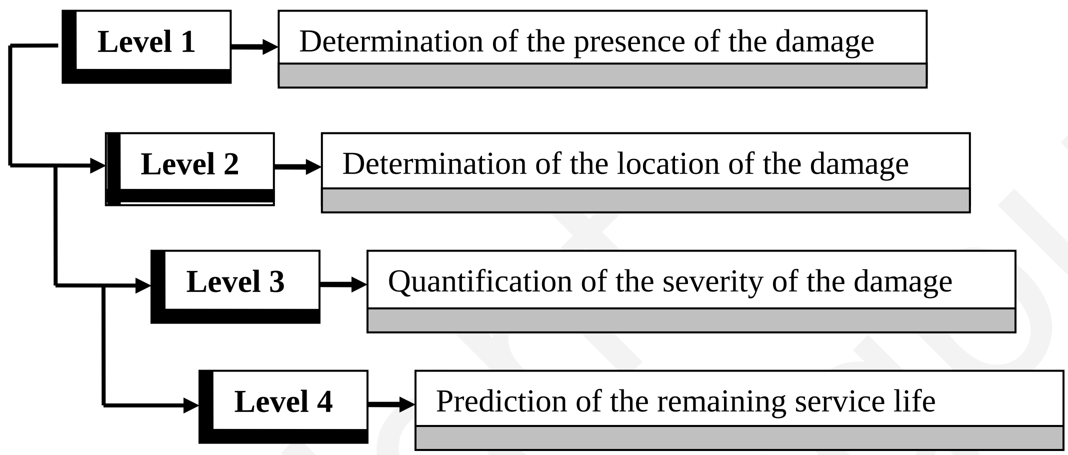

Figure 1.1: The four levels of structural health monitoring

Ideally, a robust damage detection scheme will be able to identify that damage has occurred at a very early stage, locate the damage within the sensor resolution being used, provide some estimate of the severity of the damage, and predict the remaining useful life of the structure.

The method should also be well suited to automation and to the greatest extent possible should not rely on the engineering judgment of the user or on the analytical model of the structure.

The method should be able to take into account operational constraints. For example, a common assumption with most damage identification methods reported in the literatures is that the mass of the structure does not change appreciably as a result of the damage. However, there are certain types of structures, such as offshore oil platforms, where such assumption is not valid.

Another important feature of an ideal damage identification method, specifically those which use a prior structural model, is their ability to discriminate between the model and data

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discrepancies caused by modeling errors and the discrepancies that are a result of structural damage.

The effects of damage on a structure can be classified as linear or nonlinear. A linear damage situation is defined as the case when the initially linear-elastic structure remains linear-elastic after damage. Nonlinear damage is defined as the case when the initially linear-elastic structure behaves in a nonlinear manner after the damage. A robust damage detection method should be applicable to these both types of damage.

Further, in real-life scenario the damage identification has to be performed from the measured response data of the structure. Hence, in the present study an attempt is being made to address this issue.

In nutshell, the main aim of the present investigation is to explore the problem of structural damage detection from the changes in the dynamic properties or response of the structure using various stationary/ non-stationary signal processing approaches.

1.2 Review of Literature

Vibration-based damage detection (VBDD) that utilizes the changes in the dynamic properties, such as mode shapes, modal frequencies and damping, has received considerable interest of the research community (Casas and Aparicio 1994; Doebling *et al.* 1996, 1998; Aktan *et al.* 1997; Sohn *et al.* 2003; Chang *et al.* 2003). Some of the critical issues and promising linear and nonlinear condition indices related to damage assessment of civil engineering structures, such as bridges, are discussed by Catbas and Aktan (2002).

Ndambi *et al.* (2002) presented a comparative study among damage detection methods i.e. changes in eigenfrequencies, MAC (modal assurance criteria), COMAC (coordinate modal assurance criteria), strain energy method and changes in flexibility matrices, based on the experimental results of reinforced concrete beams subjected to progressing crack damage located in symmetrical or asymmetrical positions. Results show that that eigenfrequencies are affected by accumulation of cracks and their evolutions are not influenced by the crack locations: they decrease with the crack accumulation. The MAC factors are less sensitive to

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damage than eigenfrequencies but give an indication about the symmetrical or asymmetrical nature of the damage. They further concluded that strain energy method appears to be precise than the other methods considered.

Cardan and Fanning (2004) presented the state of the art in vibration based condition monitoring with particular emphasis on structural engineering applications.

Huth *et al.* (2005) investigated the sensitivity of several damage detection, localization and quantification methods based on modal parameters for a prestressed concrete highway bridge with progressive damage by large scale tests. To examine the quality of modal parameters, they analyzed the data set of one damage step by several output-only identification techniques. It was found that the three variants of stochastic subspace identification method, i.e. unweighted principal component (UPC), principal component (PC) and the canonical variate analysis (CVA), yield similar results for the identified modal parameters. They concluded that – (1) natural frequencies and mode shapes display only minor changes even though the bridge was severely damaged. However, the relative changes of mode shapes are larger than those observed for natural frequencies; (2) damage detection or localization via changes in flexibility matrix performed better than natural frequencies or mode shape alone; (3) the direct stiffness calculation and a sensitivity-based model update technique showed results having high level of ambiguity about the location and quantification of damage also et the highest damage level.

Assessment of some usual vibration-based damage identification techniques with the help of a simply supported beam having different damage levels is discussed by Alvandi and Cremona (2006). Hsieh *et al.* (2006) reviewed the basic approaches to vibrational monitoring, provided suggestions for selecting sensor types, testing procedures and presented three example case studies of structural health monitoring. Zhou *et al.* (2007) provided laboratory-based experimental and finite element analysis study to evaluate the ability of five different vibration-based damage detection methods to detect and localize low levels of damage on the deck-slab of a two-girder, simply supported bridge, with the aim of using a small number of sensors and only the fundamental mode of vibration. A summary review of the modal parameters-based damage identification for beam-type or plate-type structures is provided by Fan and Qiao (2011). They also conducted a comparative study based on the

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finite element model of beam-type structures to evaluate five extensively used VBDD techniques.

The various methods reported in the technical literature for identifying the existence, location and extend of damage in a structure can be classified into two broad categories: model-based and non-model-based. Model-based methods employ a reliable reference model, which is obtained, for example, by updating an initial finite element model of the structure by means of baseline measurement data of the undamaged state. Based on the updated mathematical model of the structure, the damage detection is performed on the basis of the changes in the measured dynamic behavior. On the other hand, non-model-based methods aim to evaluate the damaged state of a structure directly from the measured response data without correlating to a reference model using various signal processing paradigms.

Model-based damage detection methods can be classified based on whether they utilize a global model or local model. In the global approach the method is tied to a global reference model, and the damage is determined at a global location on the structure. On the other hand, in the local approach the model is decomposed into substructures and the damage location is determined in terms of substructural quantities. This localized approach frees the user from considering the entire system. The only requirement is to have enough measurements to characterize the substructure under consideration. The localization process can be very effective at accentuating or exaggerating small changes in a structure.

Model-based approaches can also be categorized as to whether they utilize stiffness or flexibility characteristics of the structure. Though, theoretically there is no difference since the flexibility matrix is simply the inverse of the stiffness matrix, in practical applications there can be significant difference. Because perturbations in the stiffness matrix affect the highest eigenvalues of a structure; on the other hand, perturbations in the flexibility matrix affect the lowest eigenvalues. But in a typical modal testing, the low frequency eigenvalues of the structure are measured. Therefore, the dominant perturbations of the stiffness matrix are not captured. So the measured flexibility matrix is better able to capture perturbations due to damage than the measured stiffness matrix. However, it is noted that both the stiffness or flexibility matrices are rank-deficient due to the limitations inherent in measuring the high frequency structural dynamics.

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Majority of the VBDD techniques utilize the changes in the modal parameters, such as mode shapes, natural frequency and damping, of a structure for the damage assessment. A review of the previous studies based on the changes in natural frequencies of the structure for damage detection is presented by Salawu (1997). Author also discussed various factors which could limit successful application of the vibration monitoring for structural damage assessment.

Pandey *et al.* (1991) utilized curvature mode shape for identifying and locating damage in beam structures. The curvature is obtained from mode shape derivative. They computed the curvature values from the displacement mode shape using central difference approximation. It is shown that the absolute changes in the curvature mode shapes are localized in the damage region and changes in curvature mode shapes increase with increasing size of the damage. However, it is assumed that damage only affects the stiffness and mass distribution of the structure.

Pandey and Biswas (1994, 1995) utilized the changes in flexibility matrix of a structure for damage detection. It is shown that the flexibility matrix can be easily and accurately estimated from few lower frequency modes of vibration. They demonstrated the method by several numerical examples and experimental data of simple beam structures. Based on the results they concluded that the presence and location of the damage could be obtained from just the first two measured mode of the structure.

Toksoy and Aktan (1994) used dynamically measured flexibility for damage detection of a concrete bridge which is subjected to progressive damage. They observed that modal flexibility is a very sensitive damage indicator as opposed to eigenfrequencies and damping ratios. By comparing the deflection profiles from a combination of a measured flexibility matrix with a uniform load and a line load before and after damage, the damage localization was successful.

Structural damage detection from the changes in stiffness matrix of a structure is investigated by Zimmerman and Kaouk (1994). They developed a two step, decoupled algorithm to determine the location and extent of damage. Both algorithms utilize an existing finite element model of the undamaged structure and a subset of experimentally measured

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modal properties of the damaged structure. The proposed technique is then demonstrated using both the numerical and actual experimental data.

Kim and Stubbs (1995) used the concept of modal strain energy to develop a damage index for structural damage detection. They applied the technique to a model plate girder for which only few modal parameters are available. The impact of model uncertainty on the damage detection accuracy has also been investigated. It is concluded that damage can be confidently located with a relatively small localization error and a relatively small false-negative (i.e., missing detection of true damage locations) error but a relatively large false-positive (i.e., prediction of locations that are not damaged) error. However, severity of the damage can be estimated with much less confidence. Subsequently an improved damage index was proposed by Stubbs and Kim (1996).

Kim and Stubbs (2002) derived a new algorithm to predict location and severity of damage in structures using changes in modal characteristics. Initially, they reviewed two existing algorithms, i.e. damage index A (Kim and Stubbs 1995) and damage index B (Stubbs and Kim 1996). Then the new algorithm (damage index C) is formulated in order to improve the accuracy of damage localization and severity estimation by eliminating erratic assumptions and limits in the existing algorithms. The performance of each algorithm is numerically assessed in a two-span continuous beam for which pre- and post-damage modal parameters are available for only a few modes of vibration. It is shown that compared to two other algorithms damage index C enhanced the accuracy of the damage localization and severity estimation.

Ratcliffe (1997) applied a finite difference approximation of Laplace's differential operator to the mode shape for identifying the location of damage in a beam. When the damage is less severe, further processing of the Laplacian output is required before the location can be determined. The procedure is demonstrated using a one-dimensional finite element model of a beam and by experiment. The procedure solely operates on the mode shape of damaged structure, and doesn't require a *priori* knowledge of the undamaged structure. It is shown that the proposed approach is best suited to the fundamental vibration mode.

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Yoon *et al.* (2005) extended the above mentioned one-dimensional gapped smoothing method (1-D GSM) to the two-dimensional gapped smoothing method (2-D GSM) for locating stiffness variability in plate-like structure. A variability index is generated for each test point on the structure. A statistical treatment of the indices enabled the discrimination of areas with significant stiffness variability. However, it is assumed that the structure, in its undamaged state, is homogeneous with respect to stiffness. The procedure is demonstrated with a FE model of a plate, and on experimental data of composite plates with multiple delaminations and a large composite hull structure.

Reich and Park (2000) proposed an invariance property of transmission zeros of sub-structural frequency response functions for structural health monitoring. It is shown that the transmission zeros of the frequency response functions of a damaged substructure are invariant whereas those of healthy substructures are affected. They demonstrated the presented approach by numerical examples.

Maeck *et al.* (2000) determined the dynamic stiffness in each section of a reinforced concrete beam from the measured modal characteristics for non-destructive damage identification. It was assumed that the stiffness is constant for small vibrations at a certain static load level (e.g. own weight). The damaged structure results in a dynamic stiffness reduction in the cracked sections. They developed two techniques to calculate the stiffness degradation: the first one is based on model updating technique which makes use of eigenfrequencies; and the second one is direct stiffness calculation (DSC) which needs eigenfrequencies and mode shapes data in deriving the dynamic stiffness through the curvature calculation. In DSC method no numerical model is required. However, a dense measurement grid is necessary to be able to identify higher mode shapes accurately and to obtain good curvature estimate.

A flexibility-based damage identification method that has a solid theoretical and physical base is the damage locating vector (DLV) technique proposed by Bernal (2002). He showed that if a load configuration exists for which the displacements before and after damage occurred are same, the stresses caused by the loading are zero in the damaged zones. As a result, by finding a base for the null space of the difference in flexibility matrix damage localization is possible.

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Based on the changes in modal parameters (i.e., natural frequencies and mode shapes) a damage identification technique for predicting damage location and severity is proposed by Ren and Roeck (2002a). The element damage equations have been established through the eigenvalue equations that characterize the dynamic behavior. Several solution techniques are discussed and compared. The influence of simulated noise in the modal data is also discussed. The method has been illustrated by a number of damage scenarios for simulated beams and has found the exact location and severity of damage. It is concluded that the non-negative least square method with a regularization algorithm for error-based truncation ensures the right solutions. In an accompany paper (Ren and Roeck, 2002b), the proposed damage identification scheme is applied to the experimental data of a reinforced concrete beam to establish the relation between damage and changes of the structural dynamic characteristics. It is demonstrated that a realistic damage pattern that can describe damage by few representative parameters is necessary to guarantee the damage localization. Further, an adaptation of the initial FE model is required to give the best agreement with the reference measurements. It is pointed out that a possible advantage of the algorithm is that the modal forces can be directly extracted from any FE package and the mode shape expansion is involved in the damage identification scheme using a static recovery technique.

Pothisiri and Hjelmstad (2003) presented a damage detection algorithm based on a parameter estimation method using FE model and measured modal response of a structure. Damage is characterized as a reduction of the member constitutive parameter from a known baseline value. An optimization scheme is proposed to localize damaged parts of the structure. Damage probability functions are computed upon completion of the localization process for candidate elements. Monte Carlo methods are used to compute the required probabilities based on the statistical distributions of the parameters for the damaged and the associated baseline structure. The algorithm is tested in a numerical simulation environment using a planar bridge truss.

Alvin *et al.* (2003) have presented an overview of the model-based structural damage detection methods. They discussed state-space based structural identification theory specialized to structural dynamics, use of wavelet techniques for extracting impulse response functions, various input output combinations for multi-input and multi-output problems,

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robust ways of identifying parameters and the use of localized identification theory for damage detection.

Owolabi *et al.* (2003) presented experimental modal analysis results in an attempt to detect the presence of a crack in beams and determine its location and size. They utilized the changes in natural frequencies and frequency response function (FRF) amplitudes as a function of crack depths and locations in the crack detection methodology.

Kim and Stubbs (2003a) developed a crack detection algorithm to locate and size cracks in beam-type structures using a few natural frequencies. A crack location model and a crack size model are formulated by relating fractional changes in modal energy to changes in natural frequencies due to damage. The feasibility and practicality of the crack detection scheme are evaluated for several damage scenarios by locating and sizing cracks in test beams for which few natural frequencies are available. It is observed that crack can be confidently located with a relatively small localization error and crack size can be estimated with a relatively small size error.

A nondestructive crack detection (NCD) scheme using changes in the modal parameters for a class of beam-type bridges is presented by Kim and Stubbs (2003b). A new damage-index that locates damage from the modal strain energy and a crack-sizing method that estimates crack size from natural frequency perturbation are introduced. The proposed damage index is more robust than the previous damage indexes (Kim and Stubbs, 1995; Stubbs and Kim, 1996) by the fact that it is a function of the topology of the structure, the mode shapes and the associated frequencies. The applicability of the NCD scheme is verified by modal data collected from the field experiment of a full-scale plate-girder bridge. It is concluded that the proposed NCD algorithm correctly locates the crack and accurately estimates the size of the crack.

The popularity of natural frequencies as damage indicator is that they are rather easy to determine with a high degree of accuracy. However, problems exist when the size of the crack is small and existing frequency-based methods only give proper estimation of moderate damage. To overcome these difficulties many researches have focused on utilizing changes

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in mode shapes. An interesting comparison between frequency-based and mode shape-based damage detection method in beam structure has been published by Kim *et al.* (2003).

Teughels and Roeck (2004) presented an iterative sensitivity based FE model updating method in which the discrepancies in both the eigenfrequencies and unscaled mode shape data obtained from ambient vibration tests are minimized. Further, they proposed the use of damage functions (Teughels *et al.* 2002) to approximate the stiffness distribution, as an efficient approach to reduce the number of unknowns. Additionally the optimization process is made more robust by using the trust region strategy in the implementation of Gauss-Newton method. It is shown that the combination of damage functions with the trust region strategy is a practical alternative to the pure mathematical regularization techniques such as Tikhonov approach. The procedure is validated by a real application to a prestressed concrete bridge. The damage in the highway bridge is identified by updating the Young's and shear modulus, whose distribution over the FE model are approximated by piecewise linear functions.

Nam *et al.* (2005) investigated the problem of parameter identification by using additional information from a frequency response function (FRF) including antiresonant frequencies and other information, e.g., the static compliance dominant (SCD) frequencies. The performance of the proposed approach is demonstrated by simulated data of a simple mechanical system. Based on the results they concluded that the use of additional spectral information improves the accuracy in parameter identification.

A damage detection method utilizing a new form of damage index based on the changes in the distribution of the compliance of the structure due to damage is proposed by Choi *et al.* (2005). The changes in the compliance distribution are obtained using mode shapes of the pre-damaged and the post-damage state of the structure. The validity of the method is demonstrated using numerically generated data from beam structures and experimental data from a free-free beam with inflicted damage. Based on the results it is concluded that proposed compliance-based damage index can be used in structural damage identification.

A new nondestructive damage evaluation method that utilizes modal flexibility in a rational way to combine the modes of vibration for plate-like structure is introduced by Kim

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et al. (2005). The procedure consists of two steps: first, a set of flexural damage index equations (FDIEs) that represent a rigorous mechanical relationship between damage and curvature of modal flexibility are constructed. Second, a pseudo-inverse solution to the resulting system of over-determined equation evaluates damage. The objective of the proposed approach was to extend the MSC (Mode Shape Curvature) method and the DI (Damage Index) method by resolving some deficiencies of these methods. The performance of the proposed method has been numerically evaluated for a simply supported plate structure with an incomplete measurement scenario. It is shown that there is a strong linear relationship between the curvature of flexibility and flexural damage. As a consequence, the proposed method introduces a way to avoid the singularity problem and mode selection problem of the MSC and DI method.

A damage diagnosis technique based on changes in dynamically measured flexibility and stiffness of the structure is proposed by Yan and Golinval (2005). The covariance-driven subspace identification method is applied to identify modal parameters, and these are then used to assemble the flexibility matrix of dimensions corresponding to the measured degrees of freedom. The corresponding stiffness matrix is obtained by a pseudo-inversion of the flexibility matrix. Damage localization is achieved by a combined assessment of changes in these two matrices in moving from the reference state to the damaged state. As the presented approach determine the location of damage directly from the position of sensors, no FE model and geometrical measurements are needed.

A new technique for crack identification in beam structures based on fractal dimension analysis is presented by Hadjileontiadis *et al.* (2005). The fundamental vibration mode of a cracked cantilever beam is analyzed and both the location and size of the crack are estimated. The location of the crack is determined by the sudden changes in the spatial variation of the analyzed response, while the size of the crack is related to the fractal dimension measure. A fractal dimension-based crack detector (FDCD) is developed, which is suitable for practical applications. The proposed scheme is validated by experiments on cracked Plexiglas beams. It is concluded that compared to existing methods for crack detection, the proposed FDCD scheme is attractive due to the simplicity of the evaluation of fractal dimension measure and its robustness against noise. The concept of fractal dimension is extended to the case of 2D-

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structures by Hadjileontiadis and Douka (2007). However, it is noted the efficiency of the proposed method relies on the spatial resolution and the accuracy of the response data.

Unlike other VBDD methods which use mode shapes to retrieve damage information, Wang and Qiao (2007) developed a uniform load surface (ULS), which is shown to be less sensitive to ambient noise. In combination with ULS, two new damage detection algorithms, i.e. the generalized fractal dimension (GFD) and simplified gapped smoothing (SGS) methods are employed for damage detection in beam-type structure. Both methods are applied to the analytically obtained ULS of cracked and delaminated beams to determine the location and size of damage. Based on the experimentally measured curvature mode shapes, both the GFD and SGS methods are further demonstrated to detect three types of damage in carbon/epoxy composite beams.

An improved damage quantification methodology for plate structures that uses the relationship between the stiffness loss and the changes in the natural frequencies and mode shapes of the structure is developed by Choi *et al.* (2006). The methodology aims to eliminate erroneous assumptions in the existing mode shape-based methods and adopting additional modal information, i.e. natural frequencies. The validity of the proposed method is demonstrated using numerical data from a simply-supported plate with single and multiple damages. It is shown that the proposed methodology can yield superior damage quantification results to the existing damage index and compliance index methods.

Most of the vibration-based health monitoring methods is based on detecting shifts in natural frequencies or changes in the mode shapes. To be detectable, these changes have to be larger than the changes due to other environmental factors (e.g. temperature and soil-structure interaction) referred to as ‘noise’. Damage detection for real-life bridge structures using modal flexibility has been presented by Catbas *et al.* (2006). It is shown that the modal flexibility can be obtained from the frequency response function measurements of the structure. They also discussed various practical issues commonly faced in damage detection of real structures, such as environmental effects, incomplete dynamic measurements, spatial and temporal truncation effects.

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Park *et al.* (2006) presented the results of simulation studies for the IASC-ASCE SHM benchmark structure to locate and estimate the severity of damage in the blind test mode using damage index method. Modal parameters (i.e., resonant frequencies and mode shapes) for the undamaged structure and the damaged structures are extracted numerically. It is concluded that the method correctly predicts the damage locations and provides realistic estimates about damage severities.

A novel approach for vibration based damage detection is proposed by Deraemaeker and Preumont (2006). The approach relies on the use of a large network of sensors to which a programmable linear combiner, referred as modal filter, is attached. The frequency content of the modal filter is proposed as feature for damage detection. It is shown that for local damage spurious peaks appear in the FRF of the modal filter whereas if temperature changes are considered, the FRF of the modal filter is shifted but its shape remains unchanged. They also discussed issues regarding the practical implementation of the method.

Deraemaeker *et al.* (2008) investigated the problem of structural damage detection using output-only vibration measurements under changing environmental conditions. Two types of features are considered: eigenproperties of the structure using an automated stochastic subspace identification procedure and peak indicators extracted from the output of modal filters. The methodology has been applied to a numerical model of a bridge simulated in time domain and the sensitivity of the damage detection procedure to measurement noise, environment changes and damage is studied.

Mendrok and Uhl (2010) utilized the concept of modal filters for the detection of stiffness changes using the simulation data of a 7 DOF model and also from the experimental data of a laboratory stand. It is concluded that modal filter is a great indicator of damage detection with advantages as low computational efforts due to data reduction, ease of automation and lack of sensitivity to environmental changes.

Catbas *et al.* (2007) discussed about the limitations, such as the geometric complexity, uncertain boundary and continuity conditions, loading environments, and the imperfect knowledge and errors in modeling, in structural identification of large constructed structures. The authors illustrated that the density, modality and bandwidth of experimental data should

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be carefully evaluated and matched to the size and complexity of a constructed system before claiming that a FE model is validated. Further, it is shown that even more that three dozen acceleration measurement points, two dozen strain measurements, and a continuous surveillance of wind and temperature were barely sufficient for a credible structural identification for a long-span bridge.

Structural damage detection methods based on the residual force vector are studied by Yang and Liu (2007). Using residual force vector, the node residual force vector is defined to locate suspected damaged elements preliminary. Then three damage identification techniques, namely the algebraic solution of the residual force equation, the MREU (minimum rank elemental update) technique and the natural frequency sensitivity method, are studied to identify damage more precisely. A mode shape expansion algorithm utilizing the concept of best achievable eigenvector is used to solve the incomplete measurement problem. These damage detection methods are demonstrated by a numerical example of a plane truss and the effect of measurement noise is discussed.

Bayissa and Haritos (2007) proposed a vibration response parameter known as spectral strain energy (SSE) for damage identification in plate-like structures in the context of a non-model-based damage detection approach. The SSE is derived from moment-curvature response in which all the modal parameters (namely, natural frequency, mode shapes and modal damping) are taken into account. The sensitivity and performance of the proposed approach is illustrated using extensive numerical studies in simply supported plate and beam elements, and by comparing the results with those obtained from the modal strain energy (MSE) method. Further, the performance and robustness of the method is verified by experimental modal data of a full-scale bridge structure.

Sharifi and Banan (2008) used changes of strain energy in each element before and after the occurrence of damage for damage detection of the benchmark problem proposed by IASC-ASCE task group on structural health monitoring. The proposed algorithm requires only the stiffness and mass matrices of the baseline structure and few measured mode shapes of the current structure to find the location and severity of damage. Authors concluded that the most suitable method to solve the damage equations system is the nonnegative least

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square method and the presented algorithm can successfully localize and quantify both single and multiple damages.

A new structural damage detection approach based on changes in the generalized flexibility matrix is proposed by Li *et al.* (2010). The effect of truncating higher-order modes can be considerably reduced in the new approach when compared with the original flexibility matrix based approach. The effectiveness of the proposed method is illustrated by a numerical example for a simply supported beam.

Reynders and Roeck (2010) presented a method, called local flexibility (LF) method, based on quasi-static flexibility for vibration-based damage localization and quantification. In the proposed approach, the experimentally determined flexibility matrix is combined with a virtual load that causes nonzero stresses in a small part of the structure, where a possible local stiffness change is investigated. It is shown that, if the strain-stress relationship for the load is proportional, the ratio of some combination of deformations before and after a stiffness change has occurred, equals the inverse local stiffness ratio. As a result, the LF method permits not only a localization of these changes (level 2 damage identification), but also a quantification (level 3 damage identification). The method is validated with simulation examples of damaged isostatic and hyperstatic beams, and experiments involving a reinforced concrete free-free beam and a three-span prestressed concrete bridge, both of which are subjected to a progressive damage test.

Another class of model-based damage assessment approach is built on the time series. The conceptual framework of which is derived from the control and automation theory (Ljung 1999). Typical models associated with the time domain are discrete time input-output models, which have an ARMAX (AR: Auto Regressive, MA: Moving Average, X: exogenous input) or related structures (ARX, ARMA etc). The parameters of these models cannot usually be interpreted in a physical way. The models which are more closely related to physical models are based on continuous or discrete time state-space models. A structural model with second order time-derivatives can be easily transformed into a first-order state-space model.

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The use of statistically rigorous algorithms combined with active-sensing impedance methods for damage identification in engineering systems is presented by Park *et al.* (2005). The impedance-based monitoring is cast in the context of an outlier detection framework. For this a modified auto-regressive model with exogenous inputs (ARX) in the frequency domain is developed and the damage sensitive feature is obtained by quantifying the differences between the measured impedance and the output of the ARX model. The proposed approach is demonstrated by a numerical example on a 5 degree-of-freedom system and an experimental investigation on a multi-story building model.

The difficulty of applying the Extended Kalman filter (EKF) in mechanical system damage identification and localization lies in: the high computational cost, the dependence of estimation results on the initial estimation error covariance matrix, the initial value of parameters to be estimated, and on the statistics of measurement noise and process noise. Liu *et al.* (2009) addressed the problem of assessing the location and extent of damage in a vibration structure by EKF. The application of the method is illustrated by simulated and real examples. It is concluded that, the success of the damage identification by the EKF or its derivatives is strongly dependent on the quality of the original model. The advantage of EKF methods when compared with the methods in frequency domain (like FE model updating by natural frequencies) lies in the higher sensitivity to the damage and its data efficiency. However, on the other hand, the EKF methods are also sensitive to the modeling errors when compared with frequency domain estimation methods.

Figueiredo *et al.* (2010) presented a nonlinear time series analysis approach to detect damage in systems under varying operational and environmental conditions. State-space reconstruction is used to infer the geometrical structure of a deterministic dynamical system from observed time series at multiple locations. They used a Multivariate Autoregressive (MAR) model of a baseline health condition to predict the state-space, where the model encodes the embedding vectors rather than scalar time series. The applicability of the approach is demonstrated using multi-channel acceleration time series from a base-excited three-story building structure tested in laboratory condition.

There are some inherent difficulties in the model-based damage detection methods. There are always errors associated with the formulation of a theoretical model of a structure; and

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this leads to uncertain accuracy in the predicted response. There are many sources of modeling errors, such as variations of the material properties during manufacture; inexact modeling of the material constitutive behavior; uncertainties introduced during the construction process; inadequate modeling of the boundary conditions, for example there are no exact pinned or fixed joints; errors due to the spatial discretisation of the distributed structural system; and un-modeled features like neglected 'nonstructural' components.

VBDD methods that utilize changes in modal parameters of a structure in the damage identification process are seriously affected by the limitations inherent in the extraction of the modal parameters of real-life structures. It has been observed that, to a significant extend, the modal parameters are insensitive to localize changes in the stiffness parameters. Further, the available measured information is restricted by the limits on the amount of instrumentation and only a few lower modes of vibration can be identified with confidence. Also modal test data tends to show significant variation from one test to the next.

1.2.1 Probabilistic and Bayesian approaches

Bayesian probabilistic approach has been investigated by many researchers for structural damage detection to address the ill-conditioning inherent in the inverse problem of detecting stiffness changes from the vibration data.

Method based on Bayesian probabilistic approach for structural health monitoring is presented by Vanik *et al.* (2000). The method used a sequence of identified modal parameters to compute the probability that continually updated model stiffness parameters. In this approach, a high likelihood in the reduction of model stiffness at a location is taken as an indicator for damage. The method is illustrated by simulating on-line monitoring, wherein specified modal parameters are identified on a regular basis and the probability of damage for each substructure is continually updated. It is concluded that since effects such as variation in the identified modal parameters in the absence of damage, model error lead to uncertainties in the updated model parameters which in practice obscure the damage assessment, further extension of the proposed approach is needed.

Yuen *et al.* (2004) presented a two-stage structural health monitoring methodology to the Phase I benchmark study sponsored by IASC-ASCE task group on SHM. In the first stage,

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modal parameters are identified using measured response from the undamaged and then from the damaged structure. In the second stage, these data are used to update a parametrized model of the structure using Bayesian system identification. It is concluded that the location and severity of damage in all cases of the benchmark problem can be identified successfully. A similar study on the Bayesian updating methodology for the Phase II benchmark structure using experimental data generated by hammer impact and ambient vibrations is conducted by Ching and Beck (2004). It is shown that the brace damage can be successfully detected from either the hammer or ambient vibration data. However, the connection damage is much more difficult to reliably detect because the identified modal parameters are less sensitive to connection damage.

Altunok *et al.* (2007) suggested the application of possibility theory for structural health monitoring. The basic idea behind the proposed approach is that the application of possibility theory does not require probabilistic knowledge or assumptions on the damage feature and thus encompasses aleatoric and epistemic types of uncertainties. Damage detection using the proposed approach is demonstrated by means of a case study. The effect of the number of data intervals and interval overlapping on the damage detection process was examined and shown to be insignificant on the results.

Wang and Ong (2010) addressed the problem of structural damage detection through an innovative multivariate statistical approach. By using principal component analysis the vibration responses of the structure being monitored are represented by multivariate data of the sample principal component coefficients (PCCs). A damage indicator is then defined based on a multivariate exponentially weighted moving average control chart analysis formulation, involving special procedures to allow for the effects of the estimated parameters and to determine the upper control limits in the control chart analysis. The efficacy and advantages of the scheme are demonstrated by the numerical examples of a five-story shear frame and a shear wall as well as the experimental example of the I-40 Bridge benchmark. It is concluded that the proposed scheme provides a promising tool for implementing damage detection for SHM purposes.

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1.2.2 Damage detection by neural networks

Damage detection from the measured vibration signals is essentially an inverse problem. Neural network is a promising tool for such kind of problem. Therefore in recent years there has been increasing interest in using neural networks for structural damage detection.

The self-organization and learning capabilities of the neural networks have been explored for structural damage assessment by Wu *et al.* (1992). They trained a neural network to recognize the behavior of the undamaged structure as well as the behavior of the structure with various possible damage states. They explored the above idea on a simple structure and concluded that the results are promising.

Pandey and Barai (1995) used back propagation neural networks to identify damage in a bridge truss by multilayer perception. Authors used the neural network to identify the map from various nodal time histories to changes in stiffness. The stiffness parameter up to 4% accuracy was predicted. They found that the time history from a single, carefully selected node produced the best predictions.

Chen *et al.* (2003) utilized response-only data, transmissibility function to train neural networks for structural fault diagnosis. The technique is verified for two examples based on two different structural systems. They suggested that the transmissibility function is a sensible response-only data for structural fault diagnosis.

A method of damage detection based on neural networks is presented and applied to assess the overall damage at each floor in composite frames structure caused by seismic loading is presented by Zapico *et al.* (2003). The natural frequencies of the structure obtained through a FE model are used as inputs to train the NNs. A neural network is used to calibrate the initial undamaged structure, and another to predict the damage. For the validation of the method, the damage levels of the structure were obtained through the trained NNs from the available experimental modal data. The stiffness matrices of the structure predicted by the method were compared with those identified from pseudo-dynamic tests. It is concluded that the obtained values of the stiffness matrix of the undamaged structure are almost exact when compared with the experimental ones, while the absolute differences are lower than 8.6% for the damaged structure.

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Fang *et al.* (2005) used frequency response functions (FRFs) as input data to the back-propagation neural network (BPNN) for structural damage detection. Neural network based damage detection generally consists of a training phase and a recognition phase. Back-propagation algorithm incorporating gradient method can be applied to train the NN, whereas the training efficiency heavily depends on the learning rate. While various training algorithms, such as dynamic steepest descent (DSD) and fuzzy steepest descent (FSD), have shown promising features, their performance is hinged on the proper selection of certain control parameters and control strategy. A new tunable steepest descent (TSD) algorithm using heuristic approach is investigated through a series of numerical examples. The proposed approach is applied to a cantilever beam and based on the results they concluded that in all considered damage cases (i.e., trained damage cases, unseen damage cases, single damage cases and multiple-damage cases), the neural network can assess damage conditions with very good accuracy.

A damage detection procedure, using pattern recognition of the vibration signature, assessed using a FE model of a real structure – a suspension bridge more than 100 years old, is presented by Yeung and Smith (2005). Realistic damage scenarios are simulated and the response under moving traffic load is evaluated. Feature vectors obtained from the response spectra are examined by two unsupervised neural networks. It is shown that the sensitivity of the neural networks may be adjusted so that a satisfactory rate of damage detection can be achieved even in the presence of noisy signals.

Bakhary *et al.* (2007) proposed a statistical approach to take into account the effect of uncertainties in developing an ANN model for damage detection in structures based on modal parameters. By applying Rosenblueth's point estimate method verified by Monte Carlo simulation, the statistics of the stiffness parameters are estimated. The probability of damage existence is calculated based on the probability density function of the existence of undamaged and damaged states. The presented approach is applied to detect damage in a numerical steel frame model and also in a laboratory tested concrete slab. The effects of different severity levels and noise levels on the damage detection results are also discussed.

Rosales *et al.* (2009) investigated the inverse problem of the crack parameters (location and depth) determination with two approaches: a power series technique (PST) and the use of

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artificial neural networks (ANNs). Cracks in a cantilever Bernoulli-Euler (BE) beam and a rotating beam are detected by PST that solves the governing vibration problem of the beam. The ANN technique is applied for crack detection in a cantilever beam with a transverse crack. It is shown that the first methodology yields relative small errors in both the location and depth detection and the ANNs behave adequately. Finally, a combination between the two techniques is suggested.

1.2.3 Damage detection as statistical pattern recognition

Statistical pattern recognition methodologies have gained considerable attention for SHM applications to detect changes in the structure (i.e., damage). There are different approaches used by different research groups and it is widely accepted that success of a certain methodology may depend on the structure and/or structural changes to be identified.

Worden *et al.* (2003) presented three novelty detection algorithms: outlier analysis, kernel density estimation and an auto-associative neural networks technique for the experimental validation of a structural heath monitoring methodology. The proposed approach used novelty detection from the measured transmissibilities of a simplified model of a metallic aircraft wing-box, i.e., a plate incorporating stiffening elements and damage is simulated by a saw-cut to one of the panel stringers. It is noted that all these three approaches suffer to some extent from the ‘curse of dimensionality’, however, for the outlier analysis and neural network there are mitigating circumstances. Finally, the outlier analysis is recommended as a method of choice among the three as it offered a much simpler solution than neural network with no apparent deterioration in performance. However, it is pointed out that the very simplicity of the approach could preclude its use in some applications and that this should be monitored. In a sequence paper (Manson *et al.*, 2003a) the methodology is applied to a more realistic structure, namely the wing of a Gnat aircraft. An extension of the detection method for damage location is proposed and demonstrated in the last paper of the sequence, Manson *et al.*2003b.

Gul and Catbas (2009) verified various statistical pattern recognition methodologies in the context of SHM using different laboratory structures. They used time series modeling, i.e., auto-regressive (AR) models in conjunction with Mahalanobis distance-based outlier

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detection algorithms to identify different types of structural damages on different test structures. They also used random decrement functions to eliminate the effects of the exogenous input. The proposed methodology is verified by analyzing the ambient vibration data of a simply supported steel beam and a highly redundant steel grid structure. Finally, it is noted that the effects of the environmental and operational inputs should be investigated by using experimental setups where such effects exist.

The human immune system has provided a rich source of inspiration for pattern recognition, machine learning and data mining analyses. One of the properties of the immune system which proves particularly useful for novelty detection is that of self/non-self discrimination and this forms the basis of the negative selection algorithm, which has been applied by many researchers for the time-series novelty detection. The application of the negative selection algorithm to more general feature sets and also the case of novelty detection where the normal condition set is significantly non-Gaussian or varies with operational or environmental conditions is presented by Surace and Worden (2010).

The pattern recognition algorithms can be divided into two categories: supervised and unsupervised learning. When the algorithm uses data from both the undamaged and damaged structure it is referred as supervised learning. Unsupervised learning refers to the class of algorithms that are applied to data not containing examples from the damaged structure. However, the main problem associated with pattern recognition based approaches to SHM is that damage localization and quantification almost always require supervised learning. In the case of high-value engineering structures like aircraft, it is not possible to generate the training data associated with damage by experiment. It is also unlikely to generate data by simulation as the costs of development and run-time required for such high fidelity models would often be prohibitive. Papatheou *et al.* (2009) proposed an innovative simple experimental strategy, which involves adding masses to the structure, in the attempt to extract features for novelty detection. The approach is illustrated first on a simple structure by using data generated from FE simulation and then validated experimentally on a more complicated laboratory structure. It is concluded that the results show similar patterns in both cases which suggests a potential use of the method for higher level damage detection.

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1.2.4 Wavelet based approaches

Many of the recent advances in mechanical and structural damage detection are related to the new developments in the area of signal processing. Wavelet theory in particular, has been one of the promising tools for non-stationary signal processing. A summary of some of the recent developments and applications of wavelet analysis for structural damage detection has been presented by Staszewski (1998). Author suggested that wavelet analysis, combined with some pattern recognition techniques has potential for online damage detection. The state-of-the-art review of literature on the application of wavelet transform (WT) for SHM is presented by Reda Taha *et al.* (2006). They also discussed specific needs of SHM addressed by WT, classified WT for damage detection into various fields and described the features unique to WT that lends itself to SHM.

Sone *et al.* (1995) explored this approach on the numerically simulated time history of a single degree-of-freedom system with stationary noise, and damage represented as fatigue caused by reduction of stiffness. They concluded that even for noise contaminated signals, wavelet analysis leads to a good estimation of the occurrence times of the postulated damage.

An application of wavelet theory in the space domain to crack identification in structures is presented by Liew and Wang (1998). The deflection along the length of a simply supported uniform beam with a transverse on-edge non-propagating open crack is calculated numerically. The crack location is then indicated by a peak in the variations of some of the wavelets along the length of the beam. They argued that because the dynamic solution contains information of the eigenfunctions of the structure, the wavelets must be chosen to reflect the boundary conditions of the structure.

Wang and Deng (1999), using numerically simulated response data, explored the use of wavelets for detection of the spatial location of damage within a beam with a short transverse crack, under static and dynamic loading conditions. They used Haar wavelets to analyze a set of numerically simulated ‘measurements’ at various locations within the beam, and concluded that the location of the crack could be well detected, with resolution depending on the spatial resolution of the ‘measurements’.

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Hou *et al.* (2000) applied wavelet based approach for structural damage detection for a simple model subjected to harmonic excitation. The model consists of multiple breakable springs, some of which may suffer irreversible damage when the response exceeds a threshold value or number of cycles of motion is accumulated beyond their fatigue life. Based on results they have suggested that wavelet approach is a great promise for damage detection and structural health monitoring.

The wavelet packet transform is an extension of the wavelet transform that utilizes a complete level-by-level decomposition. Sun and Chang (2002) used wavelet packet transform for the damage assessment of a three-span continuous bridge using simulated dynamic response under impact excitation. Wavelet packet component energies are used as inputs into neural network model for damage assessment. In another work (Sun and Chang, 2004) they proposed a statistical pattern classification method based on wavelet packet transform for structural health monitoring. The technique has been applied to the experimental acceleration response of a steel cantilever I-beam. Based on the results they argued that the health condition of the beam can be accurately monitored even when the signals are highly contaminated with noise.

Melhem and Kim (2003) used fast Fourier transform (FFT) and continuous wavelet transform (CWT) in the analysis of dynamic response of typical highway structures. Two types of full-scale concrete structures subjected to fatigue loads are studied: Portland cement concrete pavements on grade and a simply supported pre-stressed concrete beams. Based on the results they have concluded that: both FFT and CWT can identify which frequency components exists in a signal but wavelet transform can show the time when a particular frequency occurs and FFT can detect the progression of damage in the beam but not in the slab whereas CWT analysis yielded a clear difference between the initial and damaged states for both structures.

Douka *et al.* (2003) has presented a wavelet based method for finding the location and size of the crack in beam structures. They have analyzed the fundamental vibration mode of the cracked beam using continuous wavelet transform. To estimate the size of the crack an intensity factor is defined which relates the size of the crack to the coefficients of the wavelet transform.

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An application of wavelet analysis for damage detection and locating damage region(s) for ASCE structural health monitoring benchmark data is presented by Hera and Hou (2004). They found that structural damage due to sudden breakage of structural elements and the time when it occurred can be clearly detected by spikes in the wavelet details. Further, it is shown that the damaged region can be determined by the spatial distribution pattern of the observed spikes. The effects of measurement noise and severity of damage is also discussed.

Ovanesova and Suárez (2004) explored the use of wavelet transform to detect the location of damage in a theoretical model of a fixed-end beam under static and dynamic loading, and in a simple plane frame with a cracked column subjected to horizontal and vertical loads. They considered two cases of location of the crack - one far from the column-beam joint, and the other one near to the joint. They concluded that the effectiveness of the spatial wavelet analysis is sensitive to the boundary conditions of the members and the distance from the structural supports and joints.

Han *et al.* (2005) used wavelet packet transform for damage identification in beam structures. A damage detection index called wavelet packet energy rate index is proposed for the damage detection. The measured dynamic signals are decomposed into the wavelet packet components and the wavelet energy rate index is computed to indicate the structural damage. They applied proposed method to both simulated and experimental data of beam structures to demonstrate that WPT-based energy rate index is sensitive to structural local damage.

Kim and Kim (2005) examined the ratio of the incident wave toward and the reflected wave from the damage to assess the damage size. They argued that since waves to be analyzed are of bending type, the measured signals are highly dispersive and it is almost impossible to estimate the magnitude ratio alone in the time domain. Therefore, they proposed the use of continuous wavelet transform of the measured signal and perform the ridge analysis in order to extract accurately the magnitude of the incident and reflected waves in the frequency range of interest. Wave experiments are conducted in a slender cylindrical beam and the magnetostrictive sensors are used to capture the bending waves in the beam. They conducted several experiments to check the effectiveness of the proposed wavelet-

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based method. It is concluded that except when the damage size is very small, the correlation between the proposed ratio and damage size is quite satisfactory.

Chang and Chen (2005) proposed a technique based on spatial wavelet analysis for damage detection in beam structure. The mode shapes of free vibration and natural frequencies of the multiple cracked beams are obtained first. Then the mode shapes are analyzed by wavelet transformation to get the positions of the cracks. After obtaining the positions of the cracks, the natural frequencies are used to predict the depth of the cracks through the characteristic equation. The crack type is open crack and is represented as a rotational spring in the numerical models. If the number of cracks is n, the first n natural frequencies are used to predict the depth of the cracks. It is concluded that the positions and depths of the multiple cracks can be predicted with acceptable precision.

Zabel (2005) presented an algorithm for identifying the FE model's parameters by utilizing wavelet coefficients of the measured data and their integrals or derivatives, respectively. How the wavelet coefficients of derivatives and integrals can be related to each other by connection coefficients is shown. The performance of the method is demonstrated by means of numerical example for a five degree-of-freedom system and experimental investigations on a locally damaged steel beam. Author concluded that a comparatively good agreement between original and identified parameters could be obtained from the numerical simulations even when the data is corrupted by noise of a considerable intensity. It is also emphasized that the modal properties of the identified FE model and the simulated response based on the measured excitation agreed very well with the respective measured data for the experimental study.

Rucka and Wilde (2006) presented a method based on continuous wavelet transform (CWT) for estimating the damage location in beam and plate structures. A Plexiglas cantilever beam and a steel plate with four fixed boundary conditions are tested experimentally. The estimated mode shapes of the beam are analyzed by the one-dimensional CWT. The formulation of the two dimensional CWT for plate damage detection is presented. The location of the damage is indicated by a peak in the spatial variation of the transformed response. It is concluded that the proposed wavelet analysis can effectively identify the damage location without knowledge of neither the structure characteristics nor its mathematical model.

Khatam *et al.* (2007) utilized the harmonic displacement response as the input signal in wavelet analysis for damage identification of a beam. Sudden changes in the spatial variation of transformed response identify the location of damages. It is shown that the harmonic response is superior to the static response, and the proposed approach is more effective in the presence of noise and more sensitive to the versatility of the applied harmonic loads.

A new approach for crack detection in beam-like structures is presented and applied to cracked simply supported beams by Zhong and Oyadiji (2007). The approach is based on finding the difference between two sets of detail coefficients obtained by the use of the stationary wavelet transform (SWT) of two sets of mode shape data. The two sets of mode shape data, which constitute two new signal series, are obtained and reconstructed from modal displacement data of a cracked simply supported beam. SWT is a redundant transform that doubles the number of input samples at every iteration. It provides a more accurate estimate of the variances at each scale and facilitates the identification of salient features in a signal, especially for recognizing noise or signal rapture. The modal responses of the damaged beams are computed using finite element method. Based on the results they concluded that the proposed method has great potential in crack detection of beam-structures as it does not require the modal parameters of an uncracked beam as a baseline for crack detection.

Bayissa *et al.* (2008) presented a new damage identification technique based on the statistical moments of the energy density function of the vibration responses in the time-scale domain. The continuous wavelet transform is first conducted to decompose the vibration responses into discrete energy distributions as a joint function of time and scale. The principal features are then extracted from the energy density function using moments. Consequently, the zeroth-order moment (ZOM) known as the total energy of the joint density function, is computed at each measurement grid point for the pre-damage and post-damage states and is then used for detection and localization of damage in a concrete plate model and in a steel plate girder of a bridge structure. The significant contribution is that the wavelet coefficients are transformed into a new damage identification parameter in the space domain.

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A comparison of the results from the proposed method and those obtained from existing non-model-based damage detection techniques is made, and it is concluded that the proposed method is more sensitive to damage.

Messina (2008) proposed refinements concerning the use of wavelets, when used in the guise of continuous wavelet transforms (CWT) for identifying damage on transversally vibrating structural components (e.g., beams, plates and shells). The refinements are aimed at significantly reducing those border distortions normally arising during wavelet-base damage detection. The effectiveness of the proposed algorithms is shown through numerical and experimental examples.

A 2-D continuous wavelet transform (CWT)-based damage detection for plate-type structures is presented by Fan and Qiao (2009). A concept of isosurface of 2-D wavelet coefficients is proposed and it is generated to indicate the location and approximate shape or area of the damage. The proposed algorithm is response-based and only requires the mode shapes of the damaged plates. It is applied to the numerical vibration mode shapes of a cantilever plate with different types of damage to illustrate the effectiveness and viability. A comparative study with other two 2-D damage detection algorithms, i.e., 2-D gapped smoothing method (GSM) and 2-D strain energy method (SEM), is performed, and it is demonstrated that the proposed 2-D CWT-based algorithm is superior in noise immunity and robust with limited sensor data. The algorithm is further implemented in an experimental modal test to detect impact damage in an FRP composite plate using smart piezoelectric actuators and sensors. They concluded that the proposed 2-D CWT-based algorithm can be used as a viable and effective technique for damage identification of plate- or shell-type structures.

Bagheri *et al.* (2009) proposed a new method based on curvelet transform to assess damage location in plate structure. Curvelet transform is a generalization of wavelet transform and it exhibits impressive performance in detecting line features. Curvelet transform is a new multiscale pyramid representation with many direction and positions at each length scale and needle-shaped elements at fine scale. The formulation of discrete curvelet transform using unequally-spaced fast Fourier transform is investigated for plate damage detection. The mode shapes of a four-fixed supported rectangular plate with and

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without damage is determined using finite element method. One or two damages with arbitrary length, depth and location are considered in the study. By comparing the location obtained by the proposed method and simulation model it is shown that the method is sensitive to damage. The performance of the method is also verified using experimental modal data of a plate.

Yan *et al.* (2010) developed a wavelet-based damage detection method for locating multiple damages and the moments when damage occurs. Performing wavelet transform of free vibration responses of structures in the damaged state a residual wavelet force (RWF) is defined. The locations and the moments of the damages are determined simultaneously from the ridges in the RWF. A damage location indicator, DLIRWF, is presented and it is shown that the degree-of-freedom having large magnitudes in DLIRWF are associated with the potential damage members within the structure. The proposed method is illustrated by numerical simulations of a 20-story shear building and a 5-story, 1-bay x 2-bay steel frame structure.

1.2.5 Empirical mode décomposition

Huang *et al.* (1998) proposed a new technique based on empirical mode decomposition and Hilbert transform for non-stationary and non-linear signal processing.

Yang *et al.* (2004) presented Hilbert-Huang based approach for damage detection of the benchmark problem established by ASCE Task Group on SHM. Two methods were proposed for the damage detection purpose. The first, based on the empirical mode decomposition (EMD), is employed to extract damage spikes due to a sudden change of stiffness from the measured data thereby detecting the damage time instants and damage locations. The second method, based on EMD and Hilbert transform is shown to detect damage time instants, and can determine the natural frequencies and damping ratios of the structure before and after damage. The proposed approach is demonstrated by numerical simulation results and it is concluded that the proposed methods provide new and useful tools for damage detection of structures.

Xu and Chen (2004) presented an experimental investigation on the applicability of the empirical mode decomposition (EMD) for identifying structural damage caused by a sudden

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change of structural stiffness. A 3-story shear building model was constructed and installed on a shaking table with two springs horizontally connected to the first floor of the building to provide additional structural stiffness. Structural damage is simulated by suddenly releasing two pre-tensioned springs either simultaneously or successively. Various damage severities are produced using springs of different stiffness. A series of free vibration, random vibration, and earthquake simulation tests are performed on the building with sudden stiffness changes. Dynamic responses including floor accelerations and displacements, column strains, and spring releasing time instants are measured. The EMD is then applied to measured time histories to identify damage time instant and location for various test cases. By comparing the identified results with measured ones it is shown that damage time instants can be detected accurately in terms of damage spikes extracted directly from the measurement data. The damage location is determined by the spatial distribution of the spikes along the building. They also discussed the influence of damage severity, sampling frequency, and measured quantities on the performance of EMD for damage detection.

A combined approach of EMD and wavelet analysis is examined by Li *et al.* (2007) to detect the exact location and severity of damage from the simulated response signal data of a 4-storey shear building.

1.2.6 Time-frequency distributions

The application of quadratic time-frequency distributions makes it possible to localize a nonlinear and non-stationary signal in the time-frequency plane with arbitrary time-frequency resolution. Several authors have applied the joint time-frequency distributions for the fault diagnosis of mechanical components (Staszewski *et al.*, 1997; Peng *et al.*, 2002). However studies on the use of time-frequency distributions for structural damage detection are found scanty in the technical literature.

Bonato *et al.* (1997) utilized various time-frequency transforms for structural damage assessment using synthetic and real acceleration signals recorded during the impulsive loading of damaged aluminum beams. Different position and damage levels were considered on the beams for damage identification purpose. They also used neural classification techniques for the diagnostic interpretation of time-frequency maps based on invariant

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moments. Based on the results they concluded that the Choi-Williams distribution is the best choice for such applications.

Staszewski and Robertson (2007) discussed the two main approaches, the time-frequency and time-scale analysis, for damage detection applied to the time-variant properties of structures. A number of examples are presented to discuss the applicability of the various approaches. Finally, the authors concluded that most of these applications are largely limited to academic research due to the complexity of the mathematical background and algorithms connected with the analysis, and toolboxes of disparate techniques are needed to facilitate further progress in structural health monitoring.

Although many damage detection methods have been developed and substantial progress has been accomplished, it has been observed that no one method has proven to be satisfactory across the broad spectrum of Structural Health Monitoring (SHM). Most of the methods start with various simplifying assumptions and are limited to some specific type of structure. Further, the measurement noise is a big challenge in model updating techniques. Majority of the work reported in the technical literature address the problem of linear damage detection. However, in the real-life scenarios nonlinearity plays a significant role. Nonlinear response may arise from large deflection, fatigue cracks, complex interaction between multiple damages.

1.3 Critical Observations

Based on the extensive review of the literature the following points can be summarized:

- In spite of great advances in computation tools there is a lack of some unique algorithm, which can be applied to all type of inverse problem. Most of the algorithms developed are limited to some specific type of structure but do not work well for other types of structures.
- Another profound issue for the application of any damage detection method in real-life scenarios is that - how much of a change in any measured behavior (e.g. Mode shapes, frequencies, displacement, strain) can be attributed to damage while the change is coupled with environmental effects. Answers of these questions are not always easy and straightforward because it has been observed for the same spatial

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location on the structure at different times with different temperature show that the modal frequencies shift. One of the constraints in obtaining modal parameters is the inconsistency of the data due to these shifts.

- Though probabilistic or statistical methods have been used to address the problem of ill-conditioning associated with the inverse problem of damage detection, it has been found that they are not able to identify small changes due to the process of averaging the data.
- Most of damage detection methods reported in the literature is applied to simple structures having well separated modes of vibration. Further, they assume the prior location of damage in some form. However, blind prediction of the location of damage is still an open challenge.
- Measurement noise is another issue of critical importance. Majority of the methods have been demonstrated on the basis of simulated response or tested on the data set from the laboratory test conditions. Structural damage detection from the noisy field data is having no well-established solution at present.
- Majority of the previous studied address the problem of linear damage detection. A linear damage situation is defined as the case when the initially linear-elastic structure remains linear-elastic after damage. The changes in modal parameters are results of the changes in the material and/or geometric properties of the structure; however it is assumed that the structural response can still be modeled using linear equation of motion. Nonlinear damage is defined as the case when the initially linear-elastic structure behaves in a nonlinear manner after the damage. In the real-life scenarios nonlinearity plays a significant role. Nonlinear response may arise from large deflection, opening and closing of fatigue cracks, complex interaction between multiple damages, changes in boundary conditions and environmental effects. A robust damage detection method should be applicable to both of these general types of damage.

In spite of many developments, it appears the practical implementation of damage detection across the broad spectrum of structural health monitoring is still an open challenge.

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1.4 Scope and Objectives of the Current Research

Based on the review of the literatures a broad classification of the damage detection methods is shown in Fig 1.2. The scope of the current research is motivated towards evaluating the damage state of a structure under the assumptions of linearity and as well as non-stationary, nonlinear nature of the dynamic response using various stationary/ non-stationary signal processing techniques (shaded blocks of Fig 1.2). This study is restricted towards addressing the level 1 to 3 of the problem domain.

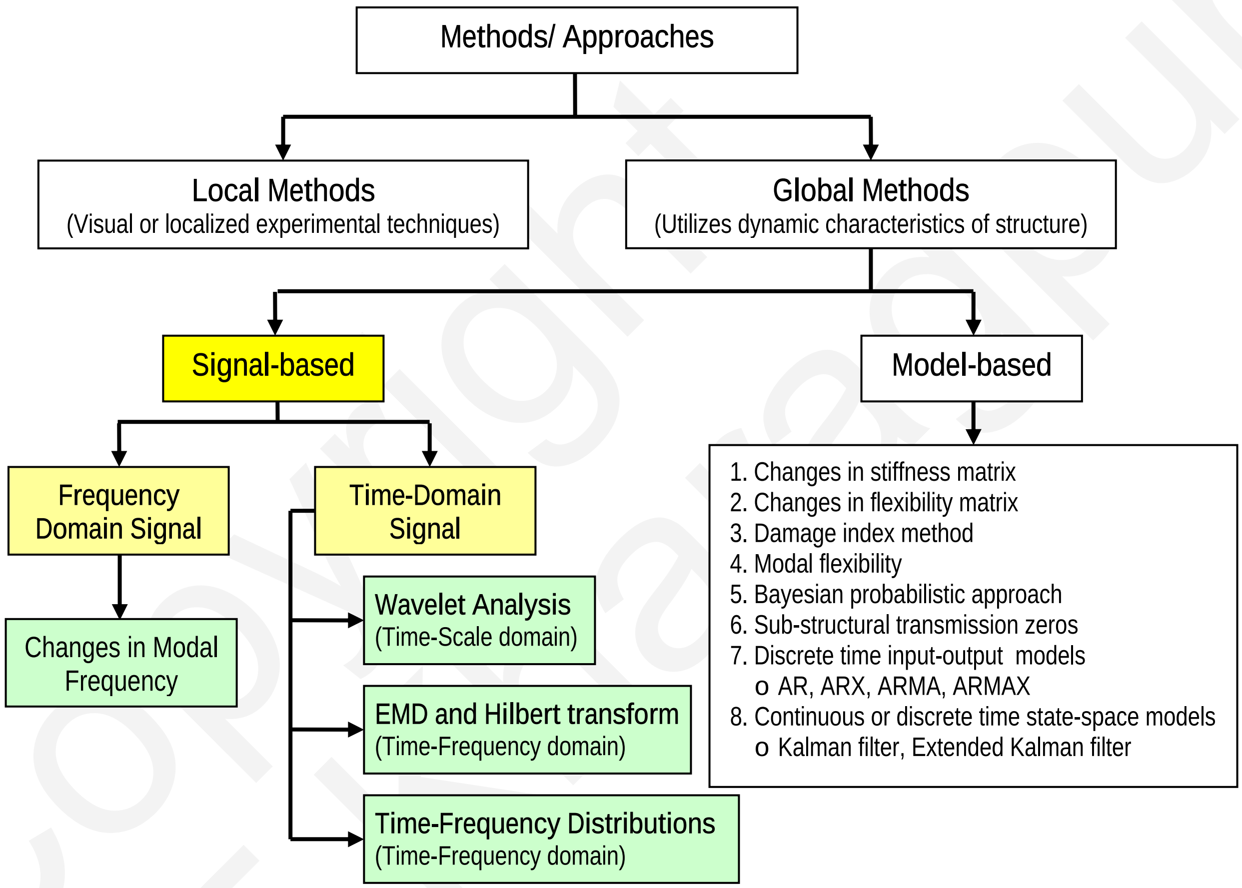

Figure 1.2: Broad classification of damage detection methods

The following objectives are identified for the present study –

- To study the effect of localized single/ multiple cracks of varied crack depth and combinations on the modal properties of a cantilever beam by experimental modal analysis.

- To explore the wavelet analysis to extract the non-stationary components of the simulated acceleration time-histories for quantifying the damage state of a frame structure.
- To explore the applicability of the techniques based on empirical mode decomposition and Hilbert transform for structural damage detection.
- To explore various energy time-frequency distributions for damage assessment of the frame structure using the simulated accelerations data.

1.5 Organization of the Thesis

In Chapter 1, an introduction to the field of Structural Health Monitoring (SHM) is briefly outlined and various important features necessary for an ideal damage detection method are discussed. An up-to-dated and comprehensive review of the technical literatures is presented highlighting salient features and limitations of various methodologies, following which the scope and the objectives of the present research are presented.

Chapter 2 describes the experimental investigations carried out to study the effect of single/ multiple cracks of varied crack depths, crack depth combinations on the modal parameters of a cantilever steel beam.

The application of wavelet analysis for structural damage detection using the simulated accelerations data of a 3-D frame structure containing single and multiple damage events is presented in Chapter 3. The effect of measurement noise is also discussed.

Chapter 4 describes the techniques based on empirical mode decomposition (EMD) and Hilbert transform for quantifying the damage state of the frame structure using the accelerations at various nodal positions.

Chapter 5 describes various quadratic time-frequency representations and explores their applicability for damage assessment of the frame structure using simulated acceleration time-histories.

Chapter 6 summarizes important conclusions from the present research and makes recommendations for future investigations. And finally, the implementation procedure to be

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followed for the implementation of each signal processing approach applied in the present investigation is given by block-diagram in the Appendix.

1.6 Closing Remarks

In this chapter, initially the field of structural health monitoring (SHM) is defined and briefly emphasized its relevance for the society with the aging, deteriorating infrastructures and modern structures exposed to extreme environmental conditions. Then various important features necessary for an ideal damage detection method are discussed. An up-to-dated and comprehensive review of the technical literatures is presented and a list of critical observations is made. Following this the scope and objectives of the present research endeavor are identified.

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