CHAPTER 2

HISTORICAL BACKGROUND FOR THE PRESENT WORK

2.1 INTRODUCTION

In practical engineering problems under dynamic environment, many structures are damaged or fail to work due to small cracks and their extensions. There are reported instances wherein the electrical connections have given way due to vibrations, causing electrical continuity failure. This failure of structural components is very costly and may be catastrophic in terms of human life and property damage. Thus, in many situations, it is desirable to undertake programs of scheduled maintenance in order to reduce or even eliminate this sort of structural failure. Large structures like offshore towers and aircraft structures are instrumented at the time of installation itself and the response signals are continuously monitored for fault diagnosis, if any. Early detection of cracks and the location of their position on the structure have become very important task.

2.2 IDENTIFICATION OF CRACK

Understanding the basic vibration phenomenon in damaged structures and the development of improved
mathematical models and solution procedures for reliable prediction of the damage have received attention, to improve the design as well as to prevent damage. As the cracks can have detrimental effects on the reliability of the structure, an early crack warning can considerably extend the durability and reliability of the structure. A detailed study of the vibration phenomenon of simple structures like beam or plate with cracks is therefore necessary to improve design and structural integrity so that the procedure can be extended to complex structures with a level of confidence.

2.3 LITERATURE REVIEW - IDENTIFICATION OF CRACK

Brief review of the literature about the analysis of crack, identification of crack, finite elements developed to analyse the crack, experimental procedures and various methods used to identify the crack in structures is presented in the following sections.

2.3.1 Analysis of Crack

In this section a brief collection of literature with respect to the modelling and analysis of a crack is presented. In the 1980's and 90's, a lot of research work has been carried out in this area.

Stahl and Keer (1972) made the earliest study to develop and demonstrate a method for determining the natural frequencies and buckling loads of rectangular plates with mixed boundary conditions arising from cracks.
Anifantis and Dimaragonas (1983) studied the stability of columns with a single crack subjected to various loads, in detail. In their work a general flexibility matrix was developed and only the bending term, which is dominant, in the matrix was considered for further analysis. The kinetic method was used and Eigen curves were developed to study the system stability. Dimaragonas and Papadopoulos (1983) studied a de Laval rotor with an open crack by way of application of the theory of shafts with dissimilar moments of inertia. Analytical solutions were obtained for the closing cracks under the assumption of large static deflection. Hillary and Ewins (1984) have proved experimentally as well as numerically that strain gauges have a useful role to play in the measurement of both dynamic response and frequency response functions, especially when using these data to determine force inputs to a structure. The strain frequency response functions have been shown to be less ill conditioned than the equivalent displacement or acceleration models.

Haisty and Springer (1988) have studied the symmetric discontinuity in the form of a double-sided open crack. Gounaris and Dimaragonas (1988) have analysed a surface crack on a beam by developing a finite element which will account for local flexibility due to the crack. Chen and Chen (1988) have applied the finite element model to study the vibration and stability of thick rotating blades with a single edge crack. The effects of transverse shear deformation and rotary inertia were also taken into account. Chondros and Dimaragonas (1989) have used Rayleigh principle for the estimation of the change in the natural
frequencies and modes of vibration of a cracked structure. Wolff and Richardson (1989) have experimentally investigated the effect of a blade crack in a model fan on mode shapes and frequencies. The effect of blade cracks was also studied with a finite element model of the physical model so as to study the sensitivity of the modal parameters to physical changes.

Lam and Hung (1990) have studied the flexural vibration of plates with full depth cracks and cutouts using a scheme which combines the versatility of the finite element technique with the computational advantage of the Royleigh-Ritz method. Ostachowicz and Krawczuk (1990) have proposed a model for the analysis of cracked beams using point finite elements which takes into account the opening and closing of the beam and the effects of the crack. Gomes et al (1990) have carried out an in depth experimental dynamic analysis on cracked free-free beams. They have also analysed the percentage variation of the bending natural frequencies as a function of the crack thickness. Their results show that a thin saw cut simulates a crack fairly well. Ostachowicz and Krawczuk (1991) have analysed the effect of two open cracks upon the frequencies of the natural flexural vibration in a cantilever beam.

Collins et al (1992) have examined the longitudinal vibrations of a cantilever bar with a transverse breathing crack. Discontinuities in compliance and damping at the crack were represented by sets of self-equilibrating concentrated forces. Sekhar and Prabhu (1992) has described the free and forced vibration analysis of a rotor bearing
system with a cracked shaft. Transient dynamic analysis of a rotor passing through its critical speed, using the crack opening and closing phenomenon has been dealt with. Krawczk (1993) has formulated a rectangular plate finite element with a non-propagating, one edge open crack. The crack was modelled by an additional flexibility matrix, the terms of which were calculated using fracture mechanics. Krawczuk and Ostachowicz (1993) have analysed the influence of transverse, one-edge open cracks on the natural frequencies of the cantilever beam subjected to vertical loads.

Sekhar and Prabhu (1994) have modeled a cracked shaft using finite element and discussed the possibilities of backward whirl due to crack. The cracked part of the beam has been modeled by a cracked beam finite element with three degrees of freedom and Krawczuk and Ostachowicz (1995) investigated the effects of transverse crack. The effect of parameters like the crack location, the depth, the volume fraction of fibers and the fiber orientation upon the change of the natural frequencies of the beam were also studied. James (1995) has combined the spectral element method, which is very suitable for solving inverse dynamic problems, with a stochastic genetic algorithm to give a scheme that can locate and measure size of cracks in structural components. Swamidas and Chen (1995) stated that the most sensitive parameters due to crack are the difference of the strain mode shapes and the local strain frequency response functions. By monitoring the changes in the local strain frequency response function and the difference between the strain mode shapes, the location and severity of the crack that occurs in the structure can be
determined. Neogy and Ramamurti (1997) have studied the effect of full depth cracks and partial cracks on the natural frequencies of twisted plates using 3D brick elements.

Solecki (1980) has used a previously derived invariant expressions for the amplitude of the displacement of harmonically vibrating plates with internal rigid supports or cracks to supplement by terms representing possible point discontinuities at the tip of the support or of the crack. Later he (Solecki 1983, 1985) demonstrated a method for determining frequencies of steady state vibration of a rectangular, simply supported, isotropic plate with a crack located parallel to one edge and also an arbitrarily located rectilinear crack. He has proved that the combined application of finite Fourier transformation and of generalized Green-Gauss theorem can simplify considerably the complexities in computing the frequencies.

Though there are quite a few published works, still the attempts were scattered. A unified approach considering all the existing work will be a worth exercise. However all the above analytical work indicates that there will be changes in modal parameters due to the presence of the crack.

2.3.2 Crack Identification

The major problem in condition monitoring is to attribute and pin point the reason for change in the monitoring output signals. Any variations in the output monitoring signals (in a dynamic environment) could be
attributed to system parameters such as K and M getting varied. The system parameters are dependent on physical and material properties. An inverse study would correlate the variations in output signals with variation in physical/material property variations. Great emphasis has been made in this area by a few researchers.

Adams et al (1978) and Cawley and Adams (1979) have shown that vibration measurements made at a single station in the structure can be used, in conjunction with a suitable theoretical model, to indicate both the location and the magnitude of a defect. Chondros and Dimaragonas (1980), have used the extracted natural frequencies to detect cracks in welding joints of complex structures and concluded that the depth detectable with confidence is of the order of 10%. Ju and Mimovitch (1988) have made use of modal frequency method to diagnose the fracture damage experimentally in simple structures, based on the theory of the spring loaded fracture hinge. Their results show that with an accurate analytical model for the experimental samples, the location of the damages can be predicted to an accuracy of 1% of the length. The damage intensity is around 4% on accuracy.

Springer et al (1988) have used variations in natural frequencies to identify damage in members that can be modeled as longitudinally vibrating beams. Wolff and Richardson (1989) have studied the change of various modal parameters due to the presence of a damage. Lin (1990) observed that in order to obtain a good estimate of the spatial stiffness matrix one needs to measure all modes of
the structure, especially the high frequency modes. Qian et al (1990) have proposed a simple and direct method for determining the crack position based on the relationship between the crack and the eigen couple of a beam. Rajab and Sabeeh (1991), Sekhar and Prabhu (1992) and Nikolakopoulos et al (1997) have predicted the crack location and depth in a structure using the first few natural frequencies. They have used J-integral concept from fracture mechanics and FEM technique to evaluate the change in natural frequencies.

Pandey et al (1991) showed that the difference between curvature mode shapes for an intact and damaged beam could find a localised change in elastic modulus of about 30%. Collins et al (1991) used axial impulses to detect a crack in rotating shafts. Yae et al (1992) concluded that measured strain mode shapes were more effective than the displacement mode shape for identifying the location of the damage. Manning (1994) has analysed the change in pole/zero information caused due to the failure of an 'at risk' member using neural networks. Sheinman (1994) characterised the location of a damage by the preservation of the stiffness ratio and subsequently reduced the number of measured modes needed to quantify the damage. Pandey and Biswas (1995) have considered the change in flexibility matrix to indicate the location of the crack and the prediction converges better on increasing the number of modes.
Ratcliffe (1997) has developed and presented a technique based on modified Laplacian operator on mode shape data to identify the location of crack having less than 0.5% depth. Rizos et al (1990) developed a method based on the amplitudes at two points in a structure vibrating at one of its natural frequencies and an analytical solution of the dynamic response. Pandey et al (1991) used curvature mode shape in identifying and locating damage in a structure. They have shown that the absolute change in the curvature mode shapes is localised in the region of damage. Ricks and Kosmatka (1992) used the measured modal test data along with a correlated analytical structural model to locate potentially damaged regions using residual modal force vectors and conducted a weighted sensitivity analysis to assess the extent of mass and/or stiffness variations, where damage is characterised. Dror Armon et al (1994) suggested a method for detection and location of slots and cracks in a beam using rank ordering of the modes according to reduction of natural frequencies.

Lim and Kashangaki (1994) presented a method by which measured modes and frequencies from a modal test can be used to determine the location and magnitude of damage in a space truss structure. The damage is located by computing the Euclidean distance between the measured mode shapes and the best achievable Eigen vectors. Manning (1994) suggested a methodology for detecting damage in structural systems using the active members that are already present for a controlled structure in conjunction with a trained artificial neural network. Mares and Surace (1996) used the residual force method to locate and quantify the extent of
the damage with genetic algorithms. Ratcliffe (1997) suggested a method to identify the crack in a beam like structure by modifying the Laplacian operator for very small cracks.

From the above literature, it was observed that there are two major modal parameters viz., local and global parameters (mode shape and frequencies) which influences the identification algorithm. The reported work in this thesis compares the influence of local and global modal parameters in identifying and locating a crack. A theoretical algorithm proposed in this work augurs well with experiments. These are reported in chapter 3.

2.3.3 Crack (Tip) Finite Element Formulation and Modelling

Holston (1976) developed a special circular crack tip finite element for the static and dynamic analysis of plates with full depth cracks. It contains the proper singularities and is applicable to the combined opening and plane shearing modes of deformation. A general beam element is derived, by Haisty and Springer (1988), which contains a symmetric discontinuity in the form of a double sided open crack. The compliance matrix was used to develop the stiffness matrix for the cracked beam element and consistent mass matrix by Gounaris and Dimarogonas (1988) to simulate the surface cracks on a beam section. The stress intensity factor (SIF) of finite plate with a through crack under bending, twisting and shearing is estimated and the element stiffness matrix of plate with a crack is derived by Qian et al (1991). Even though, crack
finite element formulation could simplify the computation to calculate and analyse modal parameters, it cannot be used in crack identification.

2.4 UPDATION OF FINITE ELEMENT MODEL

Even though the field of finite element analysis of structural dynamic problems has witnessed tremendous progress in the last three decades, greater confidence is still placed in experimental data. The reason is so simple that the finite element method is an approximate method wherein both the geometry and the variables are approximated by a polynomial. Moreover the simulation of the boundary conditions of the experiment may not be possible in FE model. Even the material property to be isotropic or the physical properties to be constant are all idealisation in FEM which may not be really true in the experiment or in-situ situation. It is often found in practice that considerable discrepancies exist between numerical and experimental results. Therefore, the finite element model of a given structure is often updated to reflect the results of a particular experiment. Usually, the computed Eigen modes are compared with the measured frequencies and mode shapes. If both sets are not in agreement, the finite element model is refined via a two-step updating procedure viz., a) locating the errors and b) correcting them. Clearly, the first step is the most challenging of the two. Once the location of the errors is known, it is relatively easy to correct them, especially if the error sources can be identified. However, locating and
identifying these errors can be a difficult task for the following reasons:

i) in general, only a few experimental modes are available,

ii) these modes may be contaminated with random and systematic measuring errors,

iii) only a subset of the degrees of freedom in the finite element model can be monitored; and

iv) as for practical and economical reasons, only a few sensors can be utilised.

2.5 LITERATURE REVIEW - MODEL UPDATION

Brief review of the literature about the experimental modal analysis and finite element model updation is presented in the following sections.

2.5.1 Experimental Modal Analysis

The selection of transducer location and the proper mounting technique influences the quality of the data. Any transducer resonance should be well above the frequency range of interest. The available standards for mounting transducers will be helpful for the selection of frequency ranges. Considerable efforts have been extended by Mitchell (1982) to improve the excitation techniques, spectral estimation and FRF computation. He has developed H2 estimator as an alternative to the conventional FRF
estimator. Hunt et al (1984) have improved excitation methods to improve the FRF estimation. A method is proposed by Ewins and Gleeson (1982) for modal identification of light damped structures which demands a minimum of input data and does not require accurate measurements around resonance.

There are many different techniques available to extract the modal parameters from the measured FRF data. Kennedy and Pandu (1947) discussed the use of vectors in vibration analysis. They developed circle fit approach to extract modal parameters for system with hysteric damping characteristics. Brown et al (1979) has given a summary of the practical features of some of these modal parameter estimation techniques. They have presented various parameter estimation techniques for modal analysis. Iwahara (1985) conducted experimental modal analysis for engine parts. He concluded that the use of the multiple-point reference is very useful for a high accuracy experiment. He felt that the strain gauge might be used instead of a response pickup whenever the excitation points moved and a modal analysis using a strain gauge is very useful in solving problems related to structural strength. Modal test of an 18' long stainless steel wind turbine blade was performed by a single shaker stepped sine sweep technique to identify the modal parameters and to verify the finite element model of the assembly by Pazargadi (1989). He suggested that if perfect correlations are expected, optimized test analysis model should be developed even for relatively simple structures. Penny et al (1994) examined the problem of choosing an optimum set of measurement
locations for experimental modal testing and suggested a criteria where the suitability of the chosen locations can be assessed. They selected the coordinates based on Guyan reduction (1965) and Fisher information matrix. Wilson and Bogy (1996) described an experimental modal analysis system which can effectively be used to obtain the modal parameters of small structures.

2.5.2 Finite Element Model Updation

Mottershead and Friswell (1993) have provided a thorough description of the finite element model updating in their survey paper. They started with system identification in control engineering to construct models in model-reference schemes. They described about the various methods available for model updating of linear models in structural elastodynamics. They are reluctant to recommend any 'preferred' updating approach suitable to handle industrial problem.

Lin and Lim (1996) examined the possible and limitations of current model updating practice and suggested that the future research effort should be more focused on full analytical model updating and, in particular, more emphasis should be placed on the direct application of measured receptance data rather than modal data. Fengquan and Shiyu (1996) presented a method used to determine the boundary conditions of the finite element model of a slender beam with measured modal parameters. Combination with the modal parameters from experiment, on FEM modal parameter equation to determine the boundary
conditions was put forward. A sensitivity-based methodology for improving the finite element model of a structure using test modal data and a few sensors was presented by Farhat and Francois (1993). Their method searches for both the location and sources of the mass and stiffness errors and does not interfere with the theory behind the finite element model while correcting these errors. The updating algorithm is derived from the unconstrained minimization of the squared norms of the modal dynamic residual via an iterative two-step staggered procedure. Mottershead and Shao (1993) have studied on the convergence criterion of Eigen values of a finite element model with reference to model updating. They presented an approach to correct the uncertain stiffness by altering the measured Eigen data to account for shape function discretisation. They considered the effect of major errors, namely ill define joints and boundary constraints and over stiffening due to the application of shape function discretisation, on the finite element model updation.

Ibrahim et al (1990) discussed the question of uniqueness in the updated models. They have updated mass, stiffness and damping matrices simultaneously by using measured data of simple problems. Foster and Mottershead (1990) applied a least-squares technique to estimate the mass, stiffness and damping parameters in spatial model of a portal frame. The method relies upon the availability of a reduced order finite element model which is improved by the processing of incomplete experimental vibration measurement. Minas and Inman (1990) have done significant research using eigenstructure assignment technique. In
eigenstructure assignment approach, state feedback is used to describe the right side of the dynamic equation of motion in terms of displacement and velocity states.

A unity check method was proposed by Lin (1990), to locate the physical positions of the modeling errors in stiffness using modal test data. The method uses the cross-unity check between a flexibility matrix derived from modal test data and the analytical stiffness matrix to locate the error. The method cannot determine the changes needed to correct the errors. Caesar (1987) used the matrix mixing approach that combines the experimental mode shape with the analytical ones to obtain a complete Eigen vector set. Structural matrices have been assembled on the basis of incomplete Eigen modes. It uses pseudo inverse in the calculation of mass and stiffness matrices. The matrix mixing method generally returns populated mass and stiffness matrices, which bear little relation to physical connectivity. Dobson (1983) conducted a validation study on a cantilever beam in which a point defect was introduced. Techniques are described for converting incomplete modal parameter data into spatial information in terms of pseudo-flexibility and stiffness matrices. Using these matrices it was shown that inaccurately modeled regions of the finite element idealisation might be identified.

Two different variations of a method for identification of linear dynamic structure were described by Baruch (1982). In both variations the reference base is the measured modal matrix. He has shown that in the identification process for structures with semi-definite
matrix, the measured mode shapes could not be kept unchanged. They have to be slightly modified. Only then can they be used to correct the given analytical mass and stiffness matrices. A matrix perturbation method was proposed by Chen and Garba (1980) to calculate the Jacobian matrix and to compute the new Eigen data for the parameter estimation procedure. The advantages of the method are the applicability to large complex structure without knowing the analytical expressions for the mass and stiffness matrices, and a cast effective approach for the recomputation of the Eigen data. This method also allows the use of other measurements such as modal forces, kinetic energy distribution, and strain energy distributions in the estimation procedure. Baruch (1978) has updated stiffness matrix elements by minimising the norm of error between two matrices by taking mass matrix as weighting matrix. Lagrange multipliers were used to enforce satisfaction of the dynamic equation and stiffness symmetry.

Collins et al (1974) used statistics as basis for updating. The variance associated with the structural parameters was minimised to determine those that reproduce the measured modal properties; measurement errors were also included as known uncertainties. Fox and Kapoor (1968) described a method to determine the sensitivity of each Eigen value with respect to each unknown system parameter. The proposed algorithms use pseudo-inverse technique and mass and stiffness matrices loss their banded characteristics.
2.6 AIM, SCOPE AND OBJECTIVE OF THE THESIS

The aim of the first part of the thesis is to develop an algorithm to identify the crack in the structure, and this ensures the structural integrity, so that preventive action can be taken before failure.

A crack in a structure will affect the modal parameters both locally as well as globally. The present work discusses the studies carried out using those parameters that get changed locally and globally, and the procedure to identify the crack location. Even though the crack can be located exactly by monitoring changes that occur in the parameters locally such as strain variation etc., this method has limitations in terms of extracting those locally varying modal parameters. A new technique is presented to identify the presence of a crack and its location from the changes that occur in a few of its lowest natural frequencies, which is one of the modal parameters that change globally. The study is carried out both analytically and experimentally and the results are presented in this thesis.

The second part of the present work aims at updating the numerical model in order to correlate it with the modal testing results, so that the updated numerical model can be utilised for further investigations or predictions.

Model updating is a process to update the matrices of an analytical (finite element) model of a structure using measured modal data such that the corrected or updated
analytical model compares well with the measured modal data of the same structure. The model updating process continues by placing more confidence in the experimental data. Good agreement between the finite element and experimental modes is an essential prerequisite for model updating. The primary advantage of correlating finite element models with measured modal data is that it is possible to relate finite element model data to the physical design parameters of the system. A meaningful model should not only possess the observed modal characteristic but also predict internal stress levels and have sensitivity to further design changes. If the updated model is to be used predictively for untested conditions or modified structural configurations, then it is important that the improved agreement in results is achieved by correcting the inaccurate modeling assumptions and not by making other alterations to the model.

The authenticity of the algorithm should be tested, verified and validated for practical field engineering problems and limitations should also be addressed as part of any research work.