FAULT DETECTION AND CONDITION MONITORING OF MACHINE-STRUCTURE: REVIEW

L.B. Bhuyar
Prof Ram Meghe Institute of Technology & Research
Badnera 444 701, Maharashtra

S.V. Kshirsagar
Sinhgad College of Engineering, Off Sinhgad Road
Pune: 411 041, Maharashtra
E-mail: sharadkshirsagar@gmail.com

G.K. Awari
T. G. P. College of Engineering & Technology
Nagpur, Maharashtra

A.S. Padalkar
Sinhgad College of Engineering, Off Sinhgad Road
Pune, Maharashtra

ABSTRACT

Engineers and researchers, particularly in the aerospace and offshore oil industries, began to utilise vibration-based damage detection during the late 1970s and early 1980s (Farrar and Doebling 1999). For the detection of crack in the machine and civil structures many efforts have been reported so far. In the recent decade many methods have been applied for the detection of crack for example using changes in modal parameters, mode shape techniques, finite element methods, visual dot pattern of acoustic and vibration signal etc. Vibration behavior of cracked structures, in particulars cracked rotors has received considerable attention in the last two decades.

Keywords: Crack Detection, Condition Monitoring, Signature Analysis

1. INTRODUCTION

It is required that structures must safely work during its service life. But, damages initiate a breakdown period on the structures. Cracks are among the most encountered damage types in the structures. Cracks in a structure may be hazardous due to static or
dynamic loadings, so that crack detection plays an important role for structural health monitoring applications. Beam type structures are being commonly used in steel construction and machinery industries. In the literature, several studies deal with the structural safety of beams, especially, crack detection by structural health monitoring. Studies based on structural health monitoring for crack detection deal with change in natural frequencies and mode shapes of the beam.

Cracks are present in structures due to various reasons. The presence of a crack could not only cause a local variation in the stiffness but it could affect the mechanical behavior of the entire structure to a considerable extent. Cracks may be caused by fatigue under service conditions as a result of the limited fatigue strength. They may also occur due to mechanical defects. Another group of cracks are initiated during the manufacturing processes. Generally they are small in sizes. Such small cracks are known to propagate due to fluctuating stress conditions. If these propagating cracks remain undetected and reach their critical size, then a sudden structural failure may occur.

Cracks present in machine parts affect their vibration behavior like the fundamental frequency and resonance. The amplitude of vibration increases and the occurrence of resonance shifted as crack length increases. Structural failure refers to loss of the load carrying capacity of a component or member within a structure or of the structure itself. Structural failure is initiated when the material is stressed to its strength limit, thus causing fracture or excessive deformations. When this limit is reached, damage to the material has been done, and its load-bearing capacity is reduced permanently, significantly and quickly. In a well-designed system, a localized failure should not cause immediate or even progressive collapse of the entire structure. Ultimate failure strength is one of the limit states that must be accounted for in structural engineering and structural design. Therefore intensive research has been going on amongst the scientists and engineers to find an effective methodology to predict the location and intensity of damage beforehand. Hence it is possible to use vibration measurements to detect cracks.

A large number of studies have been carried out on conventional (dye penetrant, magnetic particle induction, ultrasonic, etc.) and modern approaches to non-destructive testing and evaluation. The conventional methods have been well developed,
implemented in widely marketed equipment, and accepted by industry and regulatory agencies as practically applicable non-destructive evaluation (NDE) methods. The modern NDE methods are still under development, implemented in a limited manner in some equipment and not fully accepted by the industry and regulatory agencies as practicably applicable NDE methods. One of these modern methods is the vibration signature-based inspection methodology.

Literature on Fault diagnosis and condition monitoring was focused on the vibration-based method which can be classified into modal-based and signature-based methods. In modal based techniques data can be condensed from the actual measured quantities like resonant frequencies, mode shape vectors and quantities derived from these parameters for the crack detection [1, 3-14, 16].

In signature based methods the vibration signature of cracked machinery structure can be useful for the fault diagnosis and condition monitoring. Thus, the development of crack detection methods has received increasing attention in recent years. Among these techniques, it is believed that the monitoring of the global dynamics of a structure offers favorable alternative if the on-line (in service) damage detection is necessary. In order to identify structural damage by vibration monitoring, the study of the changes of the structural dynamic behavior due to cracks is required for developing the detection criterion. [2, 15, 17-24, 26, 27, 29, 31, 33].

Another class of damage identification methods is based on features related to changes in mass, stiffness and damping matrix indices associated with physical models that have been correlated so that the model predicts, as closely as possible, experimentally determined modal properties. These methods solve for the updated matrices (or perturbations to the nominal model that produce the updated matrices) by forming a constrained optimization problem based on the structural equations of motion, the nominal model, and the identified modal properties. Comparisons of the matrix indices that have been correlated with modal properties identified from the damaged structure to the original correlated matrix indices can provide an indication of the existence, location and extent of damage [6, 9, and 10].

Condition monitoring of machinery structural health is of increasing interest, much effort has been directed towards developing methods that use conventional signal
processing and pattern classification techniques. The methods developed provide a common solution methodology for the detection of different faults, utilizing a combination of modeling concepts, along with wavelet, and dynamic analysis to ensure early detection.

2. MODAL BASED METHODS:

Many methods have been proposed for the detection of a crack till now. Although these methods are applicable for non rotating parts which are assumed to be available offline and for a rotating machine parts which can be stopped and checked for damage. Many researchers have used the vibration response to detect cracks in a structure. These detection schemes are based on the fact that the presence of a crack in a structure reduces the stiffness of the structure hence reducing the natural frequencies. Well developed experimental modal analysis procedures are applied to the measured response time histories or spectra to estimate the system’s modal properties. The fitting process is done using data from the structure in some initial and usually assumed undamaged condition, and then is repeated at periodic intervals or after some potentially damaging event that triggers the assessment process. Changes in the modal parameters are then used to indicate presence and location of damage in either forward or inverse manner.

T.G. Chondros, A.D. Dimarogonas, and J. Yao [1] in 1998 developed a continuous cracked beam vibration theory for the lateral vibration of cracked Euler-Bernoulli beams with single edge or double edge open cracks. The Hu-Washizu-Barr variational formulation was used to develop the differential equation and the boundary conditions of the cracked beam as a one dimensional continuum. The displacement field about the crack was used to modify the stress and displacement field throughout the bar. The crack was modelled as a continuous flexibility using the displacement field in the vicinity of the crack, found with fracture mechanics methods.

The dynamic behavior of a rotor with two cracks was investigated by Sekhar [41] in 1999. He carried out a parametric study of two transverse open cracks in a rotor and studied the effect of various crack parameters on the eigen frequencies and stability speeds of rotors. He used finite element model of a rotor bearing system for flexural vibrations and carried out a study on two aligned open cracks.
Gounaris and Papadopoulos [2] in 2001 investigated coupled vibration response between bending and longitudinal vibration by applying lateral excitation and measuring longitudinal vibrations on a rotating shaft with open crack assumptions. The analysis presented was used to develop a method for the identification of location and depth of a transverse surface crack. The basis of the method is the measurement of the coupled vibration, in rotating shafts, due to a single harmonic excitation in one direction (bending), while measuring in an other (axial). The advantage of this analysis is the possibility to detect this existence of a crack in rotating shafts, (diesel electric generator etc.) by measuring the axial response function, for two or three different rotational speeds and loadings.

Kim and Stubbs [4] in 2002 used changes in natural frequencies of a structure as a practical method to detect cracks in beams. Fractional changes in modal energy are related to changes in natural frequencies due to damage. They presented a methodology to non-destructively locate and estimate size of crack in structures for which only a few natural frequencies are available. A crack location model and a crack size estimation model were formulated by relating fractional changes in modal energy to changes in natural frequencies using Euler–Bernoulli beam theory.

Owolabi G. M. [3] in 2002 studied the vibration behavior of aluminum beams based on changes in the natural frequencies and amplitudes of the FRFs. Galerkin’s method was utilized to solve for the frequencies and vibration modes in a simulating model.

M. Dilena, A. Morassi [5] in 2003 presented the method of identification of a single open crack in a vibrating beam, either under axial or bending vibration, based on measurements of damage-induced shifts in natural frequencies and antiresonant frequencies. It is found that an appropriate use of frequencies and antiresonances may avoid the non-uniqueness of the damage location problem, which occurs in symmetrical beams when only frequency data are employed. in 2002 They also [43] detected a single crack in a beam when damage-induced shifts in the mode shapes of the beam are known.

D.P. Patil, S.K. Maiti [7] in 2004 experimentally verified a method for prediction of location and size of multiple cracks based on measurement of natural frequencies of slender multi-cracked cantilever beams. The analysis is based on energy method and
presentation of a crack by a rotational spring. The damage index is an indicator of the extent of strain energy stored in the rotational spring. The crack size is computed using a standard relation between stiffness and crack size. Number of measured frequencies equal to twice the number of cracks is adequate for the prediction of location and size of all the cracks. A strategy to overcome failure in the prediction for cases with one of the cracks located near an anti-node has been suggested.

In the view to overcome the difficulties that traditional FEM have, B. Li, X.F. Chen, J.X. Ma and Z.J. He [6] in 2004 presented a methodology to detect crack location and size which takes advantage of wavelet finite element methods (WFEM) in the modal analysis for singularity problems like a cracked beam. First, the beam is discretized into a set of wavelet finite elements, and then the natural frequencies of the beam with various crack locations and sizes are accurately obtained. The frequency response functions, function of crack location and size, are approximated by means of surface-fitting techniques. Measured natural frequencies are used in a crack detection process and the crack location and size can be identified by finding the point of intersection of three frequency contour lines.

In a very recent paper Kisa [42] in 2004 has presented a new method for the numerical modelling of the free vibration of a cantilever composite beam having multiple open and non-propagating cracks. The method integrates the fracture mechanics and the joint interface mechanics to couple substructures. This study is an investigation of the effects of cracks on the dynamical characteristics of a cantilever composite beam, made of graphite fibre reinforced polyamide. The finite element and the component mode synthesis methods are used to model the problem.

H. Nahvi and M. Jabbari [9] in 2005 established an analytical, as well as experimental approach to the crack detection in cantilever beams by vibration analysis. The proposed method is based on measured frequencies and mode shapes of the beam. To identify the crack, contours of the normalized frequency in terms of the normalized crack depth and location are plotted. The intersection of contours with the constant modal natural frequency planes is used to relate the crack location and depth. A minimization approach is employed for identifying the cracked element within the cantilever beam.
Murat Kisa, M. Arif Gurel [10] in 2006 proposes a numerical model that combines the finite element and component mode synthesis methods for the modal analysis of beams with circular cross section and containing multiple non-propagating open cracks. The model virtually divides a beam into a number of parts from the crack sections and couples them by flexibility matrices considering the interaction forces that are derived from the fracture mechanics theory. The main feature of the presented approach is that the natural frequencies and mode shapes of a beam with an arbitrary number of cracks and any kind of two end conditions can be conveniently determined with a reasonable computational time.

Sadettin Orhan [11] in 2007 did free and forced vibration analysis of cracked beam using a finite element program in order to identify the crack in a cantilever beam. The study results suggest that free vibration analysis provides suitable information for the detection of single and two cracks, whereas forced vibration can detect only the single crack condition. However, dynamic response of the forced vibration better describes changes in crack depth and location than the free vibration in which the difference between natural frequencies corresponding to a change in crack depth and location only is a minor effect.

Shuncong Zhong, S. Olutunde Oyadiji [12] in 2007 studied theoretically natural frequencies of a damaged simply supported beam with a stationary roving mass. The natural frequencies change due to the roving of the mass along the cracked beam. Therefore the roving mass can provide additional spatial information for damage detection of the beam. The roving mass can be used to probe the dynamic characteristics of the beam by roving the mass from one end of the beam to the other. The presence of a crack causes the local stiffness of the beam to decrease which, in turn, causes a marked decrease in natural frequency of the beam when the roving mass is located in the vicinity of the crack.

Shuncong Zhong, S. Olutunde Oyadiji,[14] in 2007 proposes a new approach based on auxiliary mass spatial probing using spectral centre correction method (SCCM), to provide a simple solution for damage detection by just using the response time history of beam-like structures. The natural frequencies of a damaged beam with a traversing auxiliary mass change due to change in the inertia of the beam as the auxiliary mass is
traversed along the beam, as well as the point-to-point variations in the flexibility of the beam. Therefore the auxiliary mass can enhance the effects of the crack on the dynamics of the beam and, therefore, facilitate the identification and location of damage in the beam.

Jiawei Xiang, Yongteng Zhong, Xuefeng Chen and Zhengjia He [15] 2008, proposed a new crack detection method for detecting crack location and depth in a shaft. Rotating Rayleigh-Euler and Rayleigh-Timoshenko beam elements of B-spline wavelet on the interval (BSWI) are constructed to discretize slender shaft and stiffness disc, respectively. The cracked shaft is modeled by wavelet-based elements to gain precise frequencies. The first three measured frequencies are used in crack detection process and the normalized crack location and depth are detected by means of genetic algorithm.

Marta B. Rosales, Carlos P. Filipich and Fernando S. Buezas [16] in 2009, the detection of cracks for beam-type elements was addressed using the analysis of changes in the frequencies as a detection criterion. Two approaches were tackled, a power series technique (PST) and artificial neural networks (ANN). The use of PST provided a straightforward and efficient numerical technique to solve the inverse problem. The crack is modeled by introducing springs to represent the stiffness reduction.

The features described above have several issues associated with them that have prevented their use in most “real-world” applications. First, most of these features involve fitting a linear physics–based model to the measured data from both the healthy and potentially damaged structure. Often these models do not have the fidelity to accurately represent boundary conditions and structural component connectivity, which are prime locations for damage accumulation. Modal properties associated within lower frequency global modes have been shown to be insensitive to local damage. However, the practical limitations with the excitation and identification of the modal properties associated with these local modes, caused in part by high modal density and low participation factors, can make them difficult to identify. Finally, the inverse approaches to damage identification do not necessarily produce unique solutions and the degree of freedom mismatch between the numerical model and measurement locations can severely limit the ability to accurately perform the required matrix updates.
3. **SIGNATURE BASED METHODS:**

Some amount of research empirical and theoretical has been conducted in predicting the presence and location of a crack using the vibration signature of the structure. In a rotating system the presence of a crack produces vibration of the second and higher harmonics of the rotating frequency. However the amplitudes of those harmonics can be measurable only if the frequency of one of the harmonics closely matches one of the natural frequencies of the shaft. It is not an easy task to locate the crack using the signature because it is very sensitive to the type and depth of the crack, explaining in part the limited success of the signature analysis methods.

S. Ratan, H. Baruh and J. Rodriguez [18] in 1995 developed a method to detect the existence and location of a crack in rotating shafts. The crack detection method is based on obtaining the Fourier transform of the response of the shaft. The amplitudes at the peaks of the Fourier transform of the response are used in a residue vector to identify and locate the crack.

A.S. Sekhar and P. Balaji Prasad [19] in 1997 has considered the finite element analysis of a rotor-bearing system for flexural vibrations by including a shaft having a slant crack that has resulted from the fatigue of the shaft due to the torsional moment. The frequency spectrum of the steady state response of the cracked rotor was found to have sub harmonic frequency components at an interval frequency corresponding to the torsional frequency which can be used for crack detection.

Yongyong, [23] in 2001 presented a genetic algorithm-based shaft crack detection technique based on the finite element method. The most significant advantages of this methodology over the traditional search methods used for inverse problems are avoiding local optima, circumventing the mathematical difficulties encountered in the solution of inverse problems using traditional methods.

S. Loutridis, E. Douka, A. Trochidis [45] in 2004 presented a method for crack identification in double-cracked beams based on wavelet analysis. The fundamental vibration mode of a double-cracked cantilever beam was analyzed using symmlet wavelet, a continuous wavelet transform and both the location and depth of the cracks were estimated. The location of the cracks was determined by the sudden changes in the
spatial variation of the transformed response. To estimate the relative depth of the cracks, an intensity factor was established which relates the size of the cracks to the coefficients of the wavelet transform. It is shown that the intensity factor obeys a polynomial law and therefore can be used for accurate prediction of relative crack depths.

Jian-Da Wu, Chao-Qin Chuang [25] in 2005 investigated the fault diagnosis technique in internal combustion engines based on the visual dot pattern of acoustic and vibration signals. Acoustic emissions and vibration signals are well known as being able to be used for monitoring the conditions of rotating machineries. A visual dot pattern technique is proposed to identify the acoustic emission and vibration signals for fault diagnosis in an internal combustion engine and drive axle shaft.

4. NON-LINEAR METHODS.

Francois Led Onard, Jacques Lanteigne, Serge Lalonde and Yvon Turcotte in 2000 carried out study on cracks that occurred in metal beams obtained under controlled fatigue-crack propagation. The beams were clamped in a heavy vise and struck in order to obtain a clean impulse modal response. Spectrograms of the free-decay responses showed a time drift of the frequency and damping: the usual hypothesis of constant modal parameters is no longer appropriate, since the latter are revealed to be a function of the amplitude. Signal processing such as the worm transform and phase spectrogram methods have been developed with enough accuracy to display the behaviour of an uncracked beam where a slight non-linear stiffness is generated by the clamping. Moreover, extracted worms show that the second mode of a beam with a deep crack is modulated in frequency by the first mode. In fact, the dominant mode opens and closes the crack, thereby modulating the beam stiffness, which affects higher modal frequencies. With deep cracks, three vibration states are observed: one where the crack is alternately fully open and fully closed, a second with a crack partially opened, and a third with alternating force acting on a closed crack. In the latter case, the peak force is smaller than the intrinsic closure load of the crack. The first state is difficult for a small crack to reach since high-amplitude excitation is required to fully open the crack. For crack detection purposes, the damping criterion, harmonic distortion criterion and bispectrum appear less sensitive to small cracks than the phase spectrogram and coherent-modulated power.
S. Loutridis, E. Douka, L.J. Hadjileontiadis [37] in 2005 applied the instantaneous frequency and empirical mode decomposition methods for crack detection in a cantilever beam with single breathing crack, i.e. opens and closes during vibration. They investigated the dynamic behavior of the beam under harmonic excitation, both, theoretically and experimentally. A single-degree-of-freedom mathematical model with varying stiffness was employed to simulate the dynamic response of the beam. They modeled the time varying stiffness using a simple periodic function. Both simulated and experimental response data were analyzed by applying empirical mode decomposition and the Hilbert transform. By this way, the instantaneous frequency of each oscillatory mode was obtained. They concluded that the variation of the instantaneous frequency increases with increasing crack depth and the harmonic distortion increases with crack depth following definite trends and can also be used as an effective indicator for crack size. They also stated that the proposed time-frequency approach is superior compared to Fourier analysis.

Ugo Andreaus, Paolo Casini, Fabrizio Vestroni [38] in 2006, worked on the characterization of the non-linear response of a cantilever cracked beam to a harmonic loading, adopting a two-dimensional finite element formulation, which is capable of simulating the behavior of a breathing crack via a frictionless contact model of the interacting surfaces. To this aim a systematic investigation has been performed assuming the driving frequency as a control parameter. The results of the analyses allowed finding out some interesting phenomena that characterize the non-linear features of the motion of the cracked beam. The presence of breathing crack in the beam makes the system non-linear resulting in bilinear stiffness. It seems reasonable to get information about the more complex response of the cracked beam via the much simpler Bilinear single degree of freedom system (SDOF); in particular, easily and fast analyzing the response of the BSDOF within wide ranges of driving frequencies could guide the research towards the richer features of the cracked beam. In particular, the beam model retains information on the crack location, which is fundamental in the damage detection. The main features of the cracked beam response have been highlighted in the study; in particular when the excitation frequency is close to any one the integer submultiples ($1/n$) of the first system frequency, the amplitude of the ($1/n$)	extsuperscript{th} harmonic becomes appreciably large and hence
detectable; then, a future study of their dependence on position and severity of the crack should open interesting perspectives towards sub-resonant diagnostics for the detection of a breathing crack in a beam.

A.S. Sekhar [39] in 2007 summarized the different studies on double/multi-cracks including the influences, identification methods in vibration structures such as beams, rotors, pipes, etc. The state of the research on multiple cracks effects and their identification focuses the need for further work on this complex topic.

In his effort, Ashish K. Darpe [29] in 2007 formulated a methodology that exploits the breathing phenomenon of the transverse surface crack in a rotating shaft for its diagnosis. Variation of peak absolute value of wavelet coefficient with angle at which torsional excitation is applied is investigated. The correlation of this variation with the breathing pattern of the crack is studied. The detection methodology gives a vibration response signature that closely correlated with and is very specific to the behavior of the transverse surface crack in a horizontal rotor.

Robert Gasch [33] in 2008 introduced the dynamic behavior of a one disc rotor (Laval rotor) having a transverse crack in the elastic shaft. With the aid of a simple crack model the non-linear equations of motion were derived.

CONCLUSION OF REVIEW:

After literature review it is concluded that existence of structural damage in an engineering system leads to modification of the vibration modes. These modifications are manifested as changes in the modal parameters (natural frequencies, mode shapes and modal damping values) which can be obtained from results of dynamic (vibration) testing. Changes in the modal parameters may not be the same for each mode since the changes depend on the nature, location and severity of the damage. This effect offers the possibility of using data from dynamic testing to detect, locate and quantify damage. Results of tests conducted at different times; possibly coinciding with principal or other scheduled inspections, offer the opportunity of monitoring changes in structural condition with time. One other advantage of measuring vibration responses is the global nature of the derived natural frequencies. This allows measurement points to be chosen to suit the test situation. Modal parameters can be easily and cheaply obtained from measured
vibration responses. The responses are acquired by some form of transducer which monitors the structural response to artificially induced excitation forces or ambient forces in the service environment.

It is also seen that the detection of fatigue cracks should be more reliably based on non-linear features of FRF, rather than the natural frequency shift. Many methods have been developed to detect the existence and location of a crack in rotating shafts which are based on obtaining the Fourier transform of the response of the shaft. Although some studies are available on vibrations of cracked rotors and beams with breathing crack model [36-39], most of the previous reported work focused on open crack model. The same has not been used for the structural fault detection and condition monitoring.

REFERENCES


[10]-Murat Kisa, M. Arif Gurel, Modal Analysis of Multi-Cracked Beams with Circular Cross Section, Engineering Fracture Mechanics, 73, 2006, pp.963-977


[15]-Jiawei Xiang, Yongteng Zhong, Xuefeng Chen, Zhengjia He, Crack Detection in a Shaft by Combination of Wavelet-Based Elements and Genetic Algorithm, International Journal of Solids and Structures, 45, 2008, pp.4782-4795


[19]-A.S. Sekhar, Multiple Cracks Effects and Identification, Mechanical Systems and Signal Processing 22, 2008, pp.845-878
[26]-Weixiang Sun, Jin Chen, Jiaqing Li, Decision Tree and PCA-Based Fault Diagnosis of Rotating Machinery, Mechanical Systems and Signal Processing, 21, 2007, 1300


[35]-Kaveh Mollazade, Hojat Ahmadi, Mahmoud Omid, Reza Alimardani, Vibration-Based Fault Diagnosis of Hydraulic Pump of Tractor Steering System by Using Energy Technique, Modern Applied Science ,3(6),2009,pp.59-66


[42]-Murat Kisa (2004), Free Vibration Analysis of a Cantilever Composite Beam with Multiple Cracks, Composites Science and Technology 64,pp.1391–1402
