Crack identification in Beams by Vibration based analysis techniques – A Review

Tajammul Riaz Sial, Yan Jin, Zhang Juan

***Abstract*— The aim of this review paper is to update its readers about various crack detection techniques, studied so far. Beams are one of the most commonly used structural elements in engineering applications. Crack is the major factor that leads the component to failure. Therefore, it is necessary to identify the crack in early stages. Damage in structure alters its dynamic as well as static response parameters. Various techniques presented by researchers, have been discussed for detection of crack in beam structures. According to vibration based analysis when a crack grows in a component, it leads to changes in its vibration parameters such as natural frequency, amplitude and mode shapes which effect the crack location and crack depth. Damage also effects on the stiffness and damping of the structural component. Among different diagnosis methods vibration based analysis using finite element method seems to be economical, robust and reliable.**

***Index Terms*— Beam Structure, Crack detection, Vibration analysis, Natural Frequency, Mode Shape, Finite Element Method**

1) INTRODUCTION

Beams are one of the most commonly used structural elements in engineering applications. Beams can be circular or non-circular and are classified in different types on the basis of supports. Crack is the major factor that leads the component to failure/damage and hence it is necessary to investigate the cracks occurred in the structure at the early stage to protect it from probable catastrophic failures. Cracks can appear due to different causes like improper manufacturing, stress corrosion, hydrogen damages and fatigue failures. Currently most of the failures encountered by machines are due to material fatigue. The possibility of failure of fatigue can arise when any mechanical element or component is subjected to repeated load. In this mode of failure of fatigue, cracks develop on the surface of the component. Crack present in the component may grow during operation or running and can be the cause of component failure, if it grows beyond a critical limit. The geometry of cracks has a great influence on the dynamic properties of the cracked rotor. Therefore, they can be classified into various types such as (i) Transverse cracks (ii) Longitudinal cracks (iii) Inclined cracks. All of the cracks are well focused in present paper.

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The two types of component testing are used in engineering applications which are Destructive testing (DT) and Non-destructive testing (NDT). In destructive testing, the component can't be usable after testing because it can cut or damage for analysis. But in non-destructive testing, the component can be used in place of need after testing because it doesn't damage the component. In recent years, major efforts have been done to develop non-destructive testing techniques for damage identification in structures. Non-destructive testing techniques need that the location of the damage should be known prior and that the portion of the component which has to inspect should be readily available. Various methods of non-destructive testing can be used for crack diagnoses e.g., electromagnetic method, ultrasonic detection, acoustic emission. For detection of a crack by these methods, the whole component need to scan and has to check keenly. So to adopt this method, it can become ineffective, uneconomical and time consuming. The drawbacks of traditional non-destructive testing methods have motivated to develop the vibration based detection methods.

Therefore, there comes vibration based analysis method which can assist to know the dynamics of cracked components. When a crack grows in a component it leads to changes in its vibration parameters which cause in reduction of stiffness. A lot of studies using natural frequency as a damage detection tool are being carried out in the vibration based damage detection field. Number of research papers published so far have been studied and analysed. The number of different economical, robust and reliable theoretical and experimental methods has been discussed for vibration analysis.

2) LITERATURE REVIEW

Efforts have been made to present various analytical, numerical and experimental techniques developed by various researchers for vibration analysis to find the effect on different modal parameters of damaged beam.

Crack detection in beams using changes in frequencies and amplitudes of frequency response functions has been presented by [1]. The experimentation was done on aluminum beams. Two sets of aluminum beams were used for this experimental study. Each set consisted of seven beams, the first set had fixed ends, and the second set was simply supported. Cracks were initiated at seven different locations from one end to the other end (along the length of the beam) for each set, with crack depth ratios ranging from 0.1d to 0.7d (**d** is the beam depth) in intervals of 0.1, at each crack location. Measurements of the acceleration frequency responses at seven different points on each beam model were taken using a dual channel frequency analyzer. The damage detection schemes used in this study depends on the measured changes in the first three natural frequencies and the corresponding amplitudes of the measured acceleration frequency response functions. The vibration behavior of the beams is considered to be very sensitive to the crack location, crack depth and mode number. Since the frequencies and amplitudes depend on the crack depth and location, these values can be determined by the solution of a function having the solutions one order higher than the number of unknowns to be determined. In this case the numbers of unknowns are two, which are crack depth and crack location. This is the reason for the requirement of three modes. The location of accelerometers is shown in experimental setup.

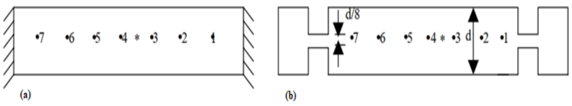

Figure 1. Location of accelerometers: (a) fixed-fixed beam; (b) simply supported beam (*, point of excitation; •, accelerometer point) [1]

A new method for the numerical modelling of the free vibration of a cantilever composite beam having multiple open and non-propagating cracks has been presented by [2]. The finite element and the component mode synthesis methods are used in this paper. The cantilever composite beam divided into several components from the crack sections. Stiffness drops due to cracks are derived from the fracture mechanics theory as the inverse of the compliance matrix calculated with the proper stress intensity factors and strain energy release rate expressions. The effects of the location and depth of the cracks, and the volume fraction and orientation of the fiber on the natural frequencies and mode shapes of the beam with transverse non-propagating open cracks, are explored. The presented method is acceptable for the vibration analysis, that by using the drop in the natural frequencies and the change in the mode shapes, the presence and nature of cracks in a structure can be detected.

[3]has developed an experimental damage identification procedure, based on structural dynamic responses and using smart sensors. It indicated that the proposed technique can be effectively and appropriately applied to full scale composite structures e.g., large fiber reinforced polymer honeycomb sandwich structures. The locations of the damage for both damage configurations (i.e., the core–faceplate debonding and core crushing, respectively) were identified properly using the curvature damage factor and damage index method, while the magnitude of the damage was evaluated through the stiffness loss. The damage detection technique proposed in this study can be implemented in inherent damage identification and health monitoring of large civil composite structures. Number of measurement points will define the maximum number of mode shapes generated. The larger number of measurement points is, the more mode shapes can be generated. However, using the lower curvature modes yields better results than using the higher modes, as at higher modes the nodal curvature points of damaged modes shifting from the original position of undamaged modes.

[4]presented a new approach for the vibration analysis of uniform and stepped cracked beams with circular cross sections. In the method, the component mode synthesis technique accompanied by the finite element method is used and a non-linear problem separated into linear substructures. These substructures are joined by using the flexibility matrices. To reveal the accuracy and effectiveness of the offered method, a number of numerical examples are given for free vibration analysis of beams with transverse non-propagating open cracks. Numerical results showed good agreement with the results of other available studies. Modal characteristics of a cracked beam can be employed in the crack recognition process, such as natural frequencies and mode shapes, of the cracked beams especially when the cracks are located at the step parts of the beams. Geometry of uniform and stepped beam is show in which **a** is the crack depth, $\mathbf{L_1}$ is the crack location and **D**, $\mathbf{D_1}$ and $\mathbf{D_2}$ are the diameters of beams respectively.

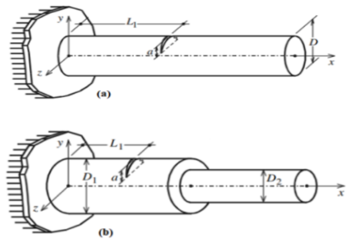

Figure 2. (a) Geometry of uniform cantilever beam with a crack; (b) Geometry of stepped cantilever beam with a crack [4]

The detection, location and sizing of transverse cracks in a composite beam, by combining damage features of Lamb wave and vibration based techniques in artificial neural network (ANN) environment, using numerical finite element model, is analyzed by [5]. It was studied that when damage features of more than one technique are combined, the damage could be identified more effectively than using damage features of each technique individually. If techniques like Lamb wave and vibration are employed individually for sizing of transverse cracks, Lamb wave technique fails when the damage zone is close to fixed boundary and vibration technique fails when the damage zone is close to free edge. By combining these two techniques the domain of damage detection is enhanced, which covers almost the whole sample. This study showed that ANN could form an efficient tool in detecting the damage location and depth.

The attempt has been made by [6] to establish a systematic method of crack detection from measurement of natural frequencies of simply supported beams. This study is an inverse problem solving technique and it validates the formulae developed for finding out the crack location and crack depth. The present work is limited to expansion and variation of natural frequencies in first two modes only. The natural frequency of beam is calculated by Modal Analysis using ANSYS whereas for experimentation purpose, Fast Fourier Transform (FFT) Analyzer is used. In this proposed method the results of Finite Element Analysis and experimental analysis is compared, which gives good agreement. The harmonic analysis predicts the amplitude of vibration under known excitation. As the amplitude of vibration can be predicted right at the design phase, it facilitates the reduction in vibrations. This method is further extended to carry out the fault analysis of shaft of blower. The fault is simulated as crack. Crack reduces the natural frequency of shaft. Natural frequency decreases with increase in severity of crack. For the same severity of crack, the frequency reduction is large for location of crack away from the support.

A method for detection of open transverse crack in a slender Euler-Bernoulli beam is presented by [7]. Crack changes the dynamic behavior of the structure and by examining this change, crack size and position can be identified. Experimental Modal Analysis was performed on cracked beams and a healthy beam by using FFT analyzer. The first three natural frequencies were considered as basic criterion for crack detection. A method for predicting the crack location and depth based on changes in the natural frequencies of the beam is also presented. To locate the crack, 3D graphs of the normalized frequency in terms of the crack depth and location are plotted. The intersection of these three contours gives crack location and crack depth. The experimental identification of crack location and crack depth is very close to the actual crack size and location on the corresponding test specimen. The experimental setup is shown.

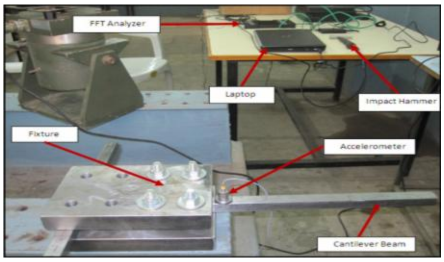

Figure 3. Experimental Setup [7]

The fault detection of multi cracked slender Euler-Bernoulli beams through the knowledge of changes in the natural frequencies and their measurements is presented by [8]. The method is based on the approach of modelling a crack by rotational spring. The spring model of crack is applied to establish the frequency equation based on the dynamic stiffness of multiple cracked beams. Theoretical expressions for beams by natural frequencies have been formulated to find out the effect of crack depths on natural frequencies and mode shapes. The positions of the cracks in relation to each other affect significantly in the case of an equal relative depth of the cracks. Any decrease in the natural frequency is largest if the cracks are near to each other; when the distance between the cracks increases, the frequencies of the beam natural vibrations also tend to the natural vibration frequencies of a system with a single crack. In the case of two cracks of different depths, the larger crack has the most significant effect on the natural vibration frequencies. These changes in mode shapes and natural frequencies will be helpful in prediction of crack location and its intensity. The geometry of beam is illustrated in which $\mathbf{a_1}$ and $\mathbf{a_2}$ are the crack depths at different locations.

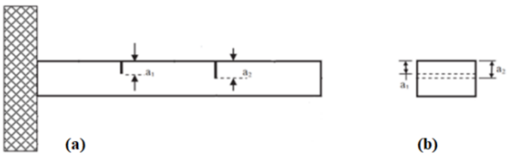

Figure 4. Geometry of beam, (a) Cantilever beam with double cracks; (b) Cross-sectional view of beam [8]

[9]have presented detection of crack in cantilever beam by using natural frequency. First two natural frequencies of the cracked beam have been obtained experimentally and used for detection of crack location and size. Crack with larger crack depth ratio (a/h) imparts greater reduction in natural frequency than that of smaller crack depth ratio. Accuracy of results can be improved with increasing the crack depth. Crack present near to the fixed end imparts greater reduction in natural frequency than that to present at away from the fixed end.

[10]explained the effect of crack on modal parameters of a cantilever beam subjected to vibration. The dynamic behavior of a whole structure is affected due to the presence of a crack as the stiffness of that structural element is altered. The cracks in the structure change the frequencies, amplitudes of free vibration and dynamic stability areas to an inevitable extent. So a diagnosis of the changes allows the experimenter to identify the cracks without aborting the system applications. The effect of an open crack on the modal parameters of the cantilever beam subjected to free vibration is analysed and the results obtained from the numerical method i.e. finite element method (FEM) and the experimental method are compared. Mode shapes and natural frequencies of the vibrating structures are susceptible to change under the influence of crack depth & crack location. The position and severity of crack can be determined by analyzing the changes. The experimental results can be verified conveniently by comparing the results obtained from cracked beam numerically. The schematic diagram of experimental setup is illustrated.

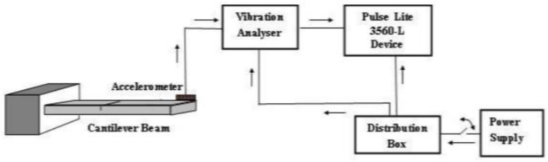

Figure 5. Schematic diagram of experimental setup [10]

[11]proposed a vibration experimental method necessary for the determination of the mechanical characteristics of the studied structure. Vibration tests are used to identify the elasticity modulus in two directions. This technique allowed to determine the two Young modulus E1, E2 by the consideration of longitudinal vibrations according to the direction x and transversal vibration according to the directions y. The strategy is applied to composite material glass / polyester. Experimental results made on a specimen in free vibration showed the efficiency of this method. Obtained results were validated by a comparison to results stemming from static tests.

A new technique of Fractal Dimension Analysis has been employed by [12] for identification of crack in rotating cantilever beam. FD analysis can be used for detection of location and depth of transverse open multiple cracks from the deformation profiles of the rotating mode shapes. The inaccuracy in input signal may produce the noise during data processing leading to misleading or false reporting of damage in beam. It is shown that higher resolution may be employed as possible measures for noise reduction. In some cases, it is better to apply FD on more than one mode for meaningful detection of multiple cracks in a rotating beam.

Damage detection in cracked cantilever beams using experimental and wavelet analysis is studied by [13]. Crack changes the stiffness of the structural element which affects the dynamic behavior of the whole structure. The crack is modeled as a rotational spring and equation for non-dimensional spring stiffness is developed. By evaluating first three natural frequencies using vibration measurements, curves of crack equivalent stiffness are plotted and the intersection of the three curves indicates the crack location and size. Experiments are performed on cantilever beams with single crack (each at different locations and having varying sizes) using FFT set up to obtain natural frequencies which are compared with those obtained by ANSYS package. The time-amplitude data obtained is further used in the wavelet analysis to obtain time-frequency data. This data is important to find out the effect of small crack parameters on the dynamic properties of the system. This method provides effective non-destructive detection technique by using the Continuous Wavelet Technique as the signal analysis tool and it can be extended for damage detection of complex structures. The crack by rotational spring is represented here.

Figure 6. Representation of rotational spring

[14]has been proposed the new concepts of numerical and experimental verification of a method for prognosis of inclined edge crack in cantilever beam based on synthesis of mode shapes. The failure rate increases as the crack growth increases due to the structure becomes weaker. Therefore, crack identification and type of crack is a key issue. The existence of cracks influence the performance of structure as well as the vibration parameters such as; natural frequencies, mode shapes, stiffness and modal damping. In this paper attempts has been made to model an inclined open edge crack in a cantilever beam and analyze the model using a finite element method, as well as experimental approach. A finite element model has been developed to analyze the variation of modal parameters according to the crack location, size and inclination in the cantilever beam having inclined edge crack. The natural frequency of the cracked beam decreases with the increase of crack depth, and increases with the increase of crack location. Determination of the crack location is more precise than the determination of the crack size. In this study some of the limitations are also defined that the crack inclination angles are valid up to 45 ° for examining the transverse vibration. The crack location in the cantilever beam can be projected for crack size of more than 10% of depth. The error increases as the crack position from the fixed end or the crack inclination angle increases. The maximum error is predicted up to 5% of all the cases calculated. The inclined crack in cantilever beam is represented below where **a** is the depth and **Θ** is the inclination of crack.

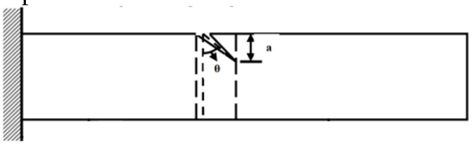

Figure 7. Representation of inclined crack in cantilever beam [14]

[15]establish a systematic method of prediction of crack characteristics from measurement of natural frequencies. In this paper Finite Element Method is used to determine the natural frequency of beam whereas the experimentation is performed using Fast Fourier Transform analyzer. In experimentation, cantilever hollow beam having circular cross section, crack is considered. This formulation can be extended for various boundary conditions as well as varying cross sectional areas. A crack in a structural member introduces local flexibility that would affect vibration response of the structure. A crack causes a reduction in stiffness and natural frequencies, an increase in the damping of the structure and deviation in the mode shape. Natural frequency of the cracked beam decreases as the crack depth increases and the crack location is constant. Natural frequency of the cracked beam increases as the crack location increases from fixed end and the crack depth is constant. Therefore it is possible to predict the crack depth and crack location by measuring changes in the vibration parameters. These properties may be used to detect the existence of a crack together with its location and depth in the structural member. The study showed, small crack depth ratios had a small effect on the sensitivity of the natural frequencies and the changes became more significant as the crack grew deeper. The effect of crack is more prominent when the cracks are near to the fixed end than at the free end.

[16]presented the validation of vibration analysis of rotating shaft with longitudinal crack. When shafts are rotating in different type of conditions serious defects can appear, but these are much suspected of fatigue cracks because of the rapidly fluctuating nature of bending stresses. Because of manufacturing flaws or cyclic loading, cracks frequently appear in rotating shaft. The tensile stress concentration resulting from shear slip causes the new cracks that propagate away from the pre-existing fault. A defect on shaft is diagnosed by vibration analysis method because when shaft rotates, due to defect the vibrational response of the rotating shaft changes. Amplitude of vibration depends on crack depth; it is different for different crack depth. As depth of crack increases, amplitude of vibration also increases. By using the regression equation, unknown depth at known frequency and speed can be calculated. Because of crack, center of gravity shifted to lower side of original center of gravity. As depth of crack increases, center of gravity shifted to lower side of the original center of gravity.

Crack Detection in Cantilever Shaft Beam Using Natural Frequency has been presented by [17]. Crack development in a beam is such that it leads to sudden failure of a system without any prior indication or warning. Different characteristics of vibration can be used to detect crack in beams. In this paper the method of finite element analysis of beam using ANSYS is done and first three natural frequencies of transverse mode are extracted. It is observed that the natural frequency of all three transverse modes of vibrations decreases with increase in depth of the crack as the presence of crack in the structural member introduces local flexibilities. The identified crack locations and sizes are in good agreement with the actual ones. Based on behavior of healthy and cracked beam, it shows that natural frequency of transverse vibrations could be used to detect crack in cantilever shaft beam**.**

A method of detection of cracks in a cantilever beam using signal processing and strain energy based model is presented by [18]. Cracks are the most common damage that initiates a breakdown phase. In this study, a vibration based non-destructive technique is presented to detect one or multiple edge cracks in beam like structures. This model is based on changes in mode shapes and natural frequencies that provide accuracy in results. The crack location is identified using mode shapes of damaged beam wherein an appropriate signal processing technique is implemented by using which the noise in the signal can be reduced. Along with this, the crack severity is also determined using a strain energy based mathematical model. In this study the model presented is capable of detecting an arbitrary number of cracks in cantilever or simply supported beams. The flow chart for detection of crack is illustrated.

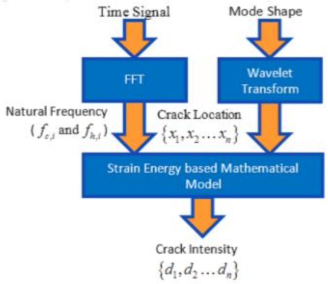

Figure 8. Flow chart of crack detection method [18]

3) MATERIALS AND METHODS

The analysis of vibration for the materials such as Mild steel, aluminum, Concrete etc. is carried by researchers by their presented methods like Finite element analysis, Theoretical analysis, Experimental analysis, Artificial Neural Network analysis, Fractal Dimension analysis and Wavelet analysis etc. The analysis of vibration for the materials such as Glass/polyester, E-glass fibre epoxy resin, fibre glass etc. is carried by researchers by their presented methods like Compliance matrix analysis, Numerical analysis, Numerical modal analysis and Experimental analysis etc.

4) DISCUSSION

Various researchers use non-destructive techniques (NDT) based on vibration analysis for identification of cracks in the machine and structural components. The method of damage detection totally depends on changes in dynamic properties of the component. This method can be used to gather the information. Researchers did a lot of work to find the relationship of vibration parameters such as crack depth, crack location and crack inclination with natural frequencies, amplitudes and mode shapes. Researchers explained the behavior of all the vibration parameters in very precise manner. Physical properties and shape of beam, crack location, crack depth, crack inclination, orientation and size of crack, number of cracks and boundary conditions influence seriously on the dynamic response of structures. For analysis and diagnosis of crack detection in a beam structure, researchers approach towards various techniques like artificial neural network, genetic algorithm, continuous wavelet analysis and fractal dimensional analysis. Researchers also discussed the knowledge and concepts of fracture mechanics theory, stress intensity factor and strain energy release rate.

5) CONCLUSION

It is concluded that natural frequencies, amplitudes and mode shapes are the vital parameters to detect the crack depth and crack location in the beam structure. Natural frequency of the cracked beam is inversely proportional to the crack depth when crack location is constant and is directly proportional to the crack location from clamped end when crack depth is constant. Amplitude of vibration increases when crack depth increases. The effect on the sensitivity becomes more significant with the growth of crack. The effect of crack is also more prominent when the cracks are near to the fixed end than at free end. Researchers are presently focusing on various methods for analyses and diagnosis of crack detection in a beam structure like artificial neural network, genetic algorithm and continuous wavelet analysis and fractal dimensional analysis.

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