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A Review on Structural Health Monitoring of Beam or Shaft with Oriented Crack

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Abstract— Dynamic behaviour of machine components is of crucial importance for aerospace, mechanical, civil engineering. Mechanical members like beams and columns are widely used in in high speed machineries or aircraft structures may contains some imperfections such as cracks. These cracks may develop from flaws due the cyclic loads, mechanical vibrations, aerodynamic loads, etc. These cracks may lead to catastrophic failure if undetected therefore it is necessary to identify location of crack, number of cracks their orientation and intensity to prevent damage due to these cracks.

Keywords- *Structural Health Monitoring,crack depth, crack position,Number of cracks.*

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1. Introduction

Dynamic behaviour of machine components is of crucial importance for aerospace, mechanical, civil engineering. Mechanical members like beams and columns are widely used in in high speed machineries or aircraft structures may contains some imperfections such as cracks. These cracks may develop from flaws due the cyclic loads, mechanical vibrations, aerodynamic loads, etc. These cracks may lead to catastrophic failure if undetected therefore it is necessary to identify location of crack, number of cracks their orientation and intensity to prevent damage due to these cracks.

1.1 Factors Affecting Dynamic Characteristics of Cracked Structures:

Usually the physical dimensions, boundary conditions, the material properties of the structure have important role in the determination of its dynamic response. Their vibrations cause changes in dynamic characteristics of structures. In addition, the crack in structures modifies its dynamic behavior. The following factors of the crack widely influence the dynamic response of the structure.

a) The crack position,
b) The crack depth,
c) The crack orientation,
d) The number of cracks.

1.2 Methods of Structural Health Monitoring (SHM):

a) Signal-based identification

i) Frequency measurements-based identification:

When there is a crack in a beam or shaft, then stiffness is reduced and consequently the eigen frequencies of the system are decreased. Measuring these Variations can help to identify a crack.

ii) Eigen mode or response based identification:

The eigen modes also get modified in cracked vibrating structures. In this case vibration measurements at different points could be used for crack identification. In order to identify the location and the depth of a crack in a beam

b) Identification based on external excitation

Nonlinear dynamic behavior caused by presence of breathing crack in a rotating shaft This behavior could be observed by measuring the vibration amplitude as a function of the angular velocity, when the rotating machine is started or shut-down. It is of great interest to check crack identification when the shaft operates at constant angular velocity.

c) Combined signal and model-based identification

A combined signal and model-based approach for crack identification could improve the accuracy of the results. In this technique few vibration data are measured and full state crack is estimated through modal expansion and systematic crack identification is simulated.

d) Coupling based Identification

When crack exists on the shaft, then coupling between different modes of vibration exists. Coupling due to crack introduces new discrete characteristics in vibration spectrum that can be only ascribed by crack. Coupling identification can be done for longitudinal, lateral, bending and torsional vibration.

e) Wavelet transforms:

Wavelets provide timescale frequency response. In wavelet transform wavelet break down a signal in series of functions (wavelets) that allows the identification of local features (crack) from the scale and position of the wavelet.

f) Nondestructive techniques:

For surface minor crack there are no significant changes in natural frequencies so become difficult by monitoring method for such NDT techniques can be used effectively. Visual inspection is conducted with unaided eye. The use of impact sensitive coatings, liquid penetrants and magnetic particles are some of the techniques developed to improve the sensitivity and resolution of the inspection. Optical methods include photo elasticity, holography and Moiré methods that identify material changes based on interference fringe patterns, diffraction properties, variations in transmission intensities, and phase changes. Optical fibre sensors and more specifically Fibre Bragg Grating (FBG) sensors are commonly used in health monitoring of structures, offering strain and temperature readings. Stereography is a different optical method that uses speckle shearing interferometers to measure displacement gradients at the surface of a structure. Eddy current test is widely used electromagnetic methods for inspecting for structures/surface/ near surface crack, delaminating, corrosion and other structural defects. It is used to discover flaws in electrically conducting materials by comparing the measured impedance with calibrated defect dimensions. Ultrasonic inspection uses concentrated high energy acoustic waves generated using a pulsar receiver and transducer in frequency ranges typically between 1 and 50 MHz to discover flaw existence and flaw dimensions, determine geometric dimensions and characterize material properties. A laser technique is sensitive and also offers the flexibility of testing structures with complex curvatures as the probe doesn`t has to be perpendicular to the surface. However, laser generated signals are usually of lower amplitude than achieved by piezoelectric transducers. The need of 2D scanning and the high cost of the method compel significant limitation to its extent level use. Acoustic Emissions (AE) generated by stress waves produced by growth of defects in solids. While the majority methods detect geometrical discontinuities AE detects movement like breakage, pull-out, matrix cracking and delamination in laminated composite plates. Radiographic transmission techniques are found to be very promising for quality control of filament wound carbon fibre reinforced plastic tubes. Radiographic inspection favors particular interest in industrial applications for isotropic material. The use of Lamb waves i.e. elastic waves that are generated in a solid plate with free boundaries and also known as plate waves. Their motion can be symmetrical or unsymmetrical with respect to neutral axis of the plate. They describe elastic perturbations that are parallel to the direction of propagation and perpendicular to the plane of plate. Various methods are available in order to generate and receive Lamb wave. These waves are used to for crack detection.

2. Literature Review

M. Karthikeya et al. [3] studied free and forced vibration for cracked beam and developed formulation for crack identification using Timoshenko beam model. This model incorporates transverse loading and damping effect. They developed crack location and sizing algorithm for estimation of bounded flexibility coefficients. The location and crack have been found from measurement of the force response measurement and fundamental natural frequency. This procedure utilized FEM, hence it is having flexibility for using for general case of loadings and constraints.

A. S. Sekhar[1] has reviewed state of art research identification of multiple cracks and their effects in vibration structure such as beams, rotors and pipes. There are different issues involved in multicrack such as orientation of crack with respect to each other change in mode shape and its complexity. Different identification methods such as model based methods, eigen frequencies, wavelets and soft computing and condition monitoring methods are used. In this study review of different multiple crack modeling methods such as transfer matrix method, Rayleigh beam theory, principle of virtual work, bond graph method and Finite Element Analysis (FEA) have been done. Paper discussed the compliance matrix method considering crack depth and angle of rotation for limited number of variables. Author proposed future study with increased number of variables for the identification of multiple cracks using wavelet transforms and Hilbert-Huang transform.

Chris A. Papadopoulos [4] used Stain Energy Release Rate along with linear fracture mechanics to calculate compliance due to crack in a circular cross section of rotating shaft. It was suggested to calculate compliance that causes surface crack in rotating shaft. This model shows reduction in stiffness at the crack location. Further, it was proposed in the future work to investigate the effect of cracks on thermal phenomenon and increase of hysteretic damping for breathing cracks filled with fluid.

A. Deraemaeker et al. [9] studied the problem of damage detection using only vibration measurements outputs under changing environmental conditions. Two kinds of features extracted from the measurements of eigen properties of the structure using an automated stochastic subspace identification method and uses indicators computed on the fourier transform of modal filters. The effects on environment are detected using factor analysis and damage is detected using statistical process control with multivariate Shewhart-T control charts.

K. Diamanti et al. [10] this paper is a review of currently used inspection methods. Authers presented some examples where Lamb wave based scanning techniques have been used to identify internal impairment in multi-layered composite structures which are commonly used in aircraft structures.

F.P. Kopsaftopoulos et al. [11] proposed vibration based statistical time series method which is capable of effective damage detection, precise localization and magnitude estimation within an integrated stochastic frame work. The method constitutes an important overview of the recently introduced functional model based technique in that it permits for precise damage localization over well-defined continuous topologies (instead of predefined specific locations) and magnitude estimation. The method is authenticated and its effectiveness is experimentally assessed via application to damage detection, precise localization and magnitude estimation on a prototype.

Mostafa Attar [5] illustrates an analytical approach to investigate natural frequencies and mode shape of a stepped beam with an arbitrary number of transverse crack & general form of boundary conditions. He proposed Direct Problem Formulation based on transfer matrix method to solve inverse problem of determining location and depth of multiple crack for stepped beams. Using Euler-Bernoulli beam theory the stepped cracked beam is formed as an assembly of uniform sub segments connected by mass less rotational spring representing local flexibility induced by non-propagating edge cracks. The simple transfer matrix which is a function of frequency, location and size of the crack, boundary conditions, geometrical and physical properties is formulated. In this method he used to form 2N equations in order to identify N cracks exploiting 2N measured natural frequencies of the damaged beam. The result obtained by this method is in good agreement with the result obtained by FEA and experimental methods.

Yu Liu et al. [7] described a quantitative identification method for radial cracks based on the GCW and CWT. The Gabor wavelet is used to extract an appropriate frequency component of a wave mode for evaluation of crack from the highly dispersive and multi- mode waves. Effectiveness of the GCW components in crack detection is compared by considering different frequencies of GCW components. Numerical simulations as well as experiments are conducted on a Plexiglas annulus with a radial crack. The solutions show that the crack location is determined with high precision using the CWT to extract an appropriate GCW component and the first mode corresponding to the Rayleigh surface wave is more reliable in crack detection than other modes under investigation. Thus a wave component which simultaneously has adequate amplitude and good sensitivity is proven to be effective for examination of crack.

Z. A. Jassim et al. [2] has reviewed vibration analysis for a damage occurrence of a cantilever beam. Objective of their review was to quantify and determine the extent of damage magnitude of a cantilever beam. For analytical study FEA software is used. The result obtained by monitoring change in natural frequency is feasible and viable tool to indicate the damage occurrence and magnitude for cracks of small depth. Mode shapes indicated good sensitivity to detect damage magnitude for all crack parameters. Authors reviewed that Frequency Reduction Index (FRI) and Modal Assurance Criteria (MAC) are found as feasible tool to find magnitude of damage in beam structures while Coordinate Modal Assurance Criteria (COMAC) and Curvature Change Index (CCI) could be feasible tools for location of crack for tested beams.

Zbigniew Kulesza and Jerzy T. Sawicki[6] in their paper introduces a new model of the propagating shaft crack. The approach is based on Rigid Finite Element (RFE) method. It has proven its effectiveness in the dynamical analysis of various complicated machines and structures. Crack is modeled using several dozen spring-damping elements (SDEs), connecting the faces of the cracked segment of the shaft. By controlling the exact behavior of individual SDEs, the breathing mechanism and the crack propagation process can be introduced. In order to accomplish this Stress Intensity Factors (SIFs) all along the crack edge are designed using the novel approach based on the modified Virtual Crack Closure Technique (VCCT). Crack propagation rate is calculated from the Paris law, based on the SIF values. The crack edge is shifted by a small increment, if the number of load cycles is greater than the constantly updated threshold number. The approach is stated with numerical results demonstrating the changes in the rotor vibration response and in the crack shape and it also explain issues about the breathing mechanism due to the propagating shaft crack. The rising amplitude of the 2X harmonic component is renowned as an evident propagating crack signature. The algebraic results correspond well with the data reported in the literature. By comparing the vibration responses obtained experimentally and numerically RFE model of the rotor is validated. Therefore, this approach may be utilized for a more dependable dynamic analysis of the rotating shafts having the potential to understanding propagating transverse cracks.

Mohsen Mehrjoo et al. [8] in their paper describes, a crack identification approach is used for detecting crack depth and their location in beam like structures. For this purpose, a new beam element with a transverse edge crack, in arbitrary position of beam component with any depth, is developed. The crack is not substantially modeled in the element but its effect on the local flexibility of the element is considered by the amendment of the element stiffness as a function of crack depth and their position. The development is based on a simplification of model where each crack is replaced by a corresponding linear rotational spring connecting two adjacent parts. The components of the stiffness matrix of the cracked component are derived using the conjugate beam concept and Betti's theorem and finally noted in closed-form expressions. The proposed beam component is efficiently employed for solving forward problem (i.e. to get accurate natural frequencies of beams-like structures knowing the cracks' characteristics). To validate the proposed component, results obtained by a new component are compared with two-dimensional (2D) FEA results as well as experimental measurements. Moreover, by knowing the natural frequencies, an inverse problem is recognized in which the cracks depth and their location are identified. In the inverse approach, an optimization problem based on the new beam component and Genetic Algorithms (GAs) is considered and solved to search the solution. The proposed approach is verified through numerous cases on cracked beams with different damage scenarios. It is shown that the existing algorithm is capable to identify various crack configurations in a cracked beam.

D. N. Thatoi et al. [12] have taken a review on various Artificial Intelligence techniques mainly consisting of Fuzzy Interference Technique (FIT), Neural network (NN), Genetic Algorithm (GA), Hybrid models and other optimization algorithms for determining the depth of cracks and their location, size in different structures.

CONCLUSION

Cracks often develop in machine parts and structures due to various types of service load. The loads can be tensile and or compressive due to axial and bending loads and shear loads due to torsional moments. Under the action of these loads in combination with each other, cracks can develop and propogate on and under surface in various orientation. Transverse cracks have received a lot of attention since the beginning of SHM studies. However, cracks in various orientations have received relatively less attention. It is therefore proposed to make some attempts in modeling and analysis of beams and shafts with crack in various orientations. The cracks can be single or multiple; open or breathing in nature. The study will further involve finding the effect of various parameters of cracks on static or dynamic behavior of the structure.

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