Developing a Novel Approach for Crack detection through frequency analysis

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Abstract:

Cyclic loading results in the formation of fatigue cracks in mechanical components. This if not detected and remedied will result in the failure of that component.

The aim of the project is to detect and locate cracks in steel plates using natural frequency and to predict their direction of propagation using the same.

Observation of changes in the natural frequencies due to presence of crack is the most popular method used for this purpose. An analytical model will be formulated. Natural frequencies from FEM analysis and experimental setup will be obtained. These theoretical and experimental results will be compared for validation.

Keyword: Crack, frequency,

1. Introduction

Components operating under high magnitude fluctuating loads are subjected to high amounts of fluctuating stresses. This cyclic loading results in the formation of fatigue cracks. Defects in manufacturing and environmental conditions (fluctuating temperatures, pressure, etc.) also contribute to the development of cracks in the structure. Formation of fatigue cracks results in the decrease in its stiffness and an overall increase in the local flexibility of the region surrounding the crack. Thus, the static and dynamic characteristics of the component are affected. This will further lead to deterioration of the component and its eventual failure. Thus, formation of fatigue cracks in components is one of the main factors influencing its failure.

It is possible to detect cracks through visual inspection to a certain extent. However, it is not practically possible to periodically check each and every machine component as several parts are rather inaccessible. Hence, it would result in an increase in the labour cost, time consumed and also low accuracy when human error is factored in. Also, it is not humanly possible to locate microscopic cracks or cracks within the structure of a component. If not detected and remedied immediately, these cracks will further propagate leading to failure of the component and probable damage to property as well as loss of human life. Hence, it is of utmost importance to detect and accurately locate the smallest of defects within the structure of the component.

Other non-destructive testing methods such as Ultrasound Testing, Electromagnetic Testing, etc. used for this purpose, while being accurate, are expensive and also complex in nature.

It has been found that when a cracked component is subjected to vibration, it affects its modal and structural characteristics i.e. the characteristics of a cracked plate differ from the characteristics of an intact plate. Modal characteristics comprise of natural frequencies and mode shapes whereas structural characteristics comprise of stiffness, mass of the component and flexibility. It is possible to locate cracks accurately by observing and comparing the changes in the above-mentioned characteristics.

In this project, we are studying the behaviour of a cracked metal plate when it is subjected to vibrations. Natural frequency of vibrating plate varies with the physical parameters of the crack such as depth, width and length. As a result, we will be comparing the behaviour of separate plates, having cracks of different dimensions and locations. The plates will be excited on an experimental setup designed and fabricated by us. The natural frequency of vibration of the plates will be measured to determine the location of cracks within them.

2. Literature survey

The research pertaining to study of cracks and the effect of vibration on the modal properties of the component in presence of crack has garnered much attention. Different techniques have been proposed to study the effects of vibrations on cracked shafts and plates. The most popular method has been finite element method to extract the change in natural frequencies. Nandwana and Maiti [1] has presented a method to examine the crack location using rotational spring method by natural frequencies in a stepped cantilever beam. First three natural frequencies were used to determine the location of crack on the beam with respect to the length of the beam. Patil and Maiti [3] combined rotational spring and TMM method to represent a crack to find location and size of multiple transverse cracks in a shaft. Chinchalkar [2] presented a numerical technique for estimating the crack location in a slender beam of variable cross section. Petrova [15] presented a comparative study for crack detection in simply supported beam between three frequency method and two frequency method. The three-frequency method is found out to be more accurate. Kin and Zahariev [6] employed Impulse Resonant Acoustic Spectroscopy method to observe the changes in natural frequency due to crack propagation. Residual fatigue life was also predicted with the help of propagation history. Israr et al [8] formulated a novel approach for analytical modelling of cracked rectangular plate subjected to transverse loading at different points with unique boundary condition sets. Galerkin's method is applied to reformulate the governing equation of the cracked plate into time dependent modal coordinates. Nonlinearity is introduced by appropriate formulations introduced by applying Berger's method. Tsujie et al [10] developed a meshfree transverse crack propagation model using boundary node method to analyse transverse crack propagation by changing the mean stress. Formulating meshfree model resulted in reduced computational time. Beigi et al [14] studied the influence of thickness of thin plates on natural frequencies for cracked and healthy plates. Chouiyakh et al [19] used Hilbert's transform to develop damage detection procedure based on dynamic response of the plate. Among other methods, Finite element method is most widely used for analysing the response of vibration through modal analysis. Gori et al [17] studied the effect of transverse crack on the natural frequencies of the cracked plate using FEM. Pardeshi and Deore [18] used FEM modal analysis to study the vibration characteristics of propeller shaft and detect the location of the crack. Pramod et al [16] investigated circumferential cracks by analysing the variation in natural frequencies of annular plate using FEM. Alfano and Pagnotta [5] used FEA to investigate the dynamic behaviour of trough crack on free twin isotropic square plates originating from one edge. Other parameters of crack such as damage severity, phase measurement, stress intensity factor has also been evaluated through various experimental methods to validate the FEM results [11, 12, 13]. Bachene et al [7] used Extended FEM method to study the trends of changes in natural frequency due to the presence of vibrations. Natarajan et al [9] evaluated the free flexural vibrations in functionally graded plates using X-FEM method. The trends in natural frequencies were studied similar to [10]. The study observed through a 3D graph that the frequency change distribution is symmetrical around the plate with the lowest frequency at its centre whereas the highest at the edges. Cha et al [20] presented a method to locate the trajectory of crack using image processing through deep learning. Overall, changes in natural frequency is one of the driving parameters in detection of cracks without visual inspection. The lack of location of cracks in 2D plane of a rectangular plate incites a potential domain of research. This paper is based on location of crack on rectangular plates based on the method from [1] which is extended to two directions, with the help of observations from [9,15,17]. The objectives of the project are:

1. To detect crack location in rectangular steel plates with the help of changes in modal parameters such as natural frequencies.
2. To predict the direction of propagation of crack with the help of Convolutional Neural Network classifier.

3. Methodology

Failure of a component can occur in many ways. However, in most components, it is found that fatigue cracks, which develop due to constantly fluctuating or cyclic loads over a long period of time, are one of most recurring reasons for the failure. Thus, detecting and locating such fatigue cracks are of utmost importance and hence, this was chosen as our area of research. Previous research done on the topic was compiled and distributed among the members. Each research paper was studied and summarised carefully and the information was arranged in a tabular form using MS Excel. By studying the contents of the Excel sheet, certain unexplored domains employing unused methods were identified, thus opening the opportunity to conduct further research in those areas. Problem statement of the project was defined using those areas to conduct research on the topic. Literature survey was formulated using the Excel sheet and objectives pertaining to the research were established. Drawing inspiration from previous research, potential methodologies which could be built-on were identified to aid in execution of the project. Based on the set objectives, resources that would be required were listed.

The excitor was designed and tested using Solidworks and ANSYS respectively. The motor cage houses the motor, which is bolted on top of two C-Channel bars, so that the structure can effectively bear the load exerted by the motor. Static structural analysis was done on the motor cage to determine the deformation caused due to the weight of the motor for verification of the modelling. The setup was designed with an aim of maximizing the transmission of vibrations generated by the motor to the test plate. The plate housing, which is a set of 4 L shaped plates joined to each other through a nut bolt assembly was designed to hold the plates, while also allowing them to vibrate freely during the experiment. This plate housing is mounted on the motor cage on springs so that sufficient amount of vibration is transmitted to the plate housing in order to excite the plate. Since accuracy is key in the experiment, the components of the setup were fabricated on a CNC milling machine. In order to fit the plate into the plate housing, each L-plate was given a V-groove, which was achieved using a shaping machine. Individual aluminium pipes were brazed together to form the cage. Based on this setup, a mathematical model can be formulated which will have the frequencies of the vibrating plate as the input. The frequencies will be extracted from the setup using a vibrometer. Using the frequencies as input, we can compute the location of the crack in the plate by solving the model. The output can be compared to the actual shape and location of the crack to verify our results and test the accuracy of the experiment. A suitable conclusion based on these findings will be derived.

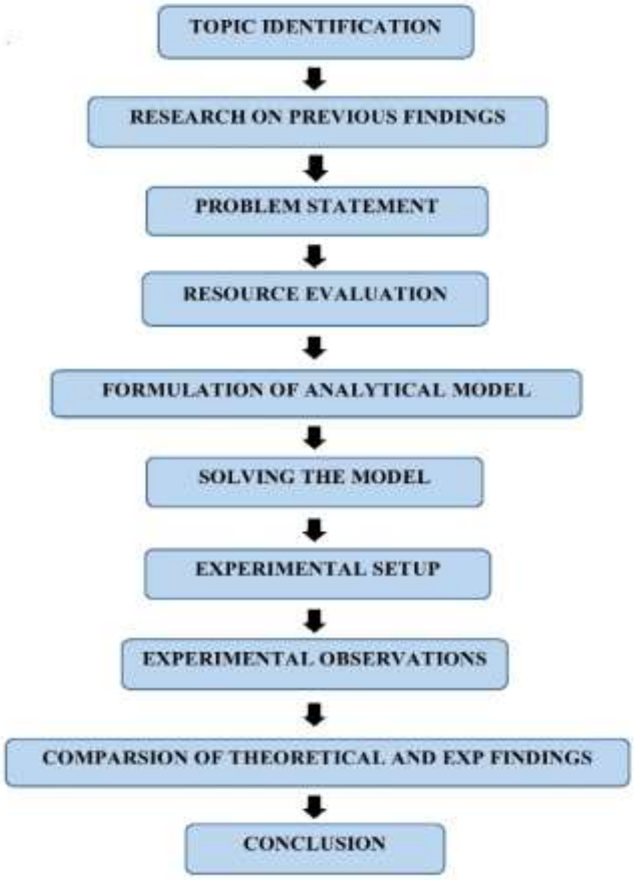

Figure 1. Methodology

4. Design and Analysis

The setup was designed on Solidworks and analysis was performed using Ansys.

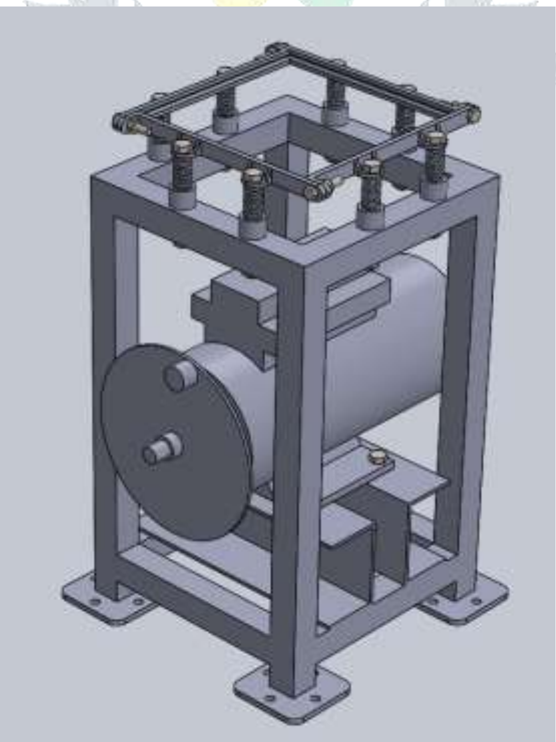

Fig (2): Excitor Assembly

Analysis was done in the following manner:

1. Mesh

The motor cage was discretized to perform finite element analysis on the C Channel bars in order to analyse the maximum deflection caused due to the weight of the motor assembly.

Fig (3): Mesh

2. Boundary conditions

Fixed supports were provided at the bottom since the setup is bolted down through 16 holes.

A force of 100N is applied over the face of C-Channel bars bearing the motor surface. The motor weighs 8kg (78.48N). 100N is considered as the force to be applied considering the margin of safe operation.

3. Results

Maximum deformation is obtained at the edge of C section since it acts as a cantilever beam. However, the deformation is 0.09mm at the maximum point. Therefore this setup can be considered as safe and the experiment can be performed safely. The von mises equivalent stress has a max value of 2.48 N/mm^2 at the supporting member of C channel. Therefore, overall design is considered to be safe to proceed.

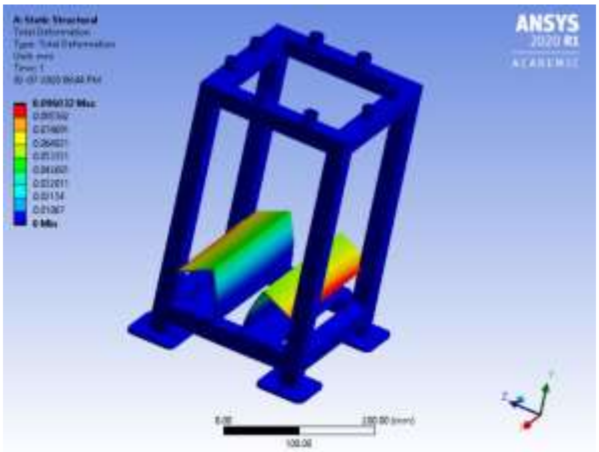

Fig (4): Deformation result

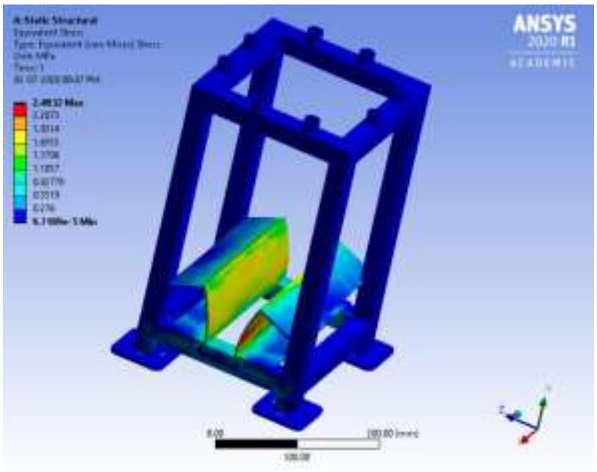

Fig (5): Von mises stress result

The magnitude of deformation seen in Ansys have been amplified by the software in order to correctly display the result of stresses applied

5. Experimental Setup

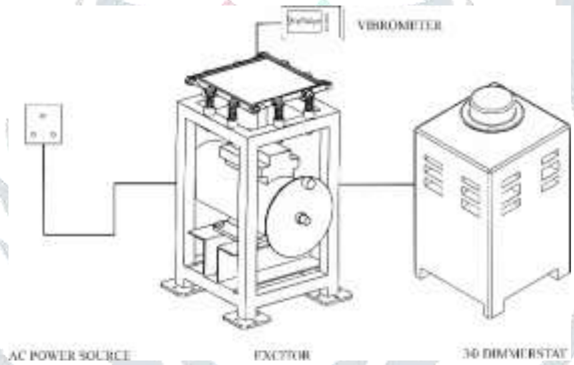

Fig (6): Experimental setup

The experimental setup consists of the following:

1) Motor
2) Motor Cage
3) Plate Housing
4) Vibrometer

1) Motor: A 3-phase AC motor having an output of 0.5hp is used as the source of vibration in order to excite the plate. An eccentric load is also attached to a disc mounted on the output shaft on the motor. This is done in order to increase the vibrations produced and thus ensuring that enough vibrations are transmitted to the plate through the structure.

A dimmerstat is connected to the motor using which the speed of the motor can be regulated.

2) **Motor Cage:** This serves as a housing for the electric motor and is made of 1In×1In Aluminium (6063 T6) box pipes. The motor is mounted on top of two C- channel bars and additional plates are attached to the bottom of the pipes so that the cage can be fixed on a surface through bolting.

3) **Plate Housing:** This houses the plates (cracked as well as healthy) to be tested. An assembly of 4 individual L-shaped machined Aluminium (6063 T6) bars joined together using nuts and bolts forms the plate housing. The L-plates have a 90° V-Groove on the inner portion in order to make sure that the plate is constrained thoroughly.
   This assembly is mounted on top of the motor cage on springs supported by a nut bolt assembly and housed within the cage so that the transmission of vibrations through the structure is possible.

4) **Vibrometer:** The value of the frequency at which the plates are vibrating are measured using a vibrometer.

6. Proposed Experiment

The motor, when started will generate a high amount of vibrations which will be transmitted through the whole structure. It is important to nullify these vibrations through the provision of a medium through which it can be dissipated. Hence, the setup will be bolted to a concrete slab which will hold it firmly. The motor itself will be mounted in the cage and will be connected to the dimmerstat and AC supply.

Using a cutting tool such as an angle grinder or a hacksaw, a slit, which will be representing the crack will be created. The test plate will be mounted on the L plate assembly. Through the dimmerstat, the speed of the motor will be varied to get desired vibrations to extract the frequency values.

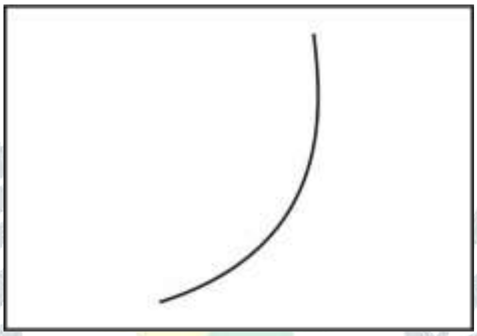

Fig (7): Plate with a crack

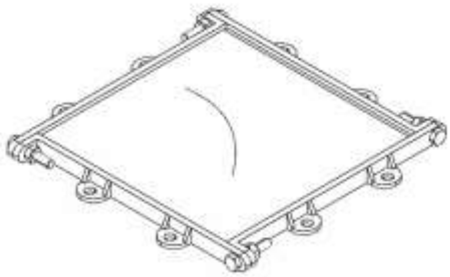

Fig (8): Test plate assembled in L-plate housing

Vibration from the motor will excite the plates. Using a vibrometer, the first three natural frequencies (ω_1, ω_2, ω_3) will be extracted. These frequencies will be fed to the mathematical model.

The plate will be divided into several strips parallel to each other uniformly. The frequency of each strip will be extracted and fed to the model as input.

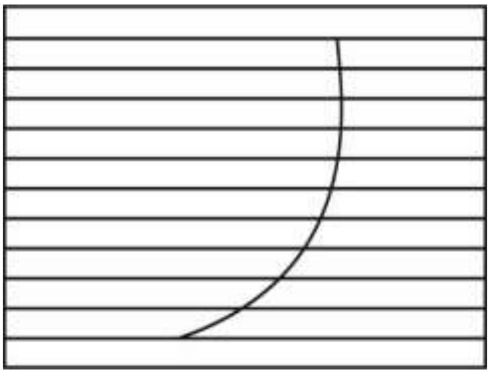

Fig (9): Test plate divided in strips

The Mathematical model will consist of a function which will help to plot the graph between stiffness of plate with respect to frequency, in terms of a variable β. β is the ratio of the length of location of crack to the total length of the surface. The intersection of the 3 curves which represent the first 3 frequencies extracted, will give a particular value of β, which will give the location of crack for that particular strip. The location of first strip will be stored in a variable x_1. Repeating this procedure for n number of strips will result in accumulation of position values from x_1, x_2….x_n.

$$\beta = \frac{x}{L}$$

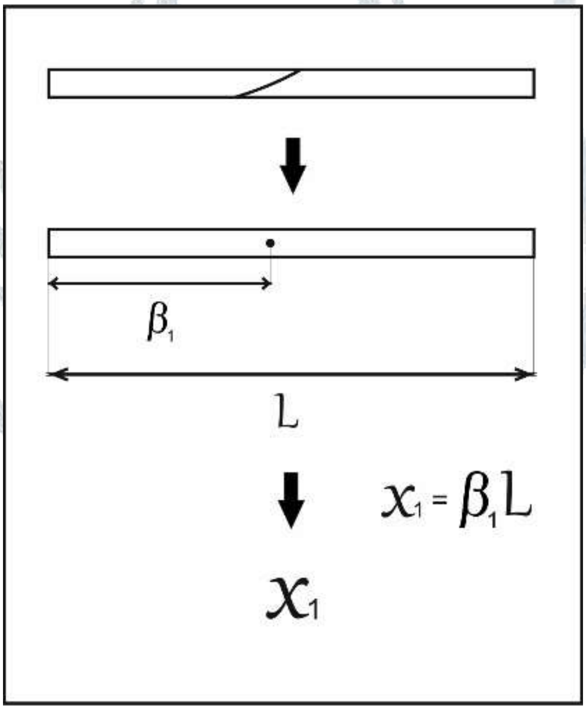

Fig (10): Obtaining x_i from a particular strip through mathematical model

Plotting x values v/s the height of the plate will yield the plot of the crack traced from the output.

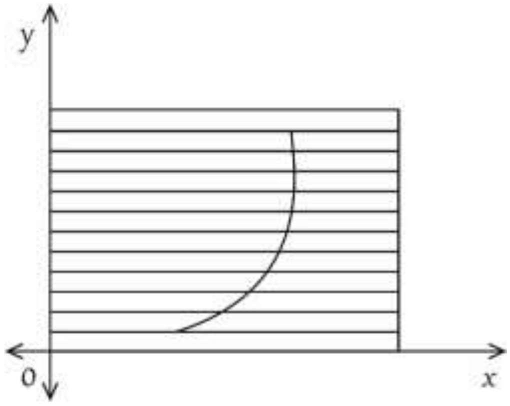

Fig (11): Graph with plate placed at origin

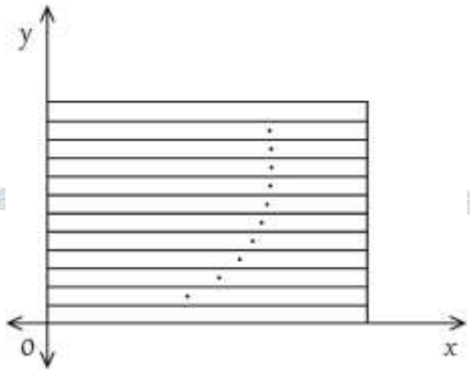

Fig (12): x_i values plotted for each strip

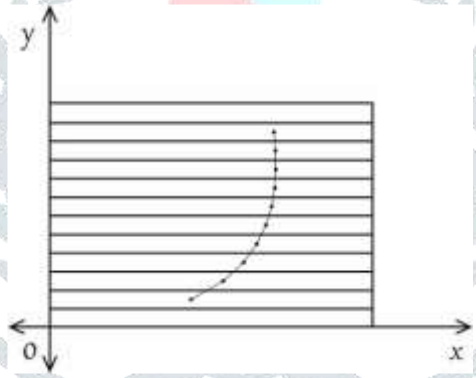

Fig (13): Connecting the points obtained in the model

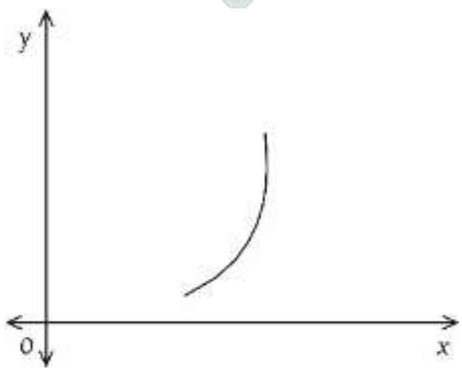

Fig (14): Plot of the crack obtained through experiment

The accuracy of the trace is directly proportional to the level of discretization of plates into strips. However, an overly refined discretization will result in difficulty in obtaining the frequency of each strip from the experimental setup.

7. Discussion

Keeping in mind the aim of the experiment, which involves the detection and finding the location of cracks present in metal plates, this methodology makes use of natural frequencies obtained by the vibration of cracked metal plates due to variation in stiffness of the plates. Theoretically, the graphical plot obtained which represents the crack shows minimal variation when compared to the actual crack present in the plate. But practically, the value of β_i obtained for a particular strip may show a slight error, depending on the geometry of the crack present in the strip. However, with high discretization of the plate more accurately sound results can be obtained. Also, even in the presence of a less discretized plate, a rough trace of the crack can be plotted.

With a greater number of iterations of test plates with varying crack geometry, a data set can be prepared which will contain the natural frequencies obtained for each cracked geometry. This data set can be used as training data with natural frequencies as the parameter to train a machine learning algorithm to accomplish various tasks involving prediction models. These models can include crack propagation prediction, prediction of severity of crack, failure of material and the remaining life of the component.

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