Experimental investigation of crack in aluminum cantilever beam using vibration monitoring technique

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ABTRACT:

It has been observed that the dynamic behaviour of a structure changes due to the presence of a crack. Analysis of such phenomena is useful for fault diagnosis and the detection of cracks in structures. An experimental setup is designed in which an aluminium cantilever beam with cracks is excited by a power exciter and accelerometer attached to the beam provides the response. The cracks are assumed to be open to avoid non-linearity. The effects of crack and positions on the fundamental frequencies of slender cantilever beams with edge cracks are investigated experimentally. The experiments are conducted using specimens having edge cracks of different depths at different positions to validate the numerical results obtained. The experimental results of frequencies can be obtained from digital storage oscilloscope (DSO).

The first three natural frequencies were considered as basic criterion for crack detection. 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. Out of several case studies conducted the results of one of the case study is presented to demonstrate the applicability and efficiency of the method suggested.

Index term: - *Cantilever Beam, Oscilloscope, Power Oscillator, Vibration Exciter, Accelerometer etc.*

I. INTRODUCTION

The interest in the ability to monitor a structure and detect damage at the earliest possible stage is pervasive throughout the civil, mechanical and aerospace engineering communities. Current damage-detection methods are either visual or localized experimental methods such as acoustic or ultrasonic methods, magnet field methods, radiographs, eddy-current methods or thermal field methods. All of these experimental techniques require that the vicinity of the damage is known a priori and that the portion of the structure being inspected is readily accessible. Subjected to these limitations, these experimental methods can detect damage on or near the surface of the structure. The need for additional global damage detection methods that can be applied to complex structures has led to the development of methods that examine changes in the vibration characteristics of the structure. Damage or fault detection, as determined by changes in the dynamic properties or response of structures, is a subject that has received considerable attention in the literature. The basic idea is that modal parameters (notably frequencies and mode shapes) are functions of the physical properties of the structure. Therefore, changes in the physical properties will cause changes in the modal properties. Ideally, a robust damage detection scheme will be able to identify that damage has occurred at a very early stage, locate the damage within the sensor resolution being used, provide some estimate of the severity of the damage, and predict the remaining useful life of the structure. The method should also be well-suited to automation. To the greatest extent possible, the method should not rely on the engineering judgment of the user or an analytical model of the structure. A less ambitious, but more attainable, goal would be to develop a method that has the features listed above, but that uses an initial measurement of an undamaged structure as the baseline for future comparisons of measured response. Also, the methods should be able to take into account operational constraints. For example, a common assumption with most damage- identification methods reported in the technical literature to date is that the mass of the structure does not change appreciably as a result of the damage. However, there are certain types of structures such as offshore oil platforms where this assumption is not valid. Another important feature of damage-identification methods, and specifically those methods which use prior models, is their ability to discriminate between the model/data discrepancies caused by modeling errors and the discrepancies that are a result of structural damage. The effects of damage on a structure can be classified as linear or nonlinear. A linear damage situation is defined as the case when the initially linear-elastic structure remains linear-elastic after damage. The changes in modal properties are a result of changes in the geometry and/or the material properties of the structure, but the structural response can still be modeled using a linear equation of motion. Nonlinear damage is defined as the case when the initially linear-elastic structure behaves in a nonlinear manner after the damage has been introduced. One example of nonlinear damage is the formation of a fatigue crack that subsequently opens and closes under the normal operating vibration environment. Other examples include loose connections that rattle and nonlinear material behavior. A robust damage-detection method will be applicable to both of these general types of damage. The majority of the papers summarized in this review address only the problem of linear damage detection.

1.1 PRESENT AIM OF WORK

For conducting the experiment, first of all we will be preparing the machine setup. This machine is already available in the market, but our aim is to prepare this machine using some conventional machining methods, so that we can have a machine at a cheap rate. The machine will be measuring the vibration response of the aluminum solid beam. Vibration response will be taken through beam with the help of oscilloscope.

II. LITERATURE REVIEW

2.1 PRESENT WORK

For the literature review primarily various journals selected. The brief reviews of these papers are as follow.

Scott W. et. al.[1] Studied this report contained a review of the technical literature concerning the detection, location, and characterization of structural damage via techniques that examine changes in measured structural vibration response. The report was first categorizes the methods according to required measured data and analysis technique. The analysis categorized includes changes in modal frequencies, changes in measured mode shapes and changes in measured flexibility coefficients. Methods that use property (stiffness, mass, damping) matrix updating, detection of nonlinear response, and damage detection via neural networks are also summarized.

Prasad Ramchandra Baviskar et. al.[2] This paper addressed the method of multiple cracks detection in moving parts or beams by monitoring the natural frequency and prediction of crack location and depth using Artificial Neural Networks (ANN). Determination of crack properties like depth and location is vital in the fault diagnosis of rotating machine equipments. For the theoretical analysis, Finite Element Method (FEM) is used wherein the natural frequency of beam is calculated whereas the experimentation is performed using Fast Fourier Transform (FFT) analyzer. In experimentation, simply supported beam with single crack and cantilever beam with two cracks are considered. The experimental results are validated with the results of FEM (ANSYSTM) software. This formulation can be extended for various boundary conditions as well as varying cross sectional areas. The database obtained by FEM is used for prediction of crack location and depth using Artificial Neural Network (ANN). To investigate the validity of the proposed method, some predictions by ANN are compared with the results given by FEM. It is found that the method is capable of predicting the crack location and depth for single as well as two cracks. This work may be useful for improving online conditioning and monitoring of machine components and integrity assessment of the structures.

Lee et. al.[3] presented a method to detect a crack in a beam. The crack was not modeled as a mass less rotational spring, and the forward problem was solved for the natural frequencies using the boundary element method. The inverse problem was solved iteratively for the crack location and the crack size by the Newton-Raphson method. The present crack identification procedure was applied to the simulation cases which use the experimentally measured natural frequencies as inputs, and the detected crack parameters are in good agreements with the actual ones. The present method enables one to detect a crack in a beam without the help of the mass less rotational spring model.

Rizos et. al.[4] Modeled the crack as a mass less rotational spring, whose stiffness was calculated using fractures mechanics. He also conducted experiments to detect crack depth and location from changes in the mode shapes of cantilever beams. A major disadvantage of using mode shape based technique is that obtaining accurate mode shapes involves arduous and meticulous measurement of displacement or acceleration over a large number of points on the structure before and after damage. The accuracy in measurement of mode shapes is highly dependent on the number and distribution of sensors employed.

Owolabi et. al.[5] used natural frequency as the basic criterion for crack detection in simply supported and fixed-fixed beams. The method suggested has been extended to cantilever beams to check the capability and efficiency. There is need to see if this approach can be used for fixed-free beams.

Kisa et. al.[6] The vibration characteristics of a cracked Timoshenko beam are analyzed. The study integrates the FEM and component mode synthesis. The beam divided into two components related by a flexibility matrix which incorporates the interaction forces. The forces were derived from fracture mechanics expressions as the inverse of the compliance matrix is calculated using stress intensity factors and strain energy release rate expressions.

III. EXPERIMENTAL SETUP

3.1 MODEL DESCRIPTION

Aluminum beams were used for this experimental investigation. The setup consisted of 64 beam models with the fixed-free ends. Each beam model was of cross-sectional area 16mm X 16 mm with a length of 450 mm from fixed end. It had the following material properties: Young's modulus, E=70GPa, density, ρ=2700Kg/m 3, the Poisson ratio, µ=0.33.

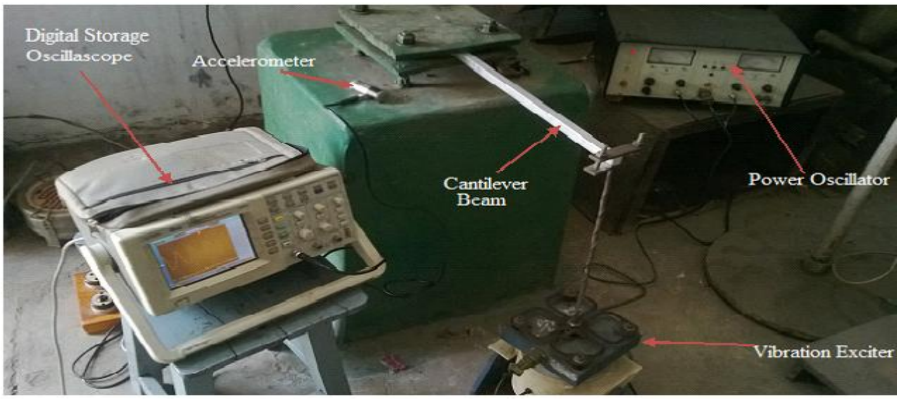

Fig: - 1. Experimental Setup

3.2 METHODOLOGY

The fixed–free beam model was clamped at one end, between two thick rectangular steel plates. The beam was excited with a vibration exciter. The first three natural frequencies of the un-cracked beam were measured. Then, cracks were generated to the desired depth using hexa blade. The crack always remained open during dynamic testing total 64 beam models were tested with cracks at different locations starting from a location near to fixed end. The crack depth varied from 2mm to 10mm at each crack position. Each model was excited by vibration exciter. This served as the input to the system. It is to be noted that the model was excited at a point, which was a few millimeters away from the center of the model. This was done to avoid exciting the beam at a nodal point. Since the beam would not respond for that mode at that point. The dynamic responses of the beam model were measured by using accelerometer placed on the model as indicated in Fig. 1. The response measurements were acquired, one at a time, using the digital storage oscilloscope (DSO).

IV. RESULTS AND DISCUSSION

4.1 RESULTS

The experimental data from the curve-fitted results were tabulated, and plotted (in a three dimensional plot) in the form of frequency ratio (ω_c/ω) (ratio of the natural frequency of the cracked beam to that of the un-cracked beam) versus the crack depth (a) for various crack location (X). Tables 1-3 show the variation of the frequency ratio as a function of the crack depth and crack location for beams with fixed-free ends.

4.2 CHANGES IN NATURAL FREQUENCY

Fig. 2 to 4 shows the plots of the first three frequency ratios as a function of crack depths for some of the crack positions. Fig.5 to Fig.7 shows the frequency ratio variation of three modes in terms of crack position for various crack depths respectively. From Fig.2 it is observed that, for the cases considered, the fundamental natural frequency was least affected when the crack was located at 360mm from fixed end. The crack was mostly affected when the crack was located at 40mm from the fixed end. Hence for a cantilever beam, it could be inferred that the fundamental frequency decreases significantly as the crack location moves towards the fixed end of the beam. This could be explained by the fact that the decrease in frequencies is greatest for a crack located where the bending moment is greatest. It appears therefore that the change in frequencies is a function of crack location. From Fig.3 it is observed that the second natural frequency was mostly affected for a crack located at the center for all crack depths of a beam due to the fact that at that location the bending moment is having large value. The second natural frequency was least affected when the crack was located at 360mm from fixed end. From Fig.4 it is observed that the third natural frequency of beam changed rapidly for a crack located at 250 mm. The third natural frequency was almost unaffected for a crack located at the center of a cantilever beam; the reason for this zero influence was that the nodal point for the third mode was located at the center of beam

TABLE: - 1 Fundamental Natural Frequency Ratio (Ω_c/Ω) As A Function Of Crack Location (X) And Crack Depth (A)

x	a=2mm	a=4mm	a=5mm	a=6mm	a=7mm	a=8mm	a=9mm	a=10mm
40mm	0.9859	0.9286	0.8998	0.8699	0.8232	0.7736	0.7214	0.6725
100mm	0.9862	0.9325	0.9101	0.8778	0.8465	0.7863	0.7446	0.6969
150mm	0.9911	0.9621	0.9326	0.8998	0.8665	0.8126	0.7864	0.75
200mm	0.9925	0.9587	0.9262	0.9046	0.8821	0.8629	0.8156	0.7956
220mm	0.983	0.97	0.9565	0.9256	0.9121	0.8956	0.8524	0.8259
250mm	0.9962	0.9762	0.9746	0.9598	0.9498	0.9356	0.9021	0.8835
300mm	0.9991	0.9897	0.9762	0.9746	0.9729	0.9721	0.9682	0.9571
360mm	1	1	1	1	1	1	1	1

TABLE:-2 Second Natural Frequency Ratio (ω_c/ω) As A Function Of Crack Location (X) And Crack Depth (a)

x	a=2mm	a=4mm	a=5mm	a=6mm	a=7mm	a=8mm	a=9mm	a=10mm
40mm	0.9911	0.9452	0.9125	0.8878	0.8489	0.8056	0.7582	0.7102
100mm	0.9931	0.9685	0.9425	0.9285	0.9189	0.9111	0.9052	0.8954
150mm	1	0.9512	0.9256	0.918	0.8803	0.8214	0.7689	0.7123
200mm	0.9937	0.9568	0.9365	0.921	0.8956	0.8521	0.7925	0.7532
220mm	0.9869	0.9765	0.971	0.9536	0.9214	0.8654	0.8452	0.8215
250mm	0.9978	0.9834	0.9705	0.9612	0.9622	0.9478	0.9389	0.9245
300mm	0.9998	0.987	0.9756	0.9702	0.9635	0.9486	0.9325	0.9246
360mm	0.9989	0.9986	0.9889	0.9898	0.9863	0.9721	0.9598	0.9563

TABLE:-3 Third Natural Frequency Ratio (ω_c/ω) As A Function Of Crack Location (X) And Crack Depth (a)

x	a=2mm	a=4mm	a=5mm	a=6mm	a=7mm	a=8mm	a=9mm	a=10mm
40 mm	0.9989	0.9465	0.9045	0.8756	0.8256	0.7732	0.6987	0.6423
100 mm	0.9931	0.9563	0.9456	0.9178	0.8849	0.8598	0.8127	0.7896
150 mm	0.991	0.9512	0.9298	0.9056	0.8569	0.8026	0.7258	0.6489
200 mm	0.9921	0.9789	0.9569	0.9365	0.8951	0.8465	0.8024	0.7598
220 mm	0.9927	0.9751	0.9632	0.9421	0.9287	0.8961	0.8365	0.7893
250 mm	0.9997	0.9758	0.9711	0.9589	0.9425	0.9245	0.8869	0.8456
300 mm	0.9982	0.9863	0.9681	0.9427	0.9156	0.8879	0.8462	0.8169
360 mm	0.9961	0.9911	0.9724	0.9568	0.9398	0.9285	0.9153	0.8896

From Fig.5 it is observed that, for the cases considered, the fundamental natural frequency was least affected when the crack depth was 6mm. The crack was mostly affected when the crack depth was 10mm. Hence for a cantilever beam, it could be inferred that the fundamental frequency decreases significantly as the crack depth increase to 61% of beam depth. This could be explained by the fact that the decrease in frequencies is greatest for a more crack depth because as more material gets removed the stiffness of the beam decrease and hence the natural frequency. It appears therefore that the change in frequencies is a function of crack depth also.

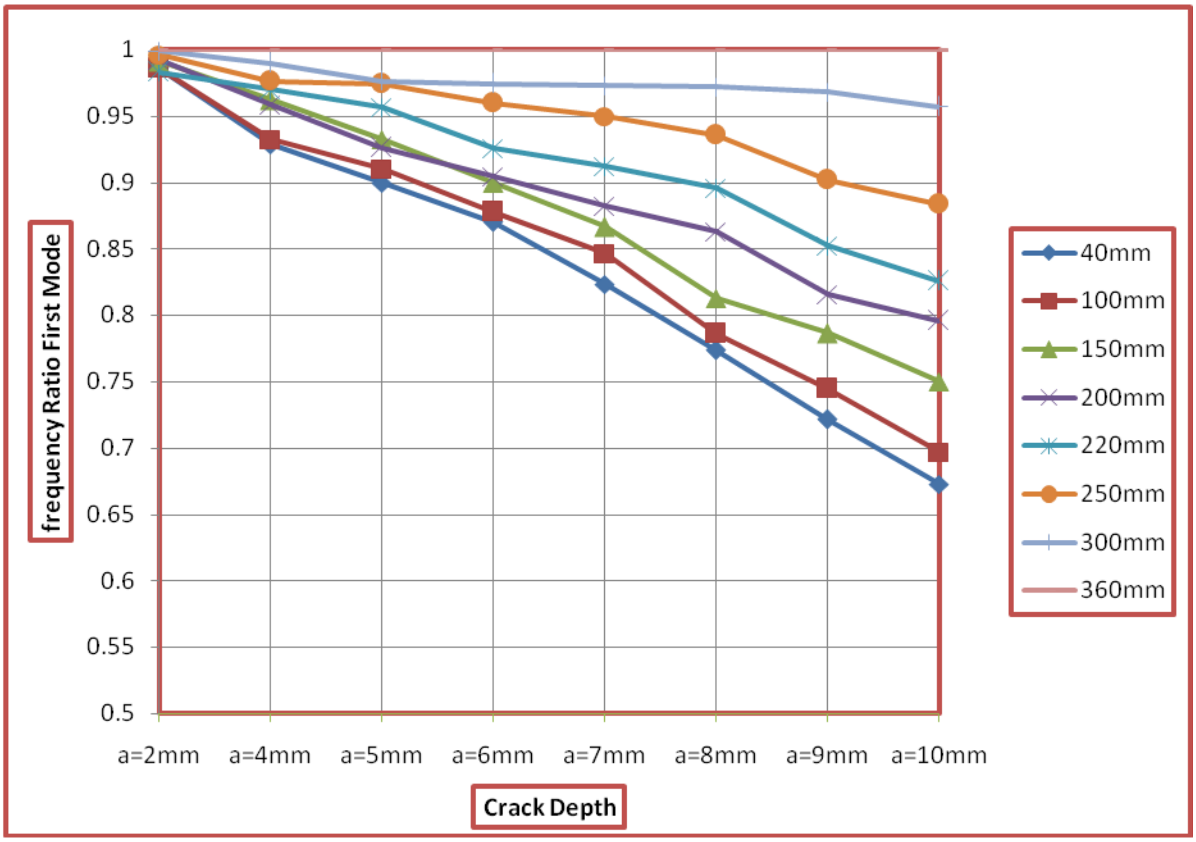

Fig.2. Fundamental natural frequency ratio in terms of crack depth for various crack positions

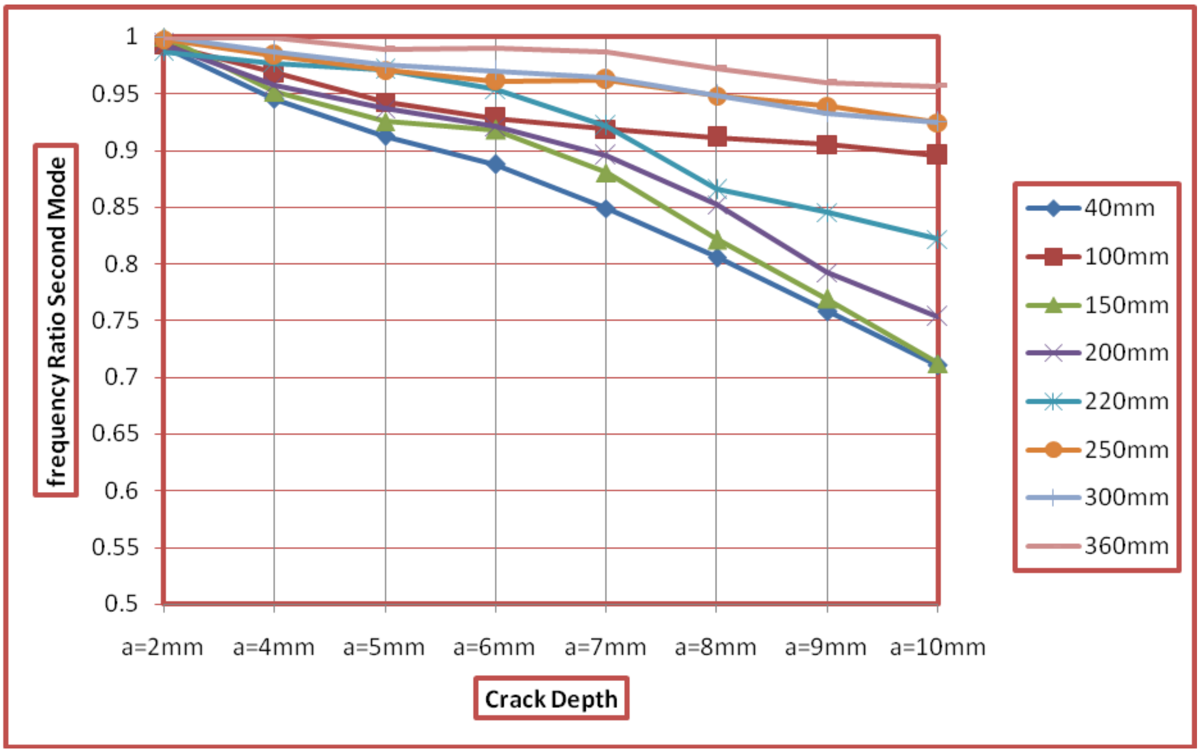

Fig.3. Second natural frequency ratio in terms of crack depth for various crack positions

From Fig.6 it is observed that the second natural frequency was mostly affected for a crack depth of 10mm at the crack location 150mm. The second natural frequency was least affected when the crack depth was 10mm. From Fig.7 it is observed that the third natural frequency of beam changed rapidly for a crack depth of 10mm. Third natural frequency was remained unaffected when crack depth was 6mm. Third natural frequency was remained unchanged at crack locations 55mm, 220mm, and 300mm due to the presence of node point at that position. Fig.8 to Fig.10 show the three dimensional plots of Normalized Frequency versus Crack Location and Crack Depth for first, second and third mode respectively for crack location of 250mm and crack depth of 6mm. To get these three dimensional plots. In Fig.8 to Fig.10, the contour line is not present due to the presence of node points.

4.3 CRACK IDENTIFICATION TECHNIQUE USING CHANGES IN NATURAL FREQUENCIES

As stated earlier, both the crack location and the crack depth influence the changes in the natural frequencies of a cracked beam. Consequently, a particular frequency could correspond to different crack locations and crack depths. This can be observed from the three-dimensional plots of the first three natural frequencies of cantilever beams as shown in Fig.8 to Fig.10. On this basis, a contour line, which has the same normalized frequency change resulting from a combination of different crack depths and crack locations (for a particular mode) could be plotted in a curve with crack location and crack depth as its axes.

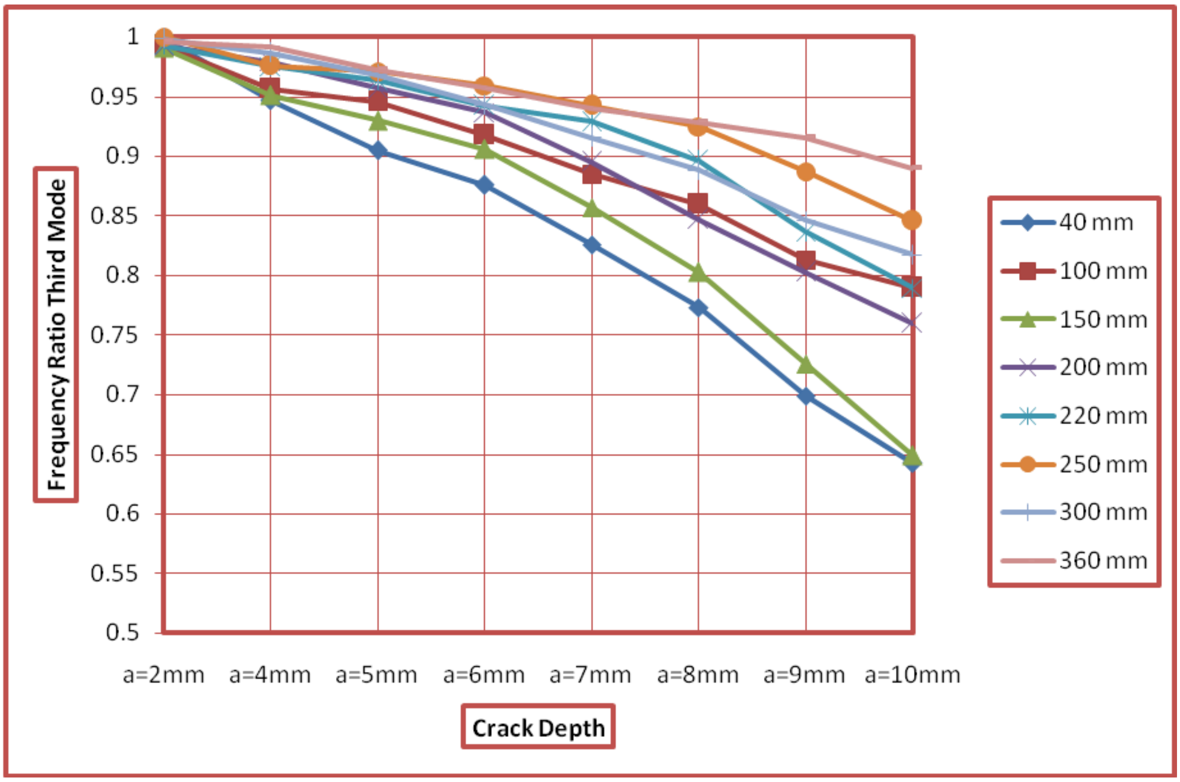

Fig.4. Third natural frequency ratio in terms of crack depth for various crack positions

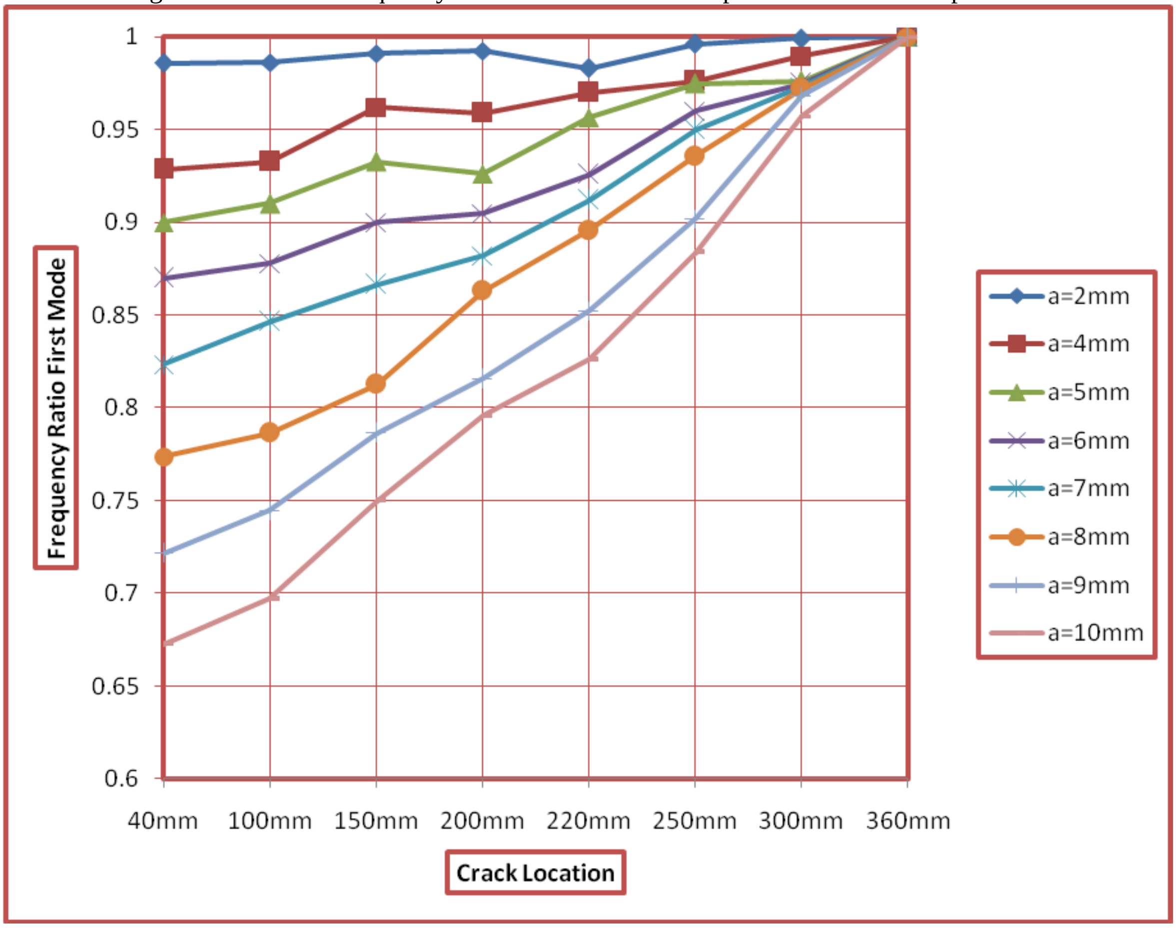

Fig.5. First Mode Frequency Ratio in Terms of Crack Position for Various Crack Depths

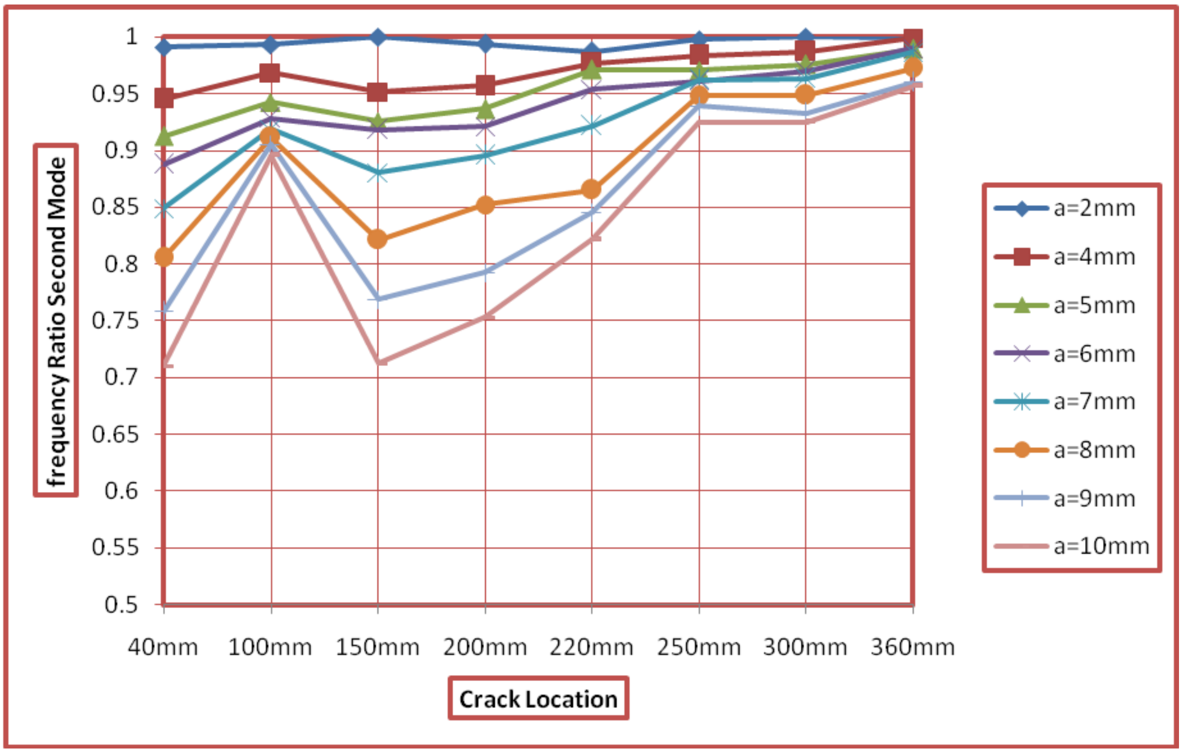

Fig.6. Second Mode Frequency Ratio in Terms of Crack Position for Various Crack Depths

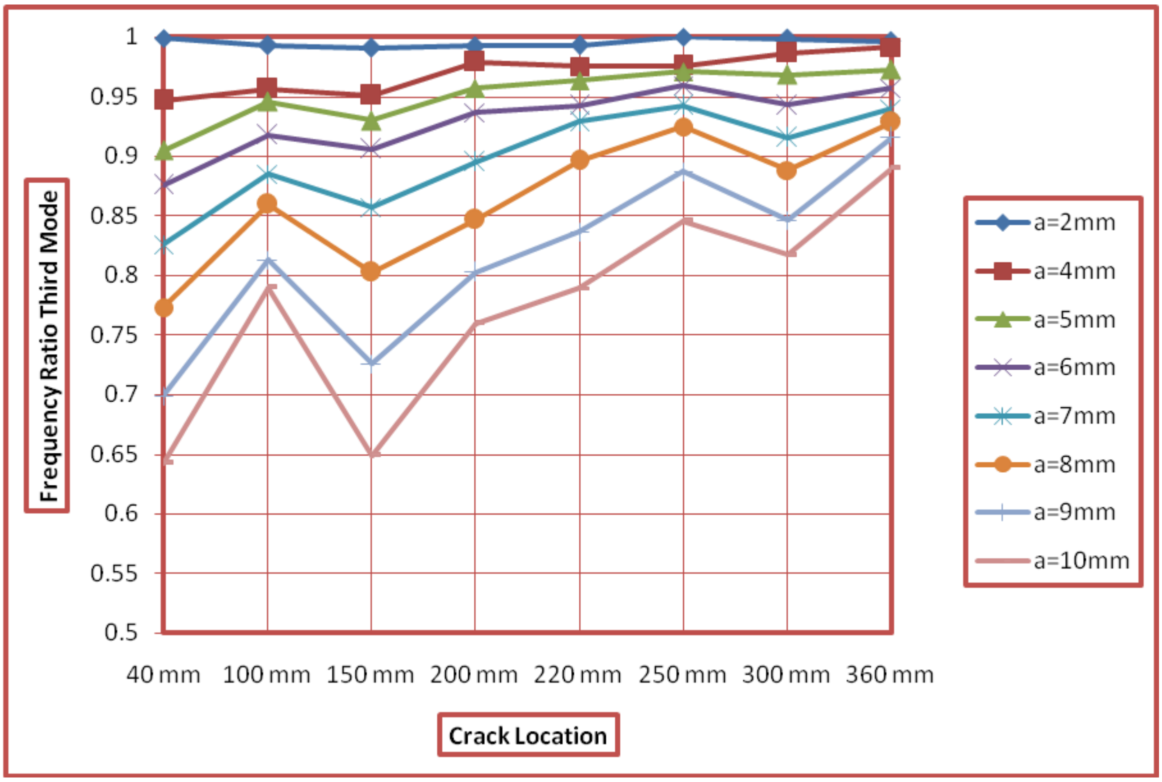

Fig.7. Third Mode Frequency Ratio in Terms of Crack Position for Various Crack Depths

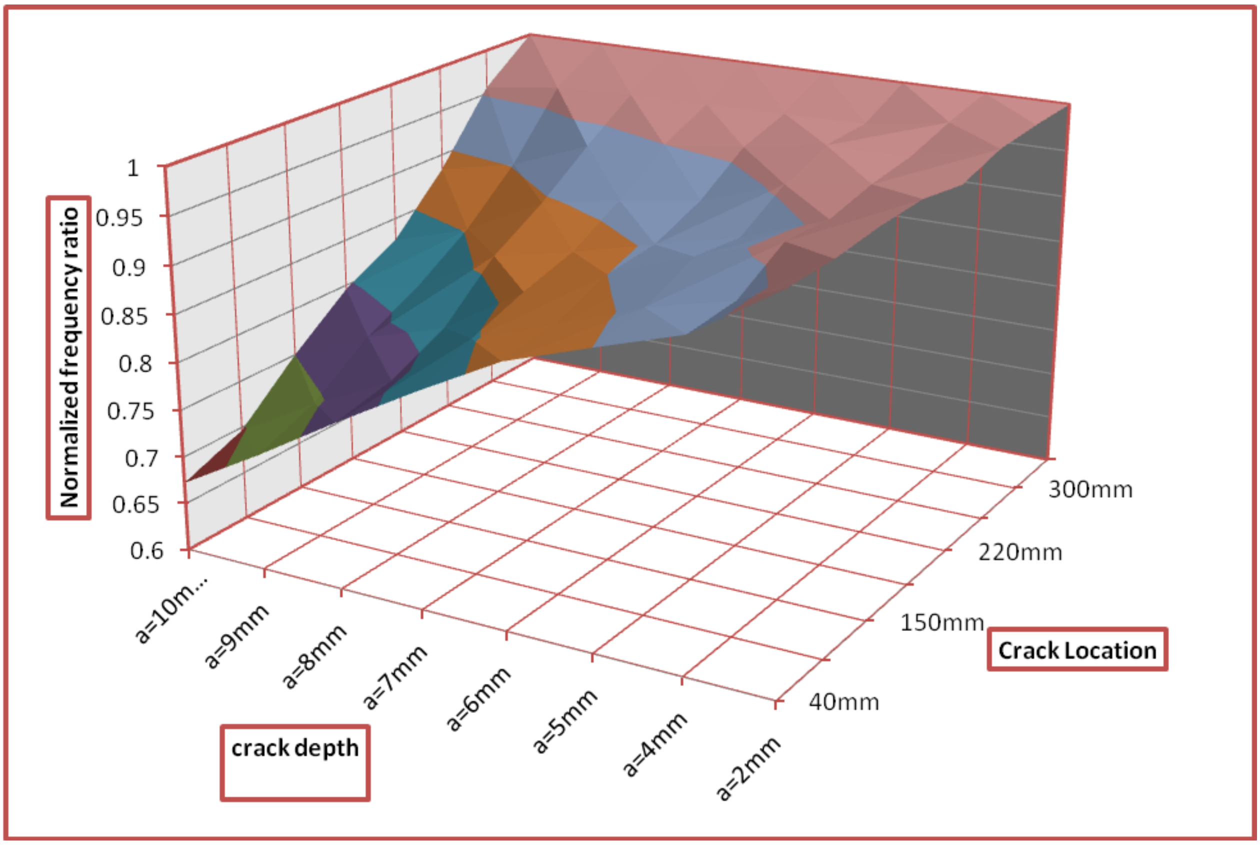

Fig.8. Three-dimensional plot with contour lines of normalized natural frequency versus crack location and crack depth for first mode for crack location of 250mm and crack depth of 6mm

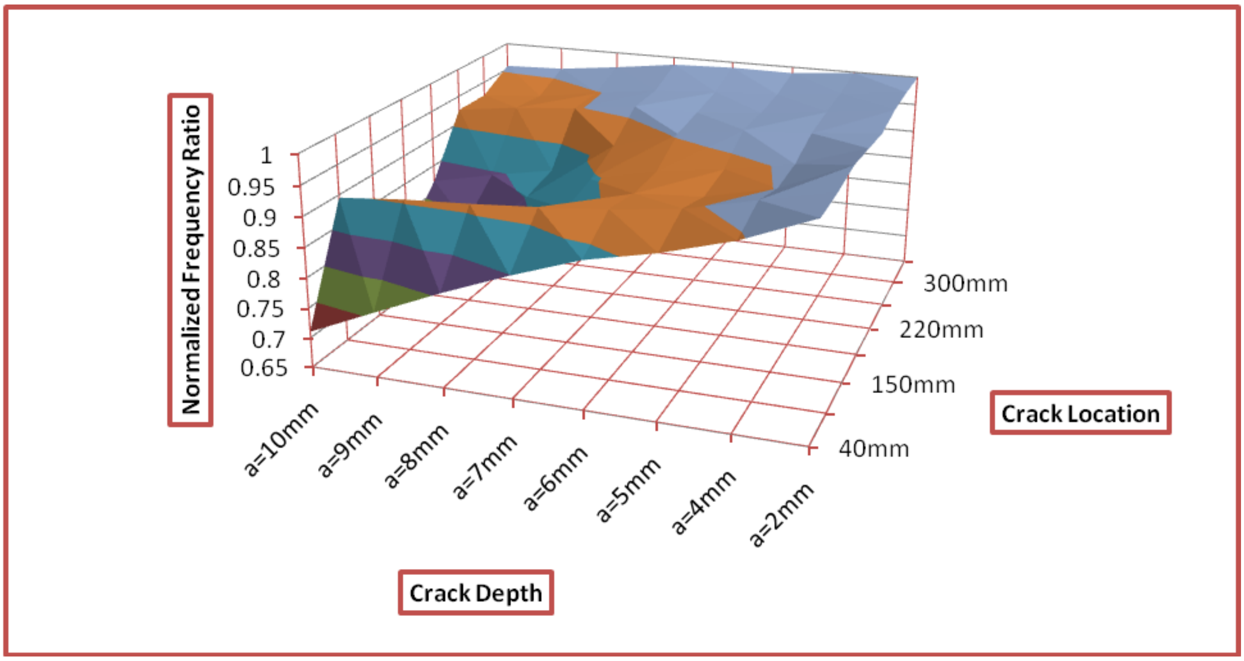

Fig.9. Three-dimensional plot with contour lines of normalized natural frequency versus crack location and crack depth for second mode for crack location of 250mm and crack depth of 6mm

For a beam with a single crack with unknown parameters, the following steps are required to predict the crack location, and depth, namely, (1) measurements of the first three natural frequencies; (2) normalization of the measured frequencies; (3) plotting of contour lines from different modes on the same axes; and (4) location of the point(s) of intersection of the different contour lines. The point(s) of intersection, common to all the three modes, indicate(s) the crack location, and crack depth. This intersection will be unique due to the fact that any normalized crack frequency can be represented by a governing equation that is dependent on crack depth (a), crack location (X). Therefore a minimum of three curves is required to identify the two unknown parameters of crack location and crack depth.

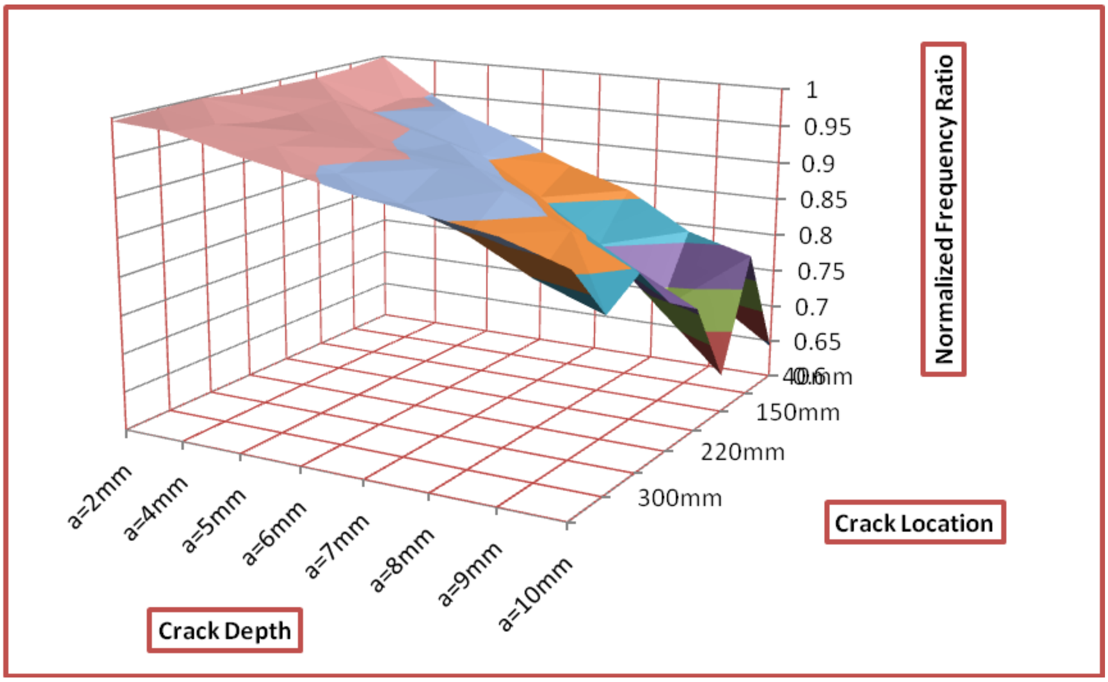

Fig.10. Three-dimensional plot with contour lines of normalized natural frequency versus crack location and crack depth for third mode for crack location of 250mm and crack depth of 6mm

From Tables 1-3, it is observed that for a crack depth of 6mm located at a distance of 250mm from fixed end of the beam, the normalized frequencies are 0.9598 for the first mode, 0.9612 for the second mode and 0.9589 for the third mode. The contour lines with the values of 0.9598, 0.9612 and 0.9589 were retrieved from the first three modes with the help of MINITAB software as shown in Fig.11 to Fig.13 and plotted on the same axes as shown in Fig.14. From the Fig.14 it could be observed that there are two intersection points in the contour lines of the first and the second modes. Consequently the contour of the third mode is used to identify the crack location (X=250mm) and the crack depth (a=6mm), uniquely. The three contour lines gave just one common point of intersection, which indicates the crack location and the crack depth. Since the frequencies depend on the crack depth and location, these values can be uniquely determined by the solution of a function having solutions one order higher (in this case, three) than the number of unknowns (in this case, two, namely crack depth and location) to be determined. This is the reason for the requirement of three modes. If there were more parameters that influence the response (besides the crack depth and location), then one will require more modes to identify the unknown crack depth and crack location.

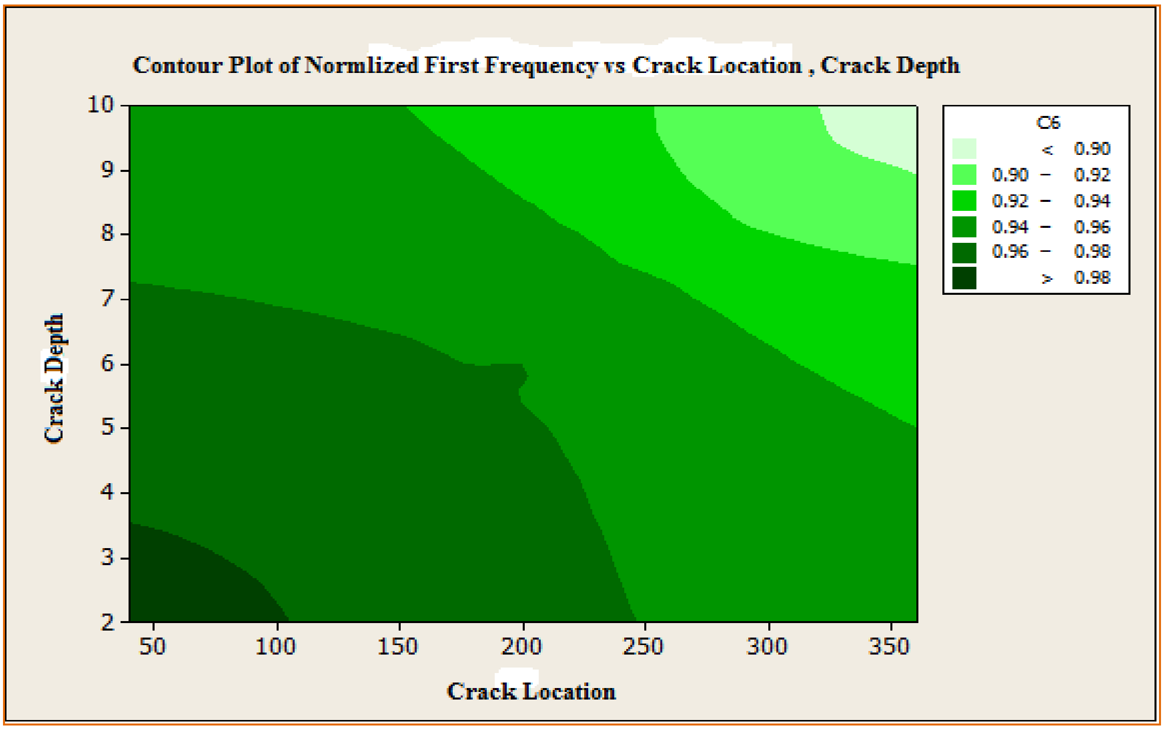

Fig.11. Frequency contour plot of mode-1 for normalized frequency 0.9598

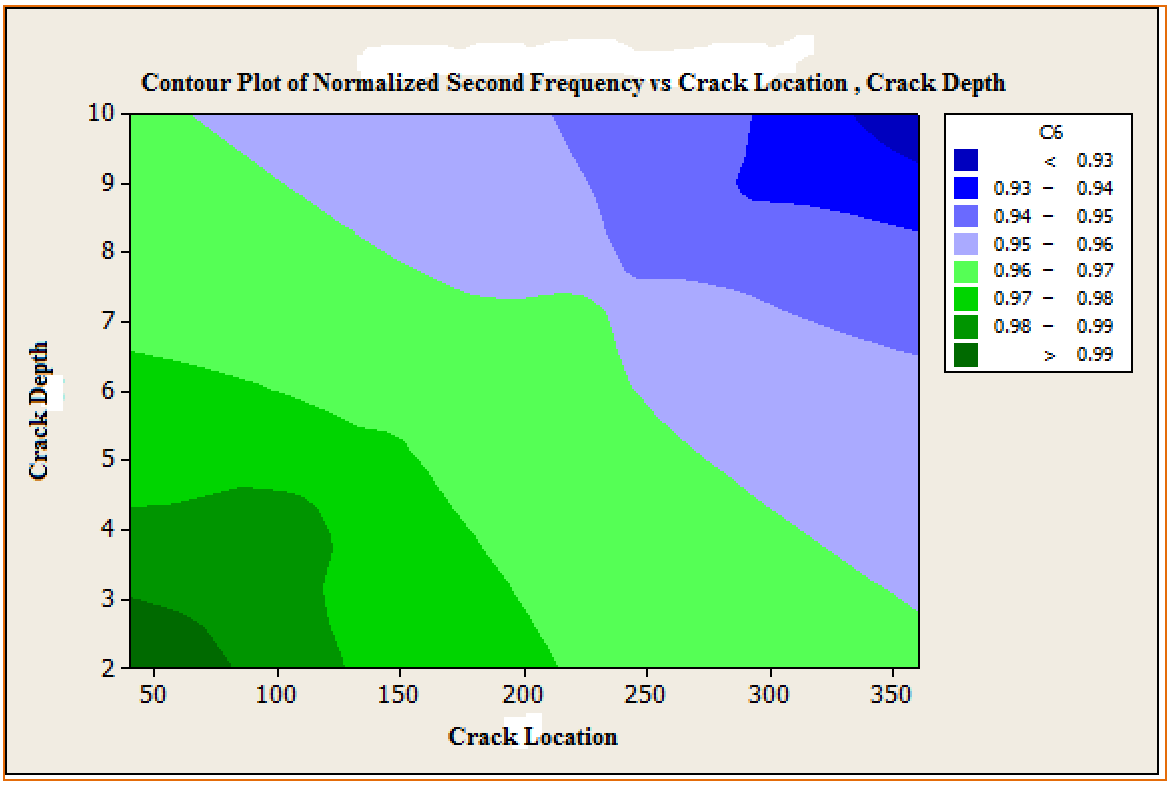

Fig.12. Frequency contour plot of mode-2 for normalized frequency 0.9612

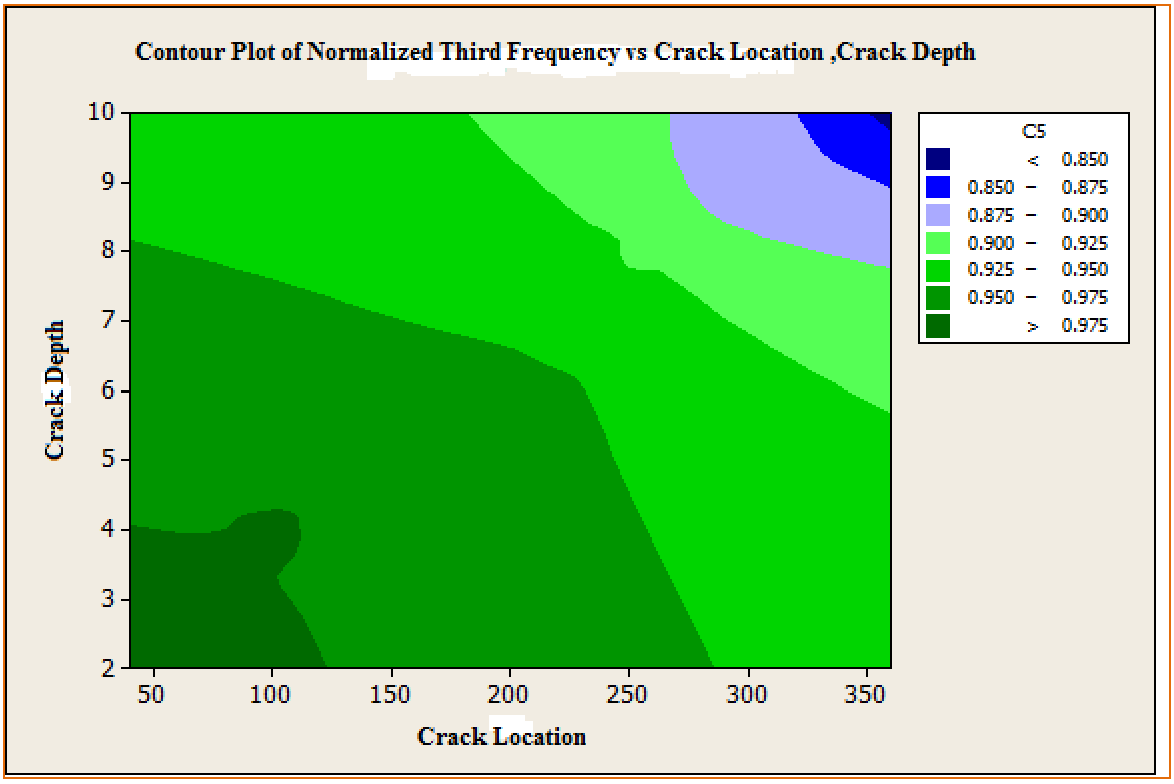

Fig.13. Frequency contour plot of mode-3 for normalized frequency 0.9589

V. CONCLUSIONS

Detailed experimental investigations of the effects of crack on the first three modes of vibrating cantilever beams have been presented in this paper. From the results it is evident that the vibration behavior of the beams is very sensitive to the crack location, crack depth and mode number. A simple method for predicting the location and depth of the crack based on changes in the natural frequencies of the beam is also presented, and discussed. This procedure becomes feasible due to the fact that under robust test and measurement conditions, the measured parameters of frequencies are unique values, which will remain the same (within a tolerance level), wherever similar beams are tested and responses measured. 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 following conclusions were drawn:-

1. With the presence of crack in the beam the frequency of vibration decreases.
2. The above information can be used to predict the failure of beam as well as shaft and preventive steps can be taken.

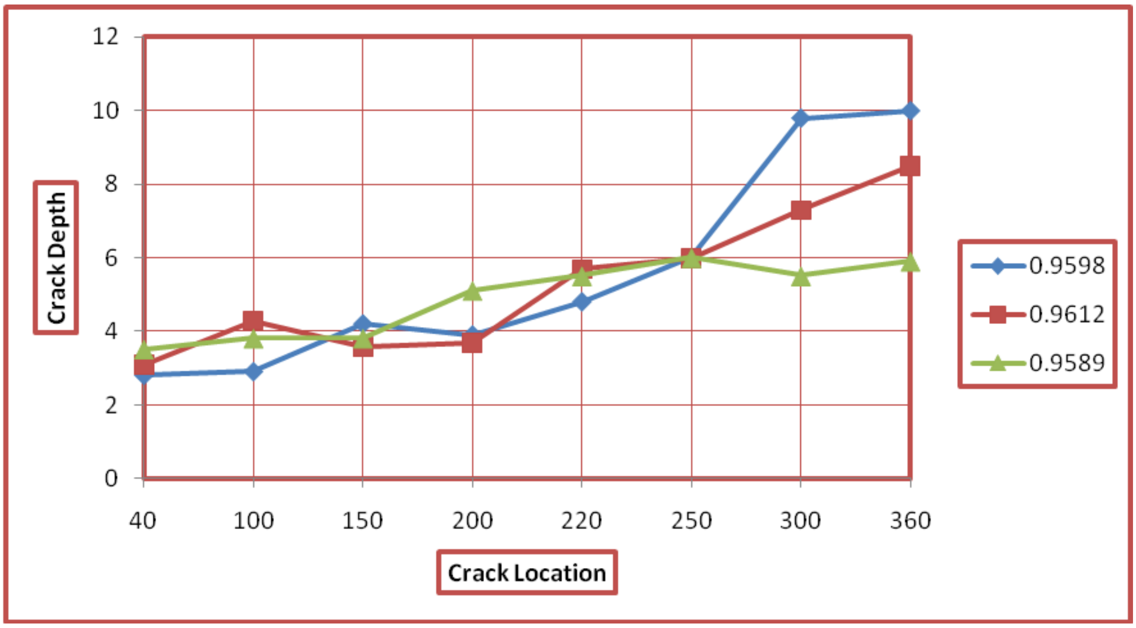

Fig.14. Crack identification technique by using frequency contours of the first three modes of beam (mode 1, normalized frequency (0.9598); mode 2, normalized frequency (0.9612); and 3: mode 3, normalized frequency (0.9589).

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