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Crack Detection in Circular Shaft Using Vibration Monitoring Technique

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***Abstract*—Crack detection using Vibration Monitoring Techniques is one of the non-destructive methods used for condition monitoring of machines in action. Machines while operating usually vibrate, and with most of them the vibrations are unwanted and the effort is to reduce the vibration. Only with some types of machines, vibrations are directly a working standard of the machine and are caused intentionally (e.g. vibrating screeners). Though, this group of machines is not of interest to Fault detection using Vibration Monitoring Techniques.**

As the name Fault detection using Vibration Monitoring Techniques suggests, machine condition is diagnosed on the base of an analysis of vibration. Successful application of vibration identification needs in practice man with considerable degree of knowledge and understanding. Routine work in data collection can be done by trained personnel without academic certificates, but data processing and assessment of the state of a machine is a job for an engineer who has information in numerous parts (design of machines, dynamics, mathematics, signal processing, etc.)

A strong interest has developed within the past several years in the dynamic performance of turbo mechanism with cracked shafts. An excellent review of the field of the dynamics of cracked rotors and of different finding techniques to identify fracture damage has been presented by researchers. Vibration investigation of a broken structure is one method for fault identification. Vibration diagnosis, as a non-destructive detection technique, has recently become of greater importance.

Theoretical calculations as well as finite element analysis are done to find out the natural frequencies of the simply supported shaft. Shaft with inclined crack and without crack is considered for the study.

***Index Terms*—Finite Element Analysis (FEA), FFT Analyzer, Mode Shapes, Natural Frequency, Vibration Monitoring Technique**

I. INTRODUCTION

The Diagnosis of shaft cracks in rotating machinery has been a research challenge for both industry and academia for several decades. Such cracks can cause total shaft failure and enormous costs in down time. Accordingly, owners of critical plant machinery are particularly interested in early detection of symptoms that can lead to in-service failure of machinery and equipment. Safe and reliable operation of equipment relies on proactive maintenance aided by newly emerging diagnostic technologies. There are several predictive maintenance techniques used to monitor and analyse critical rotating machines and equipment in a typical plant, such as vibration analysis, ultrasonics, thermography, tribology, process monitoring, visual inspection, and other non-destructive analysis techniques. Of these techniques, vibration analysis is the dominant predictive maintenance technique used with maintenance management programs, as it is non-destructive and doesn't interfere with the machine's normal operation.

In the field of vibration condition monitoring, the diagnostics of rotating machinery has been gaining importance in recent years. Shafts are basic components in most high-performance rotating equipment and utility plant, such as high-speed compressors, steam and gas turbines, generators and pumps. Although usually quite robust and well designed, serious defects can develop in shafts without much apparent warning. Total shaft failure can be catastrophic. This study focuses on the characteristic of cracked shafts, and their vibration dynamic behavior.

There are a few types of shaft cracks which can develop during the operation of rotating machines. The transverse crack remains the most important type of crack as the machine safety is significantly influenced by its occurrence. The study of transverse cracks has been extensive because, being perpendicular to the shaft they reduce the cross-sectional area and result in significant damages to rotors. Many factors can influence the occurrence of shaft cracks. Rotating shaft is subjected to different types of mechanical stresses, such as bending, torsional, shear, and static radial loads. A crack will be initiated in the local region where stresses exceed the yield strength of the shaft material, which may have already been reduced due to fatigue. As the crack grows to a certain depth, the shaft cannot support the static and dynamic loading any more. Consequently, the shaft would often experience a sudden fracture, causing enormous costs in down time and possible injuries to people. Shaft crack detection techniques adopted in the literature can be broadly grouped into two methods: vibration-based and model-based methods.

The former relies on detecting changes in vibration signals as a crack in a structure tends to modify its dynamic characteristics such as the natural frequencies and mode

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shapes. Conversely, through monitoring the trend changes in measurements of the natural frequencies and mode shapes of a rotating shaft over time, a crack present in the shaft could be predicted. The stiffness of a shaft is reduced by a crack and consequently the shaft's Eigen-frequencies decline. Measuring these changes can help with identifying an early stage crack. Unfortunately, the available indicators cannot reliably differentiate a cracked shaft from other problems that create similar vibration spectra and waveforms, such as a misaligned or unbalanced shaft. Thus, to develop more reliable diagnostic methods, a thorough understanding of periodical stiffness of a cracked shaft is necessary.

The model-based methods are based on analytical or numerical models to simulate the behavior of cracked shafts during rotation. In model-based identification, the fault-induced change in the rotor system is taken into account by equivalent loads in the mathematical model. These equivalent loads are virtual forces and moments acting on the linear undamaged system to generate a dynamic behavior identical to that measured in the damaged system. However, the approximations and assumptions used in the model-based approaches could lead to large errors for the analysis of cracked shaft dynamic behavior. Specifically in consideration of cracked shaft stiffness, the stiffness parameters used in some of the models do not really reflect its periodic change at different rotation angles.

II. LITERATURE REVIEW

Various research papers are referred and many other technical papers reviewed on the technical websites, it is observed that many researchers have carried out work vibration diagnostics.

In 2003, Jyoti K. Sinha worked on significance of vibration diagnosis of rotating machines during commissioning. She had given few case studies. The vibration based condition monitoring for the operating conventional rotating machines are matured and usually the following measurements and analysis procedures are adopted for monitoring the health of machines [1].

Z.K. Peng, Z.Q. Lang and S.A. Billings [2007] studied Crack detection using nonlinear output frequency response functions. The new concept of nonlinear output frequency response functions (NOFRFs) is introduced in their paper to detect cracks in beams using frequency domain information. The results show that the NOFRFs are a sensitive indicator of the presence of cracks providing the excitation is of an appropriate intensity [2].

M. Kotb Ali and others [2009] had undergone an "A Study on fault diagnosis by vibration analysis at different loading and speed conditions". They showed that vibration amplitude affected by changing both load and/or speed; therefore, it is important to fix the measuring positions as well as speed and load as much as possible to implement a good maintenance vibration monitoring program [3].

"Machinery Fault Detection" is a basic guide to understanding vibration analysis for machinery diagnostics by Ludeca [4].

Mohd Hanif Mohd Ramli and others [2012] studied effect vibration-based damage detection on a uniform mild steel shaft using modal response. The objective of their research was to analyze the difference in the dynamic properties between multiple cracked and uncracked shaft includes mode shape, frequency response, and natural frequency by experimental procedures using 4 channel analyzer systems [5].

Yang Liu, Jing Xiao and Dongwei Shu had undergone free vibration of delaminated beams with an edge crack. In their study, an analytical solution is developed to study the effect of edge crack on the vibration characteristics of delaminated beams. The rotational spring model, the 'free mode' and constrained mode' assumptions in delimitation vibration are adopted. This is the first study on how edge crack affects the vibration characteristic of delaminated beams and new non dimensional parameters are developed accordingly. Results show that the effect of delimitation length and thickness-wise location on reducing the natural frequencies is aggravated by an increasing crack depth. The location of the crack also influences the effect of delimitation, but such influence is different between crack occurring inside and outside the delaminated area. The difference of natural frequencies between 'free mode' and 'constrained mode' increases then decreases as the crack moves from one side of the delaminated region to the other side, peaking at the middle [6].

Pankaj Charan Jena, Dayal R. Parhi and Goutam Pohit [2012] worked on faults detection of a single cracked beam by theoretical and experimental analysis using vibration signatures. In their work, fault detection in a single cracked beam has been worked out. The identification of location and the depth of crack in a beam containing single transverse crack is done through theoretical and experimental analysis respectively. It has come to their noticed that a crack in a beam has great effect on dynamic behavior of beam [7].

Irshad A. Khan [2012] worked on the estimation of the effects of crack depth on natural frequency and mode shape of beam; Cantilever and fixed-fixed beam are engaged for analysis. The presence of cracks a severe threat to the performance of structures and it affects the vibration signatures (Natural frequencies and mode shapes). Here two transverse cracks are deemed on the beam at 200 mm and 600mm from fixed end of the beam, the depth of cracks are varied from 0.5mm to 3mm at the interval of 0.5mm for study. Natural frequency increases and Mode shape decreases as the crack depth increases. Experiments are also conducted by them, results of experiment having good co-relation with results of finite element analysis [8].

From the above papers, it has been seen that we can carry out crack detection by analytical method and its validation can be done by FEA as well as by experimental method.

III. OBJECTIVE

The main objectives of the project is

1) Theoretical calculation of the natural frequencies of simply supported circular steel shaft without crack.

2) Validation of theoretical natural frequencies of simply supported circular steel shaft with crack by finite element analysis.

IV. ANALYTICAL SOLUTION

The natural frequencies and mode shapes are obtained considering the homogeneous solution of the shaft vibration equation. We consider the un-damped mode in bending vibration of the shaft with uniform sectional property. For free vibration let f(x,t) =0 and assume that the response is given by [9],

$$y(x,t) = \phi(x)\sin\omega t \tag{1}$$

We know governing differential equation of motion for simply supported shaft,

$$\frac{\partial^2}{\partial x^2}\{EI(x)\frac{\partial^2 Y(x)}{\partial x^2}\} + m(x)\frac{\partial^2 Y}{\partial t^2} = f(x,t) \tag{2}$$

Using above equations we will get,

$$\frac{\partial^4 \phi}{\partial x^4} - a^4\phi(x) = 0 \tag{3}$$

Let us consider the shaft with both ends simply supported. The boundary conditions at the ends imply the following conditions on mode shape functions,

$$\phi(0) = \phi(L) = 0 \tag{4}$$

$$\phi''(0) = \phi''(L) = 0 \tag{5}$$

Figure 1 shows simply supported shaft and its mode shapes (Number 1, 2 & 3 denotes first three mode shape respectively). Using above boundary conditions we will get natural frequencies and mode shapes as follows,

$$\omega_n = n\Pi^2\sqrt{\frac{EI}{mL^4}} \tag{6}$$

$$\phi_n(x) = \sin\frac{n\Pi}{L}x \tag{7}$$

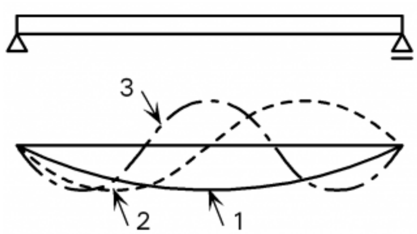

Figure: 1 Simply Supported Shaft and its Mode Shapes

Following Figure 2 shows natural frequencies and mode shapes for a simply supported shaft.
For Steel Shaft Following Properties are considered,
Length of the Shaft (L) = 800 mm
Diameter of the shaft (d) = 38 mm
(C_n) = Constant for particular mode shape
The material properties are as given below.
Young's modulus of elasticity (E) = 2.0E11 Pa
Poisson's ratio (υ) = 0.3
Density (ρ) = 7850 Kg/mm^3
I = 1.02E5 mm^4
m = Mass of the Shaft = 7.20 Kg
f=ω/2Π

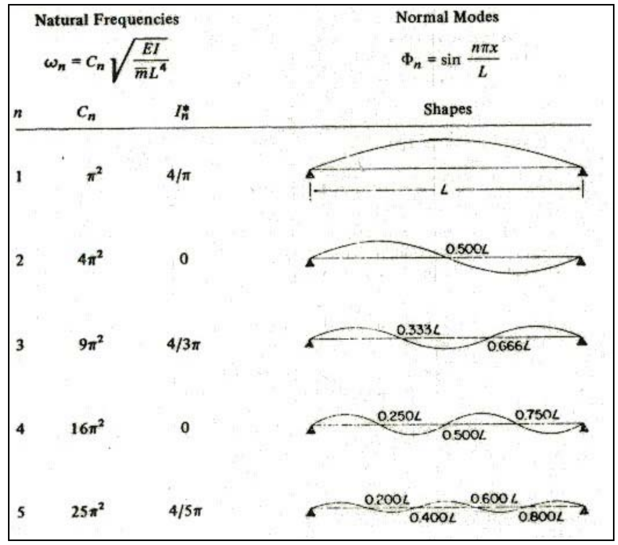

Figure: 2 Simply Supported Shaft Natural Frequencies and Mode Shapes

Using listed dimensions and material properties theoretical values of natural frequencies are calculated and that are tabulated in below Table I.

Table I Theoretical calculations:

Mode No.	ω (rad)	Frequency (Hz)
Mode 1	821.24	130.77
Mode 2	3284.96	523.08
Mode 3	7391.16	1176.94

V. NATURAL FREQENCIES USING FEA

A. Shaft without Crack

Modeling (Figure 3) and analysis of shaft is done in ANSYS Workbench 12.1. Boundary conditions are applied as shown in Figure 4 at both the simply supported ends of the shaft. Hexahedron elements are used for meshing as shown in Figure 5. Number of nodes used are 26012.

The finite element analysis is carried out using ANSYS 12 finite element program for modal analysis of the un-cracked shaft to determine the natural frequencies. Figure 5 shows the finite element mesh model of the shaft without crack. Figure 6 to Figure 8 shows mode 1, mode 2, mode 3 of simply supported shaft without crack respectively and their natural frequencies.

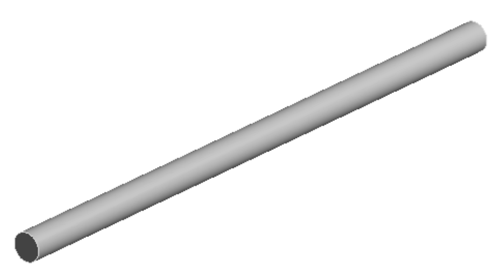

Figure: 3 CAD model of shaft without crack

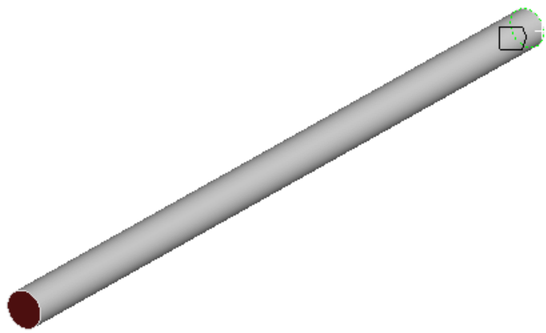

Figure: 4 LBC's of simply supported shaft

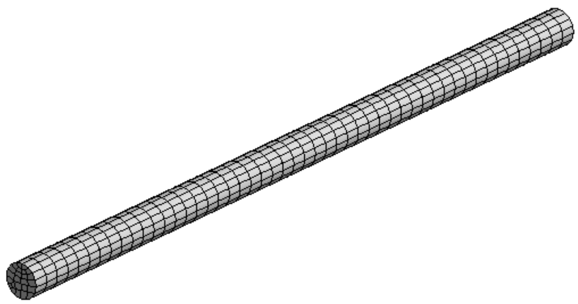

Figure: 5 Meshing of Shaft without crack

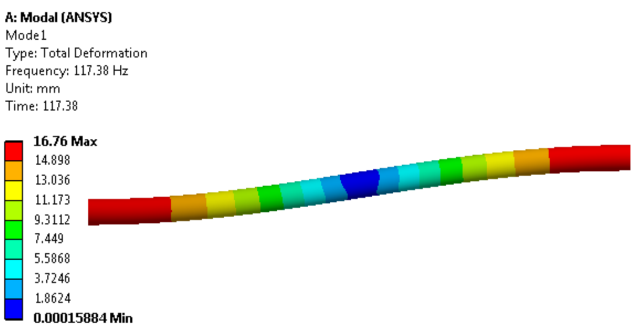

Figure: 6 Mode 1 (without crack)

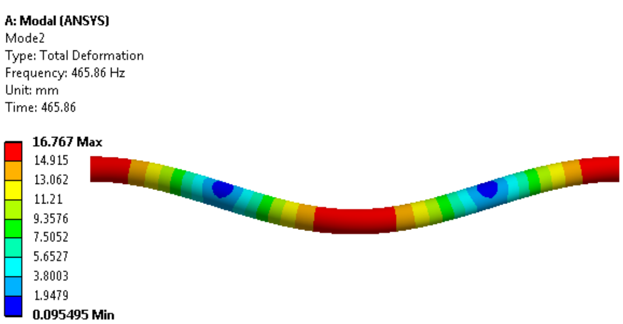

Figure: 7 Mode 2 (without crack)

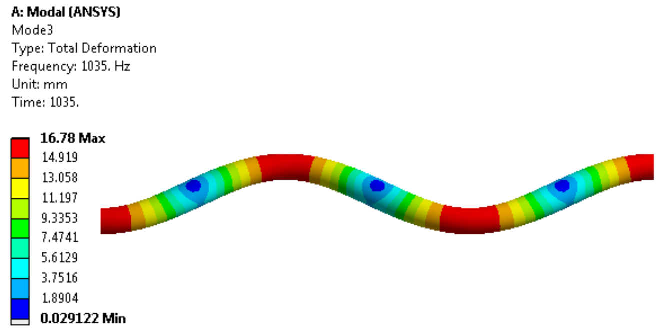

Figure: 8 Mode 3 (without crack)

Table II Comparison Theoretical Vs FEA Results Without Crack:

Mode No.	Theoretical Calculations	FEA	% Difference
Mode 1	130.77	117.38	10
Mode 2	523.08	465.86	10
Mode 3	1176.94	1035	12

Table II shows comparison of theoretical calculations and finite element analysis results. It can be seen from the results that theoretical calculations and finite element analysis results have good match between ~ 10% differences.

B. Shaft with Crack

Crack details are shown in Figure 9. Please note that Figure 9 is not to the scale. Inclined crack is introduced in the shaft at an angle of 60°.

Relative crack depth for inclined crack (α) = 0.2

Relative crack location (β) = 0.5

Crack inclination of inclined crack (θ) = 60°

Modeling (Figure 10) and analysis of cracked shaft is done in ANSYS Workbench 12.1. Boundary conditions are applied as shown in Figure 4. Here we have used same boundary condition which is used for shaft without crack. Hexahedron elements are used for meshing as shown in Figure 11. The finite element analysis is carried out using ANSYS 12.1 finite element program for modal analysis of the cracked shaft to determine the natural frequencies. Figure 11 shows the finite element mesh model of the shaft and a magnified view of mesh. 27152 nodes are present in meshing. Figure 12 to Figure 14 shows mode 1, mode 2, mode 3 of simply supported shaft with crack respectively and their natural frequencies.

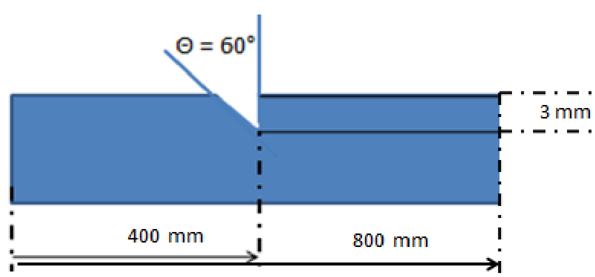

Figure: 9 Crack Details

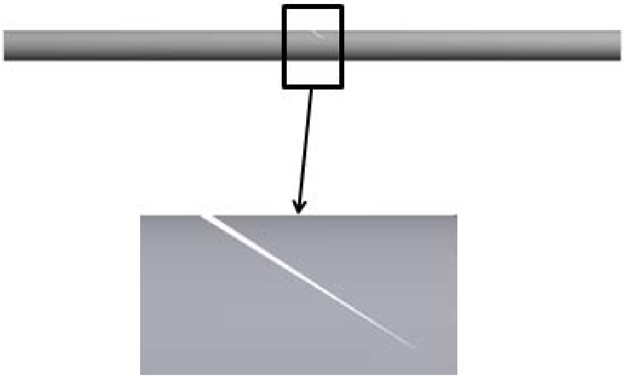

Figure: 10 CAD Model of Shaft with crack

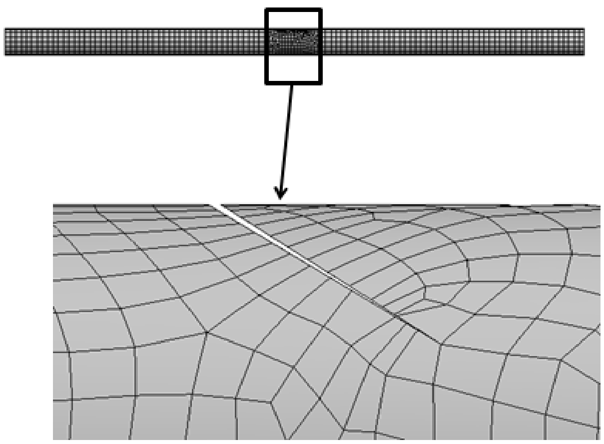

Figure: 11 Meshing of Shaft with Crack

Figure: 12 Mode 1 (with crack)

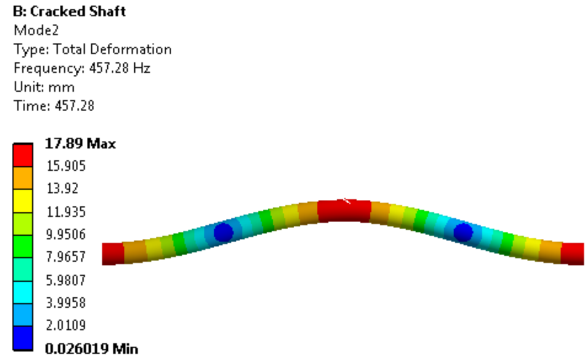

Figure: 13 Mode 2 (with crack)

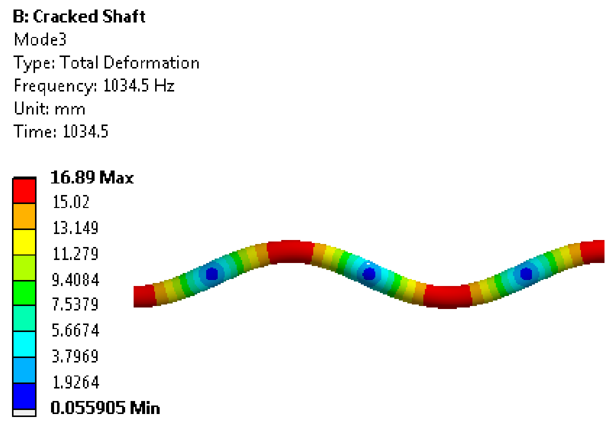

Figure: 14 Mode 3 (with crack)

TABLE III
Comparison without crack Vs with crack FEA Results:

Mode No.	FEA (Shaft Without Crack)	FEA (Shaft With Crack)
Mode 1	117.38	117.37
Mode 2	465.86	457.28
Mode 3	1035	1034.5

Table III shows comparison of finite element analysis results of shaft without crack and shaft with crack. A theoretical calculation as well as finite element analysis is done to find out the natural frequencies of the simply supported shaft. It is observed from the results that theoretical calculations and finite element analysis results have good match in between. It can be seen from the results that shaft with crack shows lower natural frequencies; this is mainly because of reduction in stiffness of the shaft due to presence of crack.

VI. EXPERIMENTATION

To validate the Finite element analysis result, an experiment on the steel shaft will be performed. Simply supported shaft of length 800 mm and diameter 38 mm will be considered for testing. Testing will be done on shaft with and without crack [8].

During the experiment the cracked and undamaged shaft will be vibrated at their 1st, 2nd and 3rd mode of vibration by using an exciter and a function generator. The vibrations characteristics such as natural frequencies and mode shape of the shafts correspond to 1st, 2nd and 3rd mode of vibration have been recorded by placing the accelerometer along the length of the shaft and displayed on the vibration indicator. Test set-up will be consist of following parts as shown in Figure 15,

1. Data acquisition (Accelerometer),
2. Vibration analyser,
3. Vibration indicator,
4. Power Distribution,
5. Function generator,
6. Power amplifier,
7. Vibration exciter
8. Simply supported shaft.

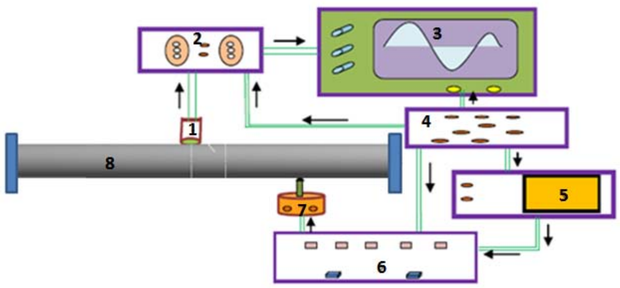

Figure: 15 Schematic Block Diagram of Test set-up

VII. RESULTS AND DISCUSSION

Table IV shows comparison of theoretical calculations, finite element analysis results of simply supported circular shaft with and without crack. It can be seen from the results that theoretical calculations and finite element analysis results have good match. It is observed from the results that shaft with crack shows lower natural frequencies; this is mainly because of reduction in stiffness of the shaft due to presence of crack.

TABLE IV

Comparison without crack Vs with crack FEA Results:

Mode No.	Theoretical Calculations	FEA (Shaft Without Crack)	FEA (Shaft With Crack)
Mode 1	130.77	117.38	117.37
Mode 2	523.08	465.86	457.28
Mode 3	1176.94	1035	1034.5

VIII. CONCLUSION

In general, the conventional vibration based condition monitoring techniques used in rotating machines are important and useful in prediction of deterioration in different components so that the defects can be rectified either by replacing the defective components or by repair well in advance before any major breakdown. However if the failure of components is frequent and repeated in nature and particularly when it is occurring due to some kind of resonance, the conventional condition monitoring may not be suitable to identify the root cause in many cases except for identification of deterioration. Hence considering all these limitations, it is always important to carry out details vibration measurements and diagnosis including the dynamic characterization by modal tests during installation and commissioning of machines to avoid many unknown sources of vibration related problems.

Theoretical calculations as well as finite element analysis are done to find out the natural frequencies of the simply supported shaft. It is observed from the results that theoretical calculations and finite element analysis results have match between ~ 10% differences.

First three modes and their natural frequencies are found out using ANSYS workbench. First three modes are bending modes of the simply supported shaft.

It can be seen from the results that shaft with crack shows lower natural frequencies; this is mainly because of reduction in mass and stiffness of the shaft. The results will be validated through testing.

References

[1] Jyoti K. Sinha, "Significance of Vibration Diagnosis of Rotating Machines during Commissioning: Few Case Studies", National Symposium on Rotor Dynamics (NSRD-2003), December 15-17, 2003, IIT, Guwahati, India

[2] Z.K. Peng, Z.Q. Lang and S.A. Billings, "Crack detection using nonlinear output frequency response functions", Journal of Sound and Vibration, 301, (2007), pp. 777–788.

[3] M. Kotb Ali and Others, "A Study on Fault Diagnosis by Vibration Analysis at Different Loading and Speed Conditions", 13th International Conference on Aerospace Sciences & Aviation Technology, ASAT- 13, May 26 – 28, 2009.

[4] Ludeca, "Machinery Fault Detection", a basic guide to understanding vibration analysis for machinery diagnostics.

[5] Mohd Hanif Mohd Ramli and others, "Effect vibration-based damage detection on a uniform mild steel shaft using modal response", Advances in Mechanical Engineering, ISSN: 2160-0619, Volume 2, Number 2, June, 2012, pp. 65 – 70.

[6] Yang Liu, Jing Xiao, Dongwei Shu, "Free vibration of delaminated beams with an edge crack", Procedia Engineering 75 (201), pp. 78 – 82.

[7] Pankaj Charan Jena, Dayal R. Parhi and Goutam Pohit, "Faults detection of a single cracked beam by theoretical and experimental analysis using vibration signatures", IOSR Journal of Mechanical and Civil Engineering, ISSN: 2278-1684 Volume 4, Issue 3 (Nov-Dec. 2012), pp. 01-18.

[8] Irshad A. Khan and Others, "Finite Element Analysis of Double Cracked Beam and its Experimental Validation" Chemical, Civil and Mechanical Engineering Tracks of 3rd Nirma University International Conference on Engineering (NUICONE 2012), PP. 703-708.

[9] S. Talukdar, "Vibration of Continuous System", Department of Civil Engineering, Indian Institute of technology, Guwahati.

[10] https://www.google.co.in