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Crack detection in Shaft by Finite Element Analysis and Experimental Modal Analysis

Deepak P Hujare[1], Nitesh R Girase[1] and Madhuri G Karnik[2]

[1]Department of Mechanical Engineering, Maharashtra Institute of Technology, Pune, India
[2]Department of Mechanical Engineering, College of Engineering, Pune, India
enitesh07@gmail.com

ABSTRACT

Crack is one of the measure catastrophic failure in mechanical machines so it's necessary to detect it in early stage. In this paper proposed a method to identify crack in early stage. The purpose of this study is to describe relation between modal natural frequencies change due to crack in shaft with respective crack parameters like Depth, Location and Width. Analysis is done for Single Crack and is evaluated. Analysis reveals how modal natural frequency decreases with change in crack size. It has been observed that when shaft suffers from a crack or any damage then its dynamic properties changes. Crack causes a reduction in stiffness and ultimately reduction in its modal natural frequencies which leads to change in dynamic response of the shaft. The results of modal analysis using FEA are validated with experimental modal analysis.

Key words: Modal natural frequency, FFA Analysis, Experimental Analysis

INTRODUCTION

There any many types for failures in mechanical machines and structures. Crack is one of the potential sources of catastrophic failure in mechanical machines and in structures. There is a need to detect crack in shaft in early stage to avoid damage. Therefore, it must be investigated using suitable technique in the early stage of formation. In practice, it is difficult to recognize cracks by using visual inspection techniques. Cracks are present in shaft due to various reasons. The presences of crack will change its dynamic characteristics in modal parameters like modal frequencies, modal value and mode shapes associated with each modal frequency [2]. This method is useful to detect crack in shaft in early stage to avoid damage. The vibration technique utilizes one or more of these parameters for crack detection. Due to crack there is frequency reduction in shaft which caused reduction in stiffness and natural frequency [4]. FEA is the most powerful tool which gives the results for complicated on line working assemblies for static and dynamic analysis. The change in natural frequency due to crack are calculated with respective crack location, depth and height for different modes are obtained using FEA.

DESIGN OF SHAFT FOR CRACK INVESTIGATION

In this Paper, rotor shaft systems which consist of shaft diameter of 40mm with 2 bearing supported and pulley at one end and coupling at other end is considered. 3D model for shaft consist of Drive end shaft, Non drive End shaft with rigid coupling arrangement, supported by two bearings and at the End pulley as shown in figure 1.

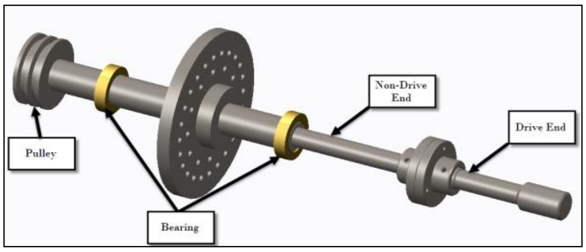
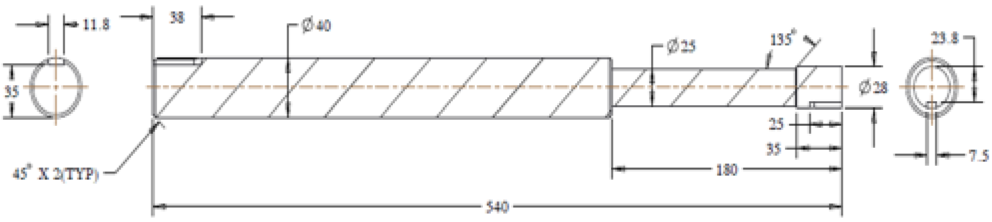


Fig.1 Rotor Shaft System



Section A-A
Fig.2 Non-Drive End Shaft 3D Model

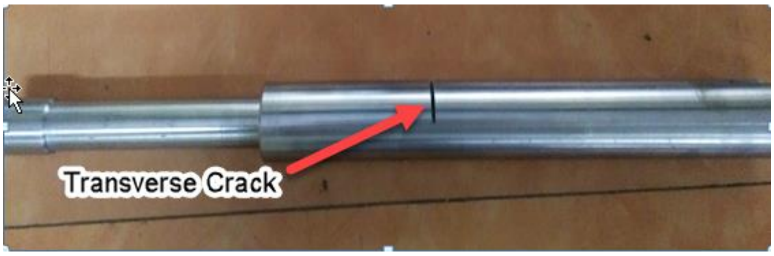


Fig.3 Crack in Shaft

Crack in Shaft

Transverse crack is introduced in non-Drive End shaft [6]. Crack produced at a distance of 300mm from coupling end with change in depth from 5mm, 10mm and 15mm with width 1.00mm to 1.5mm.

MODAL ANALSIS USING FEA FOR SHAFT WITH AND WITHOUT CRACK

Modal Analysis using FEA of a Shaft Without Crack

Computer Aided Design the engineering analysis of any complicated arrangement or system can be carried out in the shortest time by using the engineering analysis software like Finite Element Analysis (FEA) Software. ANSYS Workbench 14.5 is used to for analysis. For analysis part file is imported in ANSYS using Para solid (.x_t) format. Steps for ANSYS Workbench:

- Create or Import model
- Material used: Stainless Steel
- Boundary Condition: For static applied moment at end of 0.1Nm for Von-Mises stress calculations
  : No Boundary condition is applied for Modal analysis
- Based on the output requirements there are two types of analysis that are done:
  Static or Stress Analysis and Modal Analysis
- Meshing of Elements: "Fine Mesh" to have maximum number of elements with high accuracy
- Result Tabulation

Modal natural frequency and Von-Mises Stress are calculated from modal and static analysis from Workbench. This results are for shaft without crack. In this Modal analysis first 6 modes are Rigid Body modes hence are not considered for crack analysis. To find out dominant mode we have calculated Mode 7 to Mode 11. Von Mises stress is calculated to compare impact of crack on stress (MPa). Results of Mode shape and Stress for Shaft without crack as shown in figure 4, 5 and Table -1.

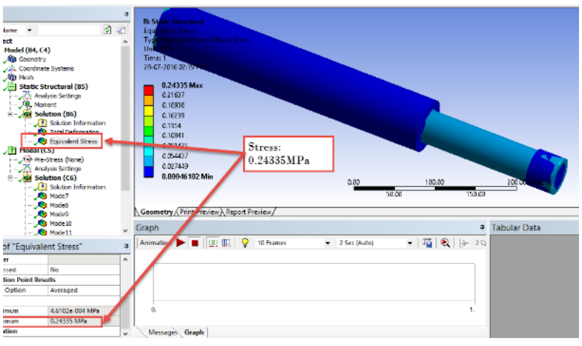


Fig. 4 Stress of shaft without crack

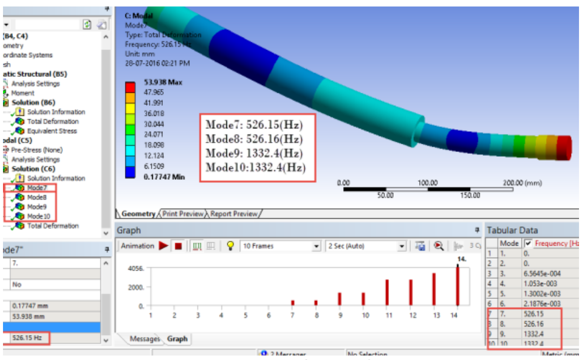


Fig. 5 Mode 7 and Mode 9 for shaft without crack

Table -1 Stress and Mode Shape for Shaft Without Crack

Stress (MPa)	Mode 7 (Hz)	Mode 9 (Hz)
0.24335	526.15	1332.4

Modal Analysis using FEA of a Shaft with Crack

Crack is propagated in ANSYS Workbench. Also to obtain better result add have impact of crack we have refine the Mesh around crack geometry. The dense type meshing can be seen for crack geometry refer Fig. 6. Readings are taken for crack locations at distance of 300mm from Coupling End, crack width is considered 1.5mm, depth consider as 5mm, 10mm, 12mm and 15mm. It is observed that due to crack there is change or decrease natural frequency of a shaft and increase in Stress. Now, to compare results with experimental, location 300mm is considered with varying depth of crack. Below Mode Shapes figures are calculated for constant Location 300mm.

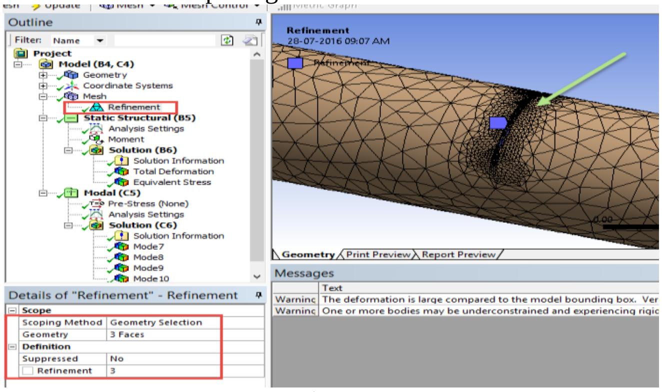


Fig.6 Meshing for Crack geometry

Mode Shape of shaft for Crack depth: 5mm

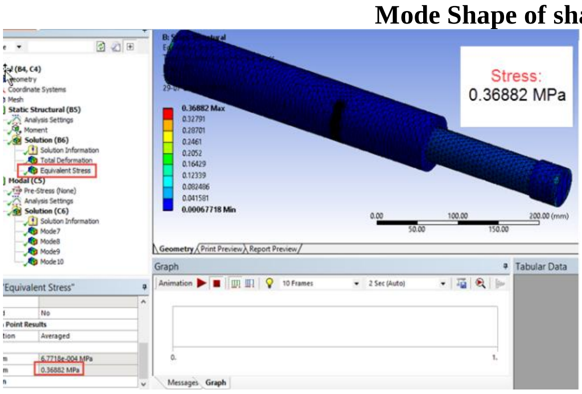


Fig.7 Stress of shaft with crack depth: 5mm

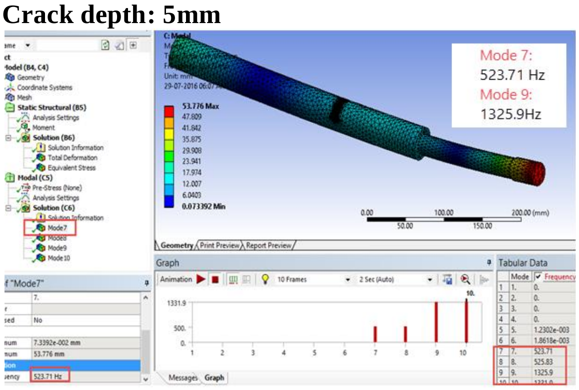


Fig.8 Mode 7 and Mode 9 for Shaft with crack depth: 5mm

Mode Shape of shaft for Crack depth: 10mm

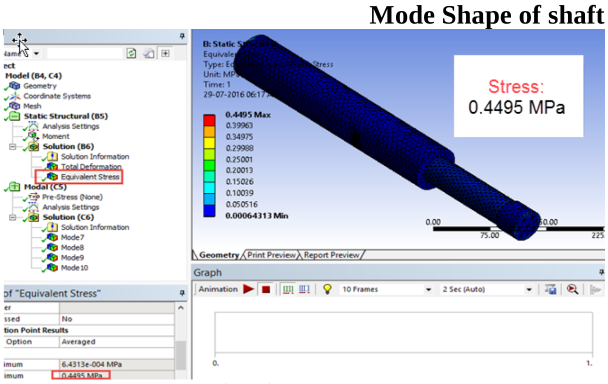


Fig.9 Stress of shaft with crack depth: 10mm

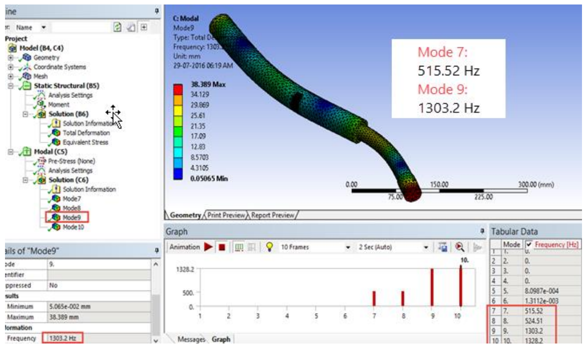


Fig.10 Mode 7 and Mode 9 for Shaft with crack depth: 10mm

Mode Shape of shaft for Crack depth: 12mm

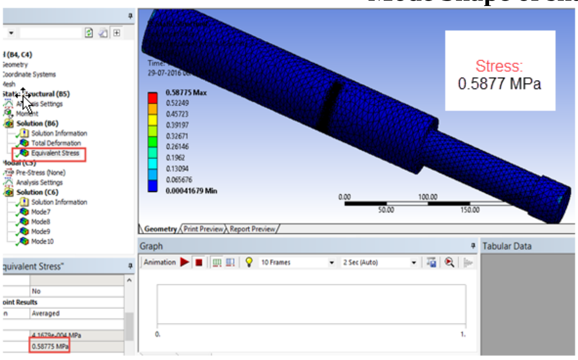


Fig.11 Stress of shaft with crack depth: 12mm

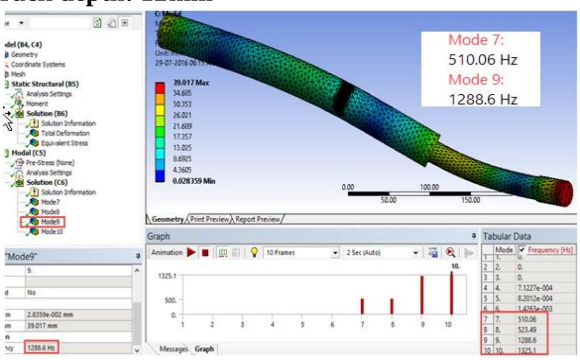


Fig.12 Mode 7 and Mode 9 for Shaft with crack depth: 12mm

Mode Shape of shaft for Crack depth: 15mm

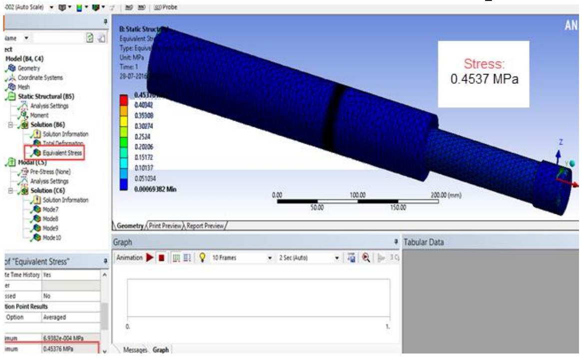


Fig.13 Stress of shaft with crack depth: 15mm

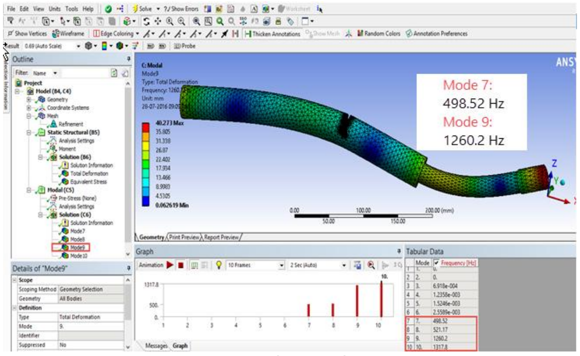


Fig.14 Mode 7 and Mode 9 for Shaft with crack depth: 15mm

Table -2 Stress and Mode Shape for Shaft with Crack

Location (mm)	Width (mm)	Depth (mm)	Stress (MPa)	Mode 7 (Hz)	Mode 9 (Hz)
300	1.5	5	0.3688	523.71	1325.9
	1.5	10	0.4495	515.52	1303.2
	1.5	12	0.5877	510.06	1288.6
	1.5	15	0.4537	498.52	1260.2

Following table -2 shows results obtained from Crack shaft at various heights of a Crack. The Mode shapes calculated are dominant modal frequencies which are decreasing as Crack size increases.

EXPERIMENTAL MODAL ANALYSIS

The setup as shown in fig. 15 contains shaft and using Vibration Analysis software (RT Pro- Photon). The Experimental setup is used to calculate natural frequency of shaft without crack and with crack shaft.

There were three accelerometers placed on the shaft. One just in vertical side, horizontal and axial direction. An FFT analyser was used to collect accelerometer signals in frequency domain signals at the output port. This FFT analyser was connected to a Computer. It had software to display the frequency spectrum as an output data on the screen.

Experimental Procedure

All the instruments were properly placed in position. Shaft without or with crack mount freely so that all DOF are free. Then three accelerometers were placed in vertical, Horizontal and axial direction on shaft as shown in Figure 15 FFT analyser was provided with accelerometer connections as input and its output port was connected to the computer as shown in Figure 16 Software in the computer was run and kept ready to capture the signals from the FFT analyser. Shaft is excited by hammer. Then vibration or response taken by accelerometer. The experimental data (Frequency spectrum) for such phenomenon was thus collected in the software.

Parameters in Experimentation

Within the experimentation, the known parameters were,
Crack size: We have introduced crack in known location with known depth and height
No boundary conditions.

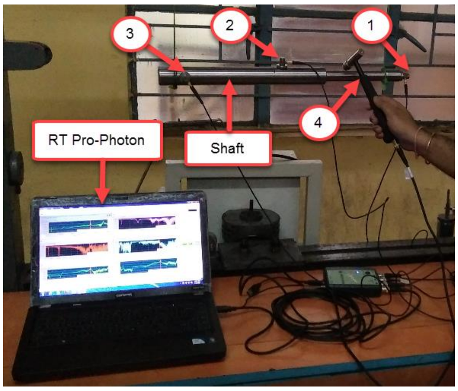


Fig.15 Experimental Setup

1. Hammer
2. Accelerometer capturing vibrations along Vertical direction
3. Accelerometer capturing vibrations along Horizontal direction
4. Accelerometer capturing vibrations along axial direction

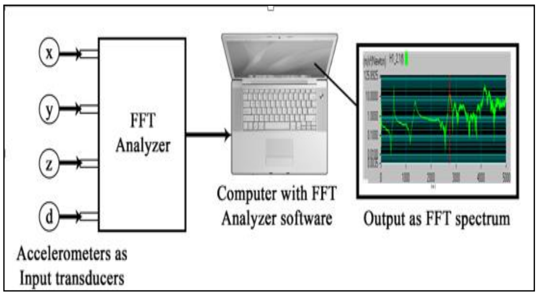


Fig.16 Block Diagram of the Test Setup Signal Capturing and Processing Unit

MODAL ANALYSIS EXPERIMENTAL RESULTS FOR SHAFT WITH AND WITHOUT CRACK

The below shown spectrums were the plots based on the experiment that was conducted.

Result for Shaft without Crack

Frequency spectrum obtained from different directions vertical, Horizontal and axial directions as per positions of accelerometers and optimized results are discussed. It was seen from figure 17 and 18 above that when the system was checked for its vibrations along Vertical direction axis, it was found that the system vibrates at a frequency of **533 Hz.**

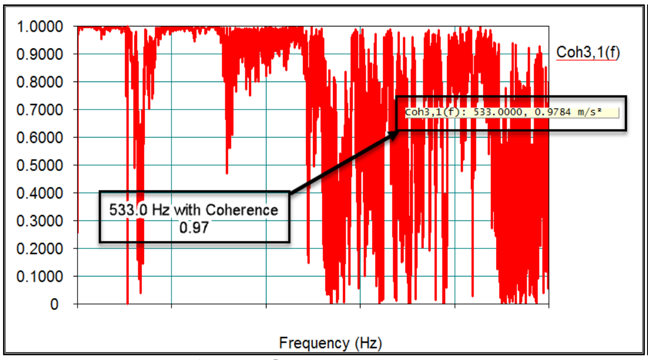


Fig.17 Coherence Spectrum

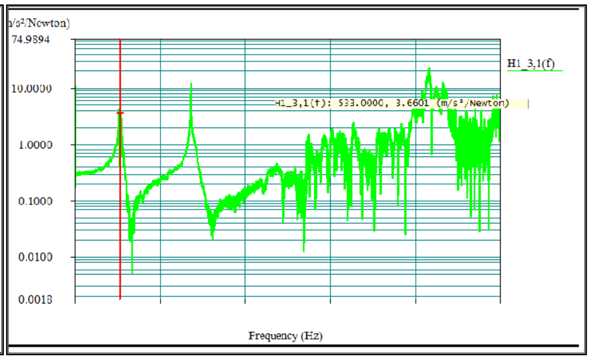


Fig.18 Frequency Spectrum

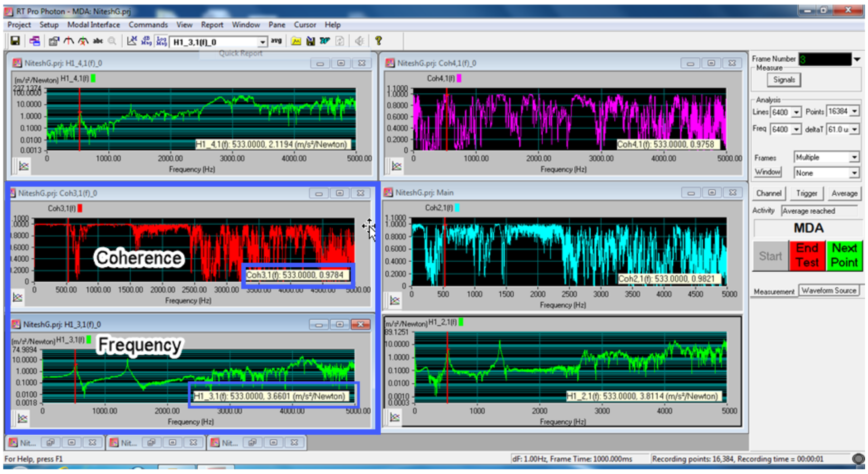


Fig.19 Frequency Spectrum for non-crack Shaft

Result for Shaft with Crack at 10mm

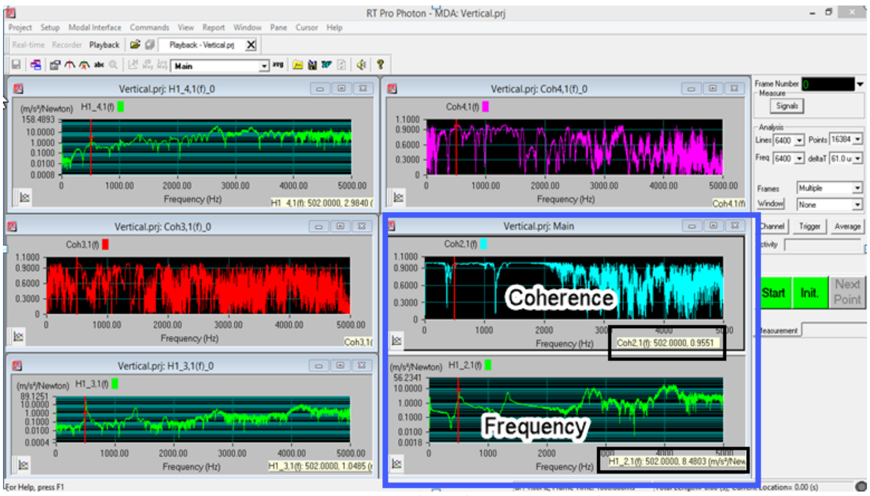


Fig.20 Frequency Spectrum of Shaft with crack of 10 mm depth

It was seen from above Fig.20 that when the system was checked for its vibrations along Vertical direction axis, it was found that the system vibrates at a frequency of **502 Hz**.

Result for Shaft with Crack at 12mm

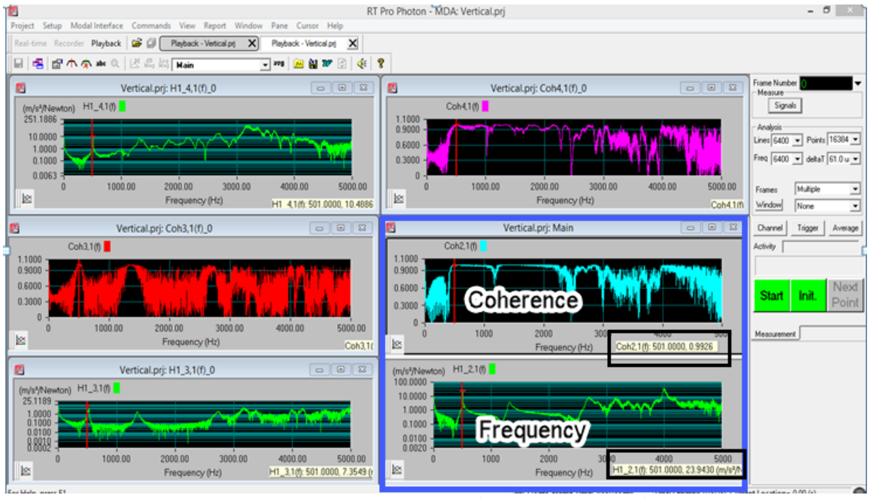


Fig.21 Frequency Spectrum for non-crack Shaft

It was seen from above Fig.21 that when the system was checked for its vibrations along Vertical direction axis, it was found that the system vibrates at a frequency of **501 Hz.**

Result for Shaft with Crack at 15mm

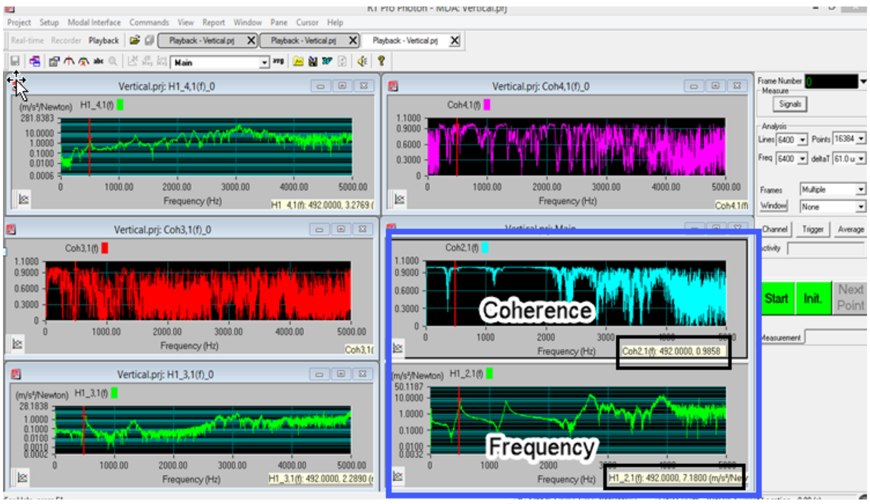


Fig.22 Frequency Spectrum Shaft without crack

It was seen from above Fig.22 that when the system was checked for its vibrations along Vertical direction axis, it was found that the system vibrates at a frequency of **492 Hz** at a coherence of **0.9858**

It was seen from the above results that there is change in natural frequency of a system or shaft due to effect of Crack. It is experimentally proved that due to crack there is change in mass, Stiffness which leads to change in natural frequency of shaft. As crack rate growth increase natural frequency also goes on decreasing.
Hence, we can conclude that as crack size increase natural frequency decreases.

Table -3 Stress and Mode Shape for shaft with crack

Location (mm)	Depth (mm)	Height (mm)	Mode 7 (Hz)	Mode 9 (Hz)
300	1.5	10	503	1303.2
	1.5	12	501	1305
	1.5	15	492	1275

EXPERIMENTAL RESULTS

From both results from Ansys and experimental, we could now compare them. This would help in understanding how valid is our model in predicting the change in behaviour of stiffness and natural frequency. So we bring together two plot (Experimental Result – Table.3 and ANSYS Result –Table.2) for both the plots as in Table-4.

Table -4 Comparison of Values Obtained from FEA and Experimentation

Mode	Width (mm)	Depth (mm)	Modal Frequency by FEA (Hz)	Modal Frequency by Experimentation (Hz)	Error (%)
7	1.5	10	515.52	503	1.98
		12	510.06	501	1.98
		15	498.52	492	1.99
9	1.5	10	1303.2	1303.2	2.00
		12	1288.6	1305	2.01
		15	1260.2	1275	2.01

If we compare the frequency values in both cases, we could say that they differ by a small value. Hence we can say that our model valid enough to predict the frequency value with which crack and without crack can estimate. It was seen that there is very less error in Numerical analysis and Experimental analysis. From above results it is concluding that crack can be calculated by FEA with addition of error can give us exact value same as experimental.

CONCLUSION

FEA results validated with experimental results. It is proved that the present crack shaft model and the FEA model are efficient enough to predict and investigate the crack. We can calculate change in properties of system like stiffness and natural frequency. This attempt is to establish a simple and systematic method of crack detection from measurement of natural frequencies of shaft. Modelling and simulation process helped to develop better understanding of Crack behaviour. This proved that Crack reduces the natural frequency of shaft. Natural frequency decreases with increase in severity of crack. Using the proposed method, fault diagnosis in any shaft, beam or rotating element with different boundary conditions, any geometrical shape and materials can be done.

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