# Analysis of a behavior of Propeller shaft for Natural Frequency using FFT analyzer

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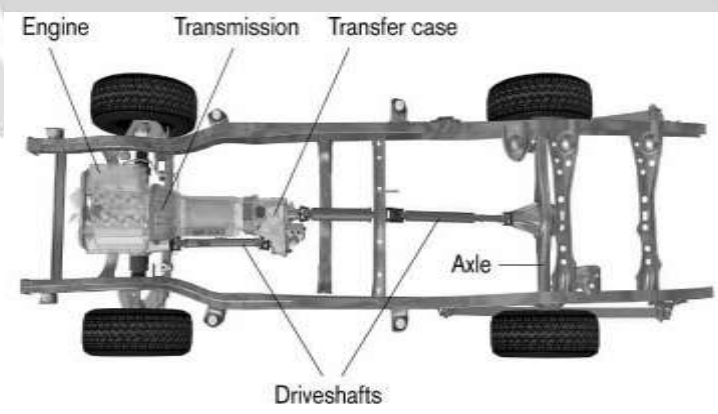
**Abstract**

*This papers presents the work related to the vibration analysis of propeller shaft. The aim of this study is to express relation between modal natural frequencies change due to availability of crack in shaft with respective crack parameters like Location, Depth and Width. Experimental results are taken with the help of FFT analyzer. Analysis is done by using these results and finally these results are validated in DEWE software. In this paper the validated results are again compared with FEA done on ANSYS results with the help of graphs*

**Index Terms—***Propeller Shaft, Natural Frequency, Fast Fourier Transform, ANSYS.*

## I. INTRODUCTION

A Propeller shaft or a drive shaft is a mechanical component which used to transmits power from the gear box to the differential in the automobile. Propeller shaft is used as a connection between gearbox and differential as they cannot be connected directly because of their position and they need a relative motion between them. Propeller shaft transmit high torque, so it is subjected to high torsion and shear stress.




A driveshaft is the connection between the transmission and the rear axle of the vehicle. It must operate through constantly changing angles between the transmission and axle. Propeller shaft consists of three parts

1. Shaft: to sustain high load, shaft is made of tubular cross-section and well balanced to avoid whirling at high speeds. Shaft is made of steel, aluminum or composites.

2. Universal joint: one or two universal joints are used for up and down movement of rear axles.

3. Slip joint: one slip joint is used for adjustment of length of propeller shaft. Slip joint formed by internal splines on

sleeve attached to left universal joint and external splines on propeller shaft.

The propeller shaft must also be capable of rotating at the very high speed required by the vehicle.The propeller shaft should provide a smooth, continuous flow of power to the axles. During the operation, it is necessary to transmit maximum low-gear torque developed by the engine. As the rear wheels roll over bumps in the road, the differential and the axle move up and down. This movement changes the angle between the transmission and the differential.

Steel SM45C is a common material for propeller shaft. There are two stages of crack development in rotating shafts: crack initiation and crack propagation. The first is caused by mechanical stress raisers: such as sharp keyways, abrupt cross-sectional changes, heavy shrink fits, dents and grooves. The second stage can accelerate the growth rate under certain conditions, viz. The presence of residual and thermal stresses in the rotor material; and Environmental conditions such as the presence of a corrosive medium.

In the present research, an effort has been prepared to formulate and develop a crack diagnostic tool using the dynamic behavior of cracked and un-cracked one piece propeller shaft by using analytical analysis and experimental analysis.

Experimental set up has been improved and is being used to get the values of first three relative natural frequencies and average relative mode shape differences of propeller shaft. The modal parameters obtained from analytical and experimental analyses have been used to formulate.

Crack is a damage that occurs in structural member. It is the separation of an object or material into two, or more, pieces under the action of stress**.** A crack in a structural member introduces local flexibility that would affect vibration response of the structure. It is difficult to recognize a crack by visual inspection techniques, when it is too fine. Hence nondestructive testing such as vibration technique is used for crack detection. If a structure is defective, there is a change in the stiffness and damping of the structure in the region of the defect. A crack on a structural member introduces a local flexibility which is a function of the crack depth. This flexibility changes the dynamic behavior of the structure, and from this change the crack position and magnitude can be identified. A crack can be transverse, longitudinal or slant type. 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.

Major characteristics of structures, which are affected due to presence of crack, are; the natural frequency, the amplitude response due to vibration, mode shape.

Crack detection is determined by variation in the dynamic characteristics of structures is a major issue that has focused here. The existence of a crack in a structural member leads a local flexibility that changes its vibration response. The main objective is that modal parameters like modal frequencies, mode shapes and modal damping are the functions of the structural properties like damping, stiffness and mass of the structure. So, the variation of structural properties will cause the variation in the modal properties.

The project work was carried out on propeller shaft of 670 mm length by using natural frequency measurement techniques. The response of the propeller shaft was obtained from accelerometer. Further, from the frequency response function, the modal frequencies were obtained. Again, inducing crack in the propeller shaft, modal frequency has to be obtained and from the experimental modal analysis using FFT analyzer and crack detection has to be carried out. Experimental mode shapes of the structural elements were obtained using the dynamic technique.

## II. LITERATURE REVIEW

A. Tlaisi et al. presented "Crack Detection in Shaft Using Lateral and Torsional Vibration Measurements and Analyses". In this paper identify the presence of a crack in a cylindrical overhanging shaft with a propeller at the free end and proved by experimental and numerical investigations. Shaft response parameters for lateral and torsional vibrations are obtained using the modal analysis software. A numerical method was developed for determining the location of a crack in varying depths when the lowest three natural frequencies of the cracked beam are known.

Yogesh D. Shinde et al. presented "Vibration analysis of cantilever beam with single crack using experimental method." In this paper, vibration analysis of a cantilever beam with single open transverse crack for different crack depth and a different crack location is done using experimental method. This analysis is done to study the response characteristics (i.e. frequency and amplitude) of cracked cantilever beam and to find effect of crack on these response characteristics. From the modal test data, it is found that, as crack depth increases natural frequency decreases and as crack position shifted towards fixed end natural frequency decreases.

Vignesh kumar Arumugam presented "Vibration analysis of drive shaft with transverse crack by using finite element analysis." In this paper, the effects of cracks at different locations and crack depth at various operating angles of the cracked propeller shaft were studied. In this work a propeller shaft is connected with two universal joints and analyzed to identify the presence of transverse crack. The crack locations and crack depth are changed and the variations of the vibrational characteristics with respect to various operation angles were studied. It is observed that the decrease in the natural frequency of the system is the primary indication of the presence of crack. These effects were interpolated by modal and harmonic analysis on the propeller shaft system.

Prof. S. B. Belkarpresented "Vibration analysis of multiple cracked shafts". In this paper, vibration analysis of multiple cracked shaft beams is performed. An Euler Bernoulli beam fixed at one end with two transverse cracks is considered. The mode shapes and natural frequencies of the beams are studied and their variation with change in position and depth of the crack is also studied.

Prof. Susenjit Sarkar presented "Free vibration analysis of an un-cracked & cracked fixed beam". This paper focuses on the theoretical analysis of transverse vibration of a fixed beam and investigates the mode shape frequency. All the theoretical values are analyzed by using ANSYS software and co relate the theoretical values with the numerical values to find out percentage error between them. Also in this paper, a model for free vibration analysis of a beam with an open edge crack has been presented. Variations of natural frequencies due to crack at various locations and with varying crack depths have been studied. A parametric study has been carried out.

AkashVardhana et.al presented "Non-Destructive testing based method for crack detection in beams". In this paper, efforts are made to develop suitable methods that can serve as the basis to detect crack location and to crack size from measured axial vibration data. This method is used to address the inverse problem of assessing the crack location and crack size in various beam structure. The method is based on measurement of axial natural frequencies, which are global parameter and can be easily measured from any point on the structure. In theoretical analysis, the relationship between the natural frequencies, crack location, and crack size has been developed. The experimental analysis is done to verify the practical applicability of the theoretical method developed.

## III. CRACK MODELING THEORY

For a shaft with a transverse surface crack and loaded with bending moment and shear force, the displacement in the i direction is given by

$u_i = \frac{\delta}{\delta p}\int J(a)d(crackarea)$……………………….(1)

where Pi is the load in the same direction as the displacement andJ(a) is the J-integral

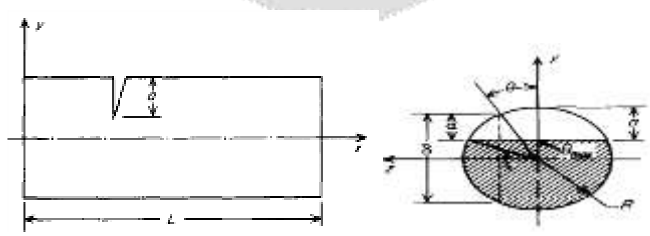


Fig. shows a simply supported system with a crack in shaft occurred on segment $L_1$.A transverse crack of depth **δ** is considered on a shaft of diameter $d_1$ (the corresponding radius is $r_1$). Here, axial forces which give coupling with transverse motions of the cracked shaft will not be considered. Therefore, the shaft is bent by a pure bending moment and the additional angular deflection of the shaft end relative to the other will be computed. The local stiffness $k_t$ due to the crack is

$$K = \frac{\pi E {r_1}^8}{32(1-\mu)} * \frac{1}{\int_{r_1\sqrt{1-(1-2\alpha)^2}}^{r_1\sqrt{1-(1-2\alpha)^2}} \left[\int_0^{\alpha(\varepsilon)} nF^2\left(\frac{n}{H}\right)dn\right]d\varepsilon} \ldots\ldots\ldots(2)$$

$\alpha=\delta/2r_1$ denotes normalized crack size,

$$\alpha(\varepsilon)=2r_1\alpha-[r_1-\sqrt{(r_1^2-\varepsilon^2)}\ ]\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

$$H = 2\sqrt{r_1^2-\varepsilon^2}$$

The function F(n/H) can be given by the experimental formula

$$F(n/H) = 1.122 - 1.40(n/H) + 7.33(n/H)^2 - 13.80(n/H)^3 + 14(n/H)^4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

The diagnosis of shaft cracks in rotating machinery has been a research challengefor industry. Such cracks can cause total shaft failure due to presence of cracks,failure require particular time, during this crack affect dynamic behavior.Transverse crack lead to dangerous and castrophic effect on dynamic behavior of rotating structure.

The appearance of transverse cracks in overhanging shafts having propellers carries with it a greater risk; it will considerably affect its dynamic behavior. Various techniques are used for crack determination. Such as vibration-based methods using modal and numerical analysis, Non-traditional methods based on ultrasonic guided waves, Numerical procedures using FEM in conjunction with modal analysis, genetic algorithms and fuzzy set theory.

Vibration analysis is a powerful diagnostic and troubleshooting tool of major process machinery. On-load monitoring can be performed mainly in three ways - Periodic field measurements with portable instruments; Continuous monitoring with permanently installed instruments; Signature Analysis.

Vibration methods study the structural or modal parameters of a structure. Structural parameters include mass, stiffness, and flexibility. The modal parameters include natural frequencies, modal damping, and mode shapes. Natural frequency has been studied most often due to its relative ease of measurement. Natural frequencies may be poor indicators of damage. Either very large cracks or very precise measurements are necessary to detect damage with vibration based methods. Compared to other methods, much power is necessary to excite multiple vibration modes.

The presence of crack in structure changes its dynamic characteristics. The change is characterized by change in modal parameters like modal frequencies, modal value and mode shapes associated with each modal frequency. It also alters the structural parameters like mass, damping matrix, stiffness matrix and flexibility matrix of structure. The vibration technique utilizes one or more of these parameters for crack detection.

Finite Element Analysis is the most powerful tool which gives the results for complicated on line working assemblies for dynamic analysis

## IV. DESIGN AND ANALYSIS OF PROPELLER SHAFT

The length of the drive shaft must also be capable of changing while transmitting torque. A slip joint is used to composite for this motion. It is located on front end of the drive shaft and is connected to the transmission. When the length of steel drive shaft is beyond 1500 mm, it is manufactured in two pieces to increase the fundamental natural frequency. The drive shaft outer diameter should not exceed 100 mm due to space limitations. So here outer diameter of the shaft is taken as 68 mm with little compromise between strength of drive shaft and decrease chassis height. Various materials are used for propeller shaft like SM45C, aluminum and composites. Here,SM45C is used.

TABLE I
MATERIAL COMPOSITION OF SM45C

| Material | C | Si | Mn | P | S | Cr | Cu | Ni |
|---|---|---|---|---|---|---|---|---|
| % | 0.45 | 0.20 | 0.80 | 0.03 | 0.03 | 0.2 | 0.25 | 0.2 |

TABLE II
MECHANICAL PROPERTIES OFSM45C

| Mechanical Properties | Symbol | Unit | Steel |
|---|---|---|---|
| Young modulus | E | GPa | 207 |
| Shear modulus | G | GPa | 80 |
| Poisson ratio | μ | - | 0.3 |
| Density | ρ | $Kg/m^3$ | 7600 |
| Yield strength | $S_Y$ | MPa | 370 |

TABLE III
DESIGN PARAMETERS OF STEEL DRIVE SHAFT

| Sr. No | Parameter of Shaft | Symbol | Value | Unit |
|---|---|---|---|---|
| 1 | Outer Diameter | Do | 68 | Mm |
| 2 | Inner Diameter | Di | 62 | Mm |
| 3 | Length of the Shaft | L | 670 | Mm |
| 4 | Thickness of shaft | T | 2 | Mm |

TABLE IV
DESIGN PARAMETERS OF STEEL DRIVE SHAFT

| Sr. No | Derived Quantities | Symbol | Unit | Calculated |
|---|---|---|---|---|
| 1 | Mass | M | Kg | 3.11 |
| 2 | Torque Transmition Capacity | T | Nm | $5.244 * 10^{-3}$ |
| 3 | Moment of inertia | I | $M^4$ | $3.24 * 10^{-7}$ |
| 4 | Area | A | $M^2$ | $6.126 * 10^{-4}$ |

*Theoretical Analysis*

To determine natural frequency two method are used

1. Timoshenko beam theory
2. Bernoulli-Euler beam theory

*A. Timoshenko Beam Theory*

Natural frequency based on the Timoshenko beam theory is given by

$$Fnt = K_s \left(\frac{(30\pi P^2)}{L^2}\right) * \sqrt{\frac{Er^2}{2\rho}} \text{ ……………………….(5)}$$

$f_{nt}$= natural frequency based on Timoshenko theory, HZ
Ks = Shear coefficient of lateral natural frequency
p = 1, first natural frequency
r = mean radius of shaft,
Fs = Shape factor, 2 for hollow circular cross section
n = no of ply thickness, 1 for steel shafts

*B. Bernoulli – Euler Theory*

It neglects the both transverse shear deformation as well as rotary inertia effects. Natural frequency based on

Fnbe = $\frac{\pi P^2}{2L^2}\sqrt{\frac{EI_x}{m}}$ …………………………(6)

TABLE V
NATURAL FREQUENCY BY BERNOULLI – EULER THEORY

| Uncracked Shaft | |
|---|---|
| No. of Modes( p) | Natural Frequency(Hz) |
| 1 | 535.23 |
| 2 | 546.56 |
| 3 | 1496.12 |

*C. Identification of Crack Location*

The shaft is with simply supported boundary conditions. The length of the shaft is L and it has a crack at a distance $L_1$ from the left support.

e =$\frac{1}{\pi}\cos^{-1}(1-\frac{(^{\Delta f2}/_{f2})(^{\Delta f1}/_{f1})}{2})$ ……………(7)

Where Δfn = fn – fn. fn and fn are the natural frequencies of uncracked and cracked. This relation suggests that the ratio of the relative vibrations of two modes depends on the location of the crack and is independent on crack geometry or properties.

*D. Determination of Crack Size*

Based on the consideration of the characteristic equations of the physical model, the change of Eigen frequency ratio Δfn/fn and the dimensionless stiffness K is given as,

Δfn/fn = 2gn(x)(1/k)………………….(8)

Where x is non – dimensional crack location which is equal to $L_1$/L or (e+1)/2

K = $(K_1L)$/EI……………………………..(9)
Δfn is the difference between uncracked and cracked beam

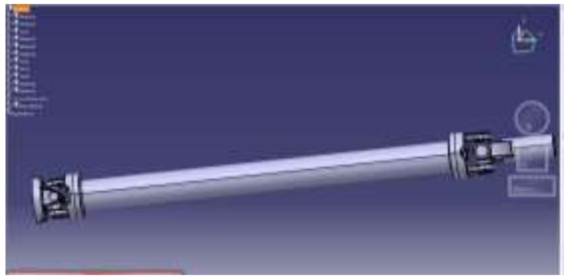
$(a/h)^2$ = $\left(^{\Delta fn}/_{fn}\right)$ ({$9.9563 sin^2\left[\frac{n\pi(e+1)}{2]} h/L\right\}$)…..(10)

Using equation 15, the crack depth ratio (a/h) can be easily found if the natural frequency of uncracked and crack location is known.

## V. ANALYTICAL ANALYSIS

### A. The cad model

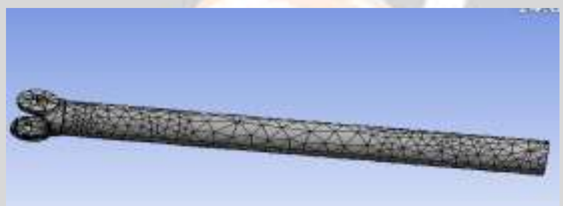
The cad model of the drive shaft was generated in CATIA and imported in Ansys workbench in IGS format. Figure 6.1 shows cad model



Here, FEA is carried out by using the ANSYS 15.0. Basic theme is to make calculation at only limited number of points and then interpolate the result for entire domain (surface & volume).

### B. The Meshed Model

The number of elements is equal to 25109 and number of nodes equal to 12739



### C. Modal Analysis

Modal analysis is used to determine the vibration characteristics such as natural frequencies and mode shapes of a structure or a machine component while it is being designed. The rotational speed is limited by lateral stability considerations. Most designs are sub critical, i.e. rotational speed must be lower than the first natural bending frequency of the shaft.

| Sr No. | Name | |
|---|---|---|
| 1 | Analysis type | Modal 3-D |
| 2 | number of nodes | 25109 |
| 3. | number of elements | 12739 |
| 4 | Element Control | Program Controlled |
| 5 | Smoothing | Medium |
| 6 | Solver Target | Ansys 15.0 Workbench |

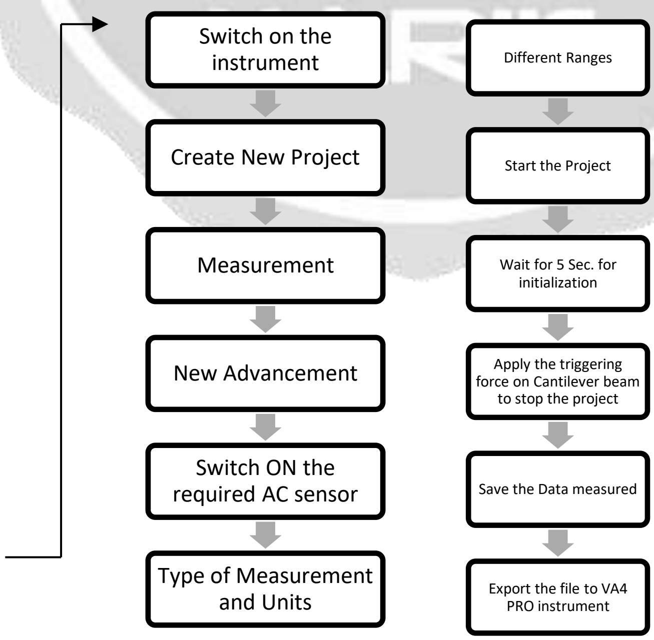
## VI. EXPERIMENTAL SETUP

Here, propeller shaft of vehicle, Tata sumo is used. Propeller shaft is fixed between two supports for performing the FFT analyzer test. This is used as boundary condition .The change of natural frequency due to a saw cut is monitored. The experiment is designed to test for correlation of the physical system to the analytical model. The shaft is actuated by Impact hammer and the resulting mechanical vibrations are analyzed by an accelometer. The accelerometers was attached to the shaft and then connected by a cable to the data acquisition system. The propeller shaft specimen was clamped with a vice and the cut made with a hacksaw. The cross sectional dimensions of the propeller shaft are 68 mm diameter and length 670 mm. The fixture holds the shaft firmly at both end and the fixture rests on a table. A small (miniature) accelerometer is attached at to the middle of the bar.The Propeller shaft used for the transverse vibration experiment hack saw-cut crack depths (2 mm, 4 mm) at two different positions (50 mm, 100 mm) on the propeller shaft specimen.

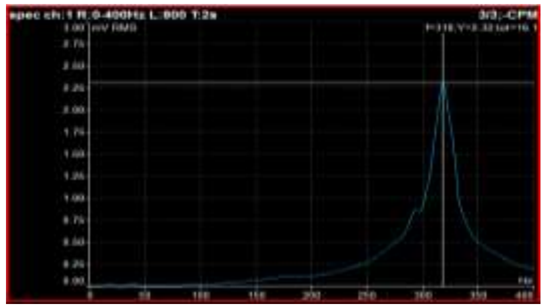
The schematic of the experimental setup is shown in Fig. The propeller shaft is fixed by Vice. This setup consists of a propeller shaft, an exciter, controller/amplifier, transducers (e.g., accelerometer), a data-acquisition system, and a computer with vibration analyzer.

Exciter is used to give desired excitation to the propeller shaft. The power is given to the exciter by controller which is connected with a computer to select the excitation parameter. The different type of excitation can be generated by exciter e.g. sine, swept sine, rectangular, triangular etc. In case of forced vibration, we use swept sine force signal, in which user have to select the initial and final frequency, and the sweep rate.

Data acquisition system receives voltage signal from the accelerometer and calibrate the data into equivalent accelerometer scale through its sensitivity and send it to computer where by using a software these data can be analyzed as time history (displacement-time) and in frequency domain (i.e., using FFT). In this experimentation, The A4400 - VA4 Pro is a unique instrument for machinery vibration diagnostics. The A4400 - VA4 Pro includes modules foranalyzing, data collecting and the recording of vibration signals.



The procedure is repeated for the shaft with a 2 mm crack depth at a position of 50 mm from the left. The frequency of excitation corresponding to the frequency of free natural acceleration of vibration is then measured with the accelerometer. The experimental procedure is repeated for the different crack depths and positions. The results are recorded in Table**.**



Screenshot of FFT analyzer

## VII. RESULTS

After performing experimental analysis, the results are obtained for uncracked shaft and cracked shaft for 2 mm and 4 mm crack depth at a distance of 50 mm from fixed end and at a distance of 100 mm from fixed end.

| Frequency (Hz) | Un cracked | a=2mm | a=4mm |
|---|---|---|---|
| Comparison of natural frequency at 50 mm distance | | | |
| 1st | 535 | 533.3 | 532.9 |
| 2nd | 545.54 | 543.1 | 542.79 |
| Comparison of natural frequency at 100 mm distance | | | |
| 1st | 535 | 530.18 | 528.45 |
| 2nd | 545.54 | 541.7 | 538.56 |

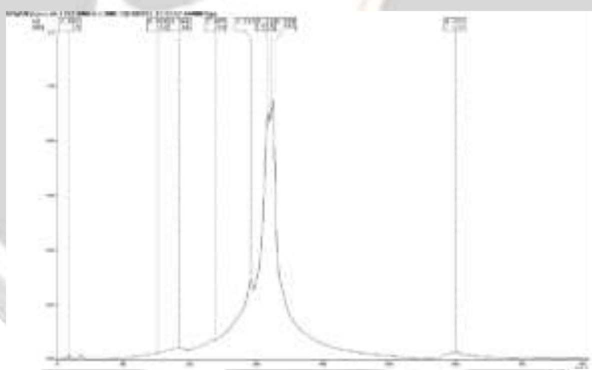
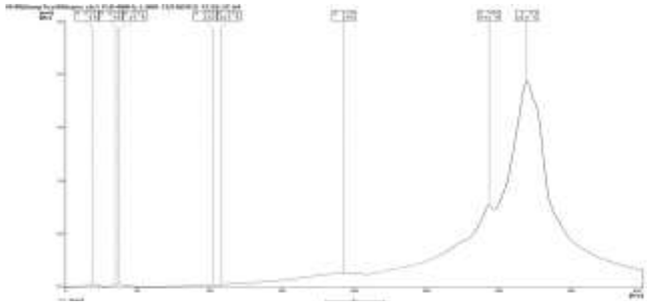


Fig shows graph for uncracked propeller shaft. This graph shows natural frequency for uncracked shaft. The highest peak is the natural frequency of shaft.

FFT analyzer result for 2mm depthat 50mm from fixed end

Fig shows natural frequency for propeller shaft at 2 mm crack depth from 50 mm distance from fixed end.

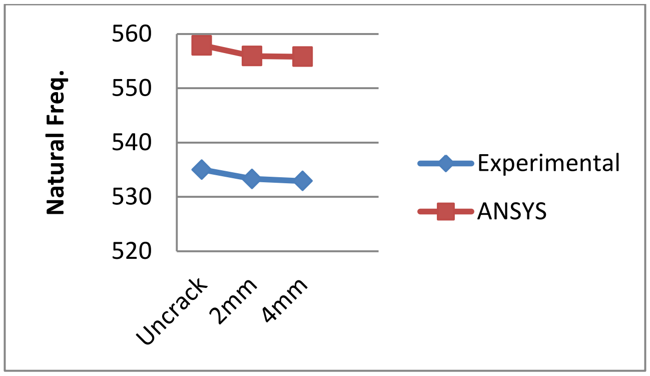


Crack depth of 4mm from 50 mm distance

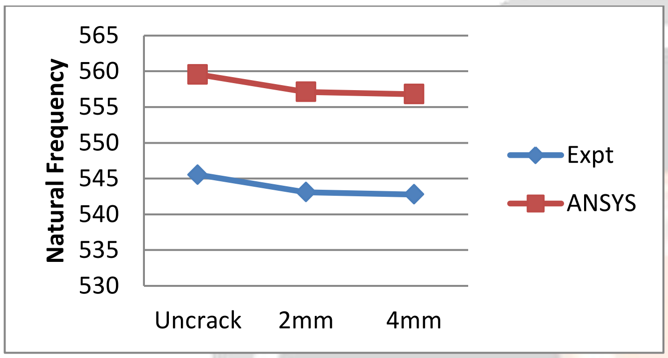
*A. Result Comparison*

After performing experimental analysis, the results are obtained for uncracked shaft and cracked shaft for 2mm and 4mm crack depth at a distance of 50 mm from fixed end and compared with FEA done in ANSYS.

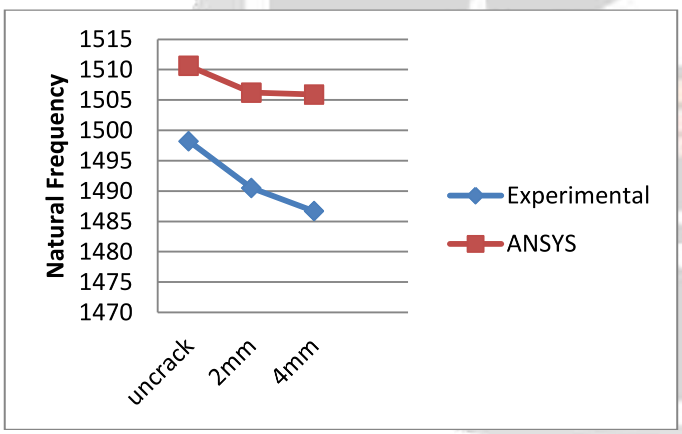
| Crack Depth | Freq 1st Mode | Freq. found in ANSYS | Freq 2nd Mode | Freq found in ANSYS | Freq 3rd Mode | Freq found in ANSYS |
|---|---|---|---|---|---|---|
| Uncrack | 535 | 557.9 | 545.54 | 559.54 | 1498.2 | 1510.6 |
| 2 mm | 533.3 | 555.91 | 543.1 | 557.1 | 1490.5 | 1506.2 |
| 4 mm | 532.9 | 555.79 | 542.79 | 556.79 | 1486.67 | 1505.9 |




GRAPH FOR MODE 1 NATURAL FREQUENCY AND ANSYS




Graph for Mode 2 Natural Frequency And ANSYS




Graph for Mode 3 Natural Frequency and ANSYS

## CONCLUSION

The results obtained from Experimental analysis are compared with results from ANSYS. The variation of the Natural Frequencies of first two transverse modes with increase in crack depth is studied. The orientation of the crack in the structure caused the local flexibility. The Natural Frequency of vibration decreases with increase in depth of the crack.

It has been observed that the mode shapes of the healthy shaft and the cracked shaft has different shapes. This is because of increase in flexibility causes increase in amplitude of vibration.

There is a Variation in natural frequencies of first two modes is observed as they are predominant in crack properties. For the same severity of crack, the frequency reduction is more for location of crack away from the support because of the stiffness of the structure; vibrations get suppressed near the supports. The variation in the experimental results is due to structure prone vibrations and vibrations getting transmitted through foundation.

## VIII. FUTURE SCOPE

Here, the considered Shaft has uniform cross section but this method can be extended to components with varying cross section, different geometry and different boundary condition.

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