EXPERIMENTAL INVESTIGATION AND ANALYSIS OF CRITICAL SPEED OF SHAFT

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Abstract: One of the methods to determine natural frequency and the mode shapes of an object is by using modal analysis. In the present work, analysis of a 1m length shaft of diameter 6 mm is performed experimentally for two different boundary conditions and first two modes are extracted for fixed-free and free-free boundary condition. The critical frequency of the shaft is determined and the results are compared with theoretical results. The shaft is analyzed using ANSYS software with pre-determined boundary conditions and mode shapes are extracted. A Campbell diagram is plotted to determine the shafts response as a function of its oscillation.

Index Terms **- Natural frequency, Modal Analysis, Critical speed, Campbell diagram, ANSYS Workbench.**

I. INTRODUCTION

Rotating machinery such as compressors, turbines, pumps, jet engines, turbochargers, etc., are subject to vibrations. These vibrations are broadly classified as synchronous (due to unbalance) or nonsynchronous such as caused by self-excited rotor whirling. The three major areas of concern are rotor critical speeds, system stability and unbalance response. Critical speeds are the un-damped natural frequencies of the rotor system. As a first step in turbo rotor design, an analysis is performed to determine the system critical speeds, mode shapes and energy distribution.

The objective of this paper is to determine the critical speed of a shaft of 6mm diameter and study the mode shapes under different end conditions using fixed and flexible bearings. The modal analysis has been carried out additionally in ANSYS Workbench 15.0 and the critical speeds are determined for the different end conditions. The modal analysis was helpful in accurately visualizing the mode shapes and their corresponding natural frequencies. The experimental results are confirmed by theoretical calculations using Dunkerley's equation to calculate natural frequency and critical speed. The geometry modeling of the shaft was done using CATIA V5.

II. LITERATURE REVIEW

Thorough literature survey was done on the procedure to obtain critical speed of shaft, analyze the shaft using ANSYS and the past studies done.

Ankit J. Desai et al [1] measured the critical speed of shafts of various diameters and have also evaluated the self-excited motion based on the change of amplitude ratio with respect to frequency ratio.

Mr. Balasaheb Keshav Takle [2] has obtained the natural frequency of shafts of different diameters and has validated them experimentally and has also determined the critical speed of shaft theoretically.

Shelar Santosh Ashok et al [3] studied and obtained the critical speed of shafts of different lengths and diameters by using analysis method.

Dr. C. M. Ramesha et al [4] carried out modal analysis of a single cylinder engine crankshaft and the natural frequencies for two conditions were found and harmonic response of crankshaft was studied.

Do-Kwan Hong et al [5] analyzed rotor dynamics of a rotor with shrink fit by using 3D FEA method. The 3-D rotor dynamics analysis and Campbell diagram considering shrink fit are examined for the critical speed of rotor

III. OBJECTIVES

- Determine critical speed of shaft experimentally.
- Obtain mode shapes experimentally for different end conditions.
- Calculate the critical speed theoretically using Dunkerley's formula.
- Perform modal analysis using ANSYS Workbench 15.0 to determine critical speed.
- To plot rotating speed of shaft against natural frequency (Campbell Diagram).

IV. CRITICAL SPEED/ WHIRLING SPEED OF SHAFT

The critical speed of a rotating shaft is the speed at which the shaft starts to vibrate violently in the transverse direction. Critical speed is also called 'whipping' or 'whirling' speed. The main reason for the whirling speed is the mass unbalance of the shaft when the shaft centre does not coincide with the geometric centre.

When the shaft vibrates with maximum amplitude i.e. when the working frequency is equal to the natural frequency, we get the first mode shape and the corresponding speed is called the first critical speed. Fig.1 shows the 1st mode shape.

When the working frequency is equal to the second natural frequency, we get the second mode shape and the corresponding speed is called the second critical speed. Fig.2 shows the second mode shape.

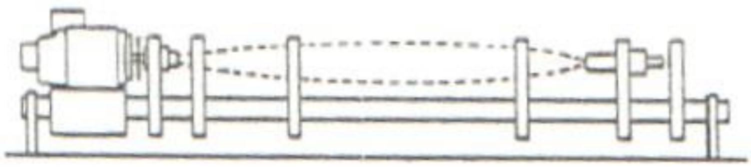

Fig.1 1st Mode Shape

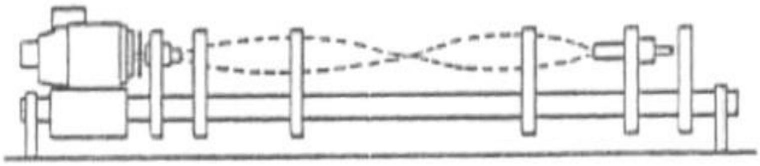

Fig.2 2nd Mode Shape

V. Campbell diagram

The Campbell diagram is one of the most important tools for understanding the dynamic behavior of the rotating machines. It basically consists of a plot of the natural frequencies of the system as functions of the spin speed. Although being based on complete linearity, the Campbell diagram of the linearized model can yield many important information concerning a nonlinear rotating system. A critical speed of order k of a single – shaft rotor system is defined as spin speed for which a multiple of that speed coincides with one of the system's natural frequencies of precession.

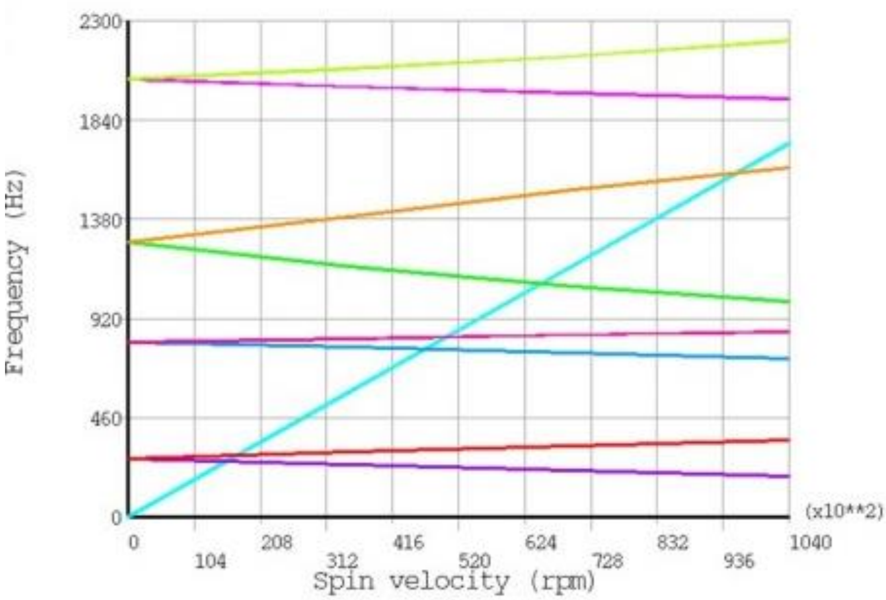

Fig.3 Campbell Diagram

VI. Natural frequency

Natural frequency is the frequency of free vibration of a body vibrating of its own without the help of an external agency.

VII. Critical speed by analytical method

Critical or whirling or whipping speed is the speed at which the shaft tends to vibrate violently in the transverse direction. It has been observed that if the critical speed is instantly run through, the shaft again becomes almost straight. But at some other speed, the same phenomenon recurs, the only difference being that the shaft now bends into bows and so on.

A critical speed is said to exist when the frequency of the rotation of a shaft equals one of the natural frequencies of the shaft. When the rotational speed is equal to the critical speed, the rotor undergoes large deflections, and the force transmitted to the bearing can cause the bearing failures.

The critical speed of shaft is calculated using Dunkerley's method as follows.

(i) Mass/unit length of shaft, $m = \rho \times A \times L$ (1)

Where, ρ = Density of the shaft material

A= Cross-sectional area of the shaft

L = Length of the shaft

(ii) Theoretical Frequency, $f_c = K * \sqrt{\frac{E*I}{m*L^4}}$ (2)

Where, I = Momentum of inertia of the shaft

L = Length of the shaft

E = Modulus of elasticity of the material of shaft

m = Mass per unit length

K = End condition constant

(iii) Critical Speed, $N_c = f_c \times 60$ (3)

Table 1 Values of K for different end conditions

K	Mode – 1	Mode – 2
Fixed – Support	2.459	7.96
Support – Support	1.573	6.30

VIII. CRITICAL SPEED BY EXPERIMENTAL METHOD

The length and material of the shaft set up are noted down. The shaft is fixed between two bearings. Fixed or flexible bearing is fixed at both ends of the shaft depending on the required end condition. The motor is switched ON and the speed is adjusted using a dimmer stat until the 1st mode shape is observed. The speed at the 1st mode shape is noted down and the same procedure is followed for the second mode shape. The critical speeds for different end conditions are obtained experimentally and the same is compared with analytically calculated speeds.

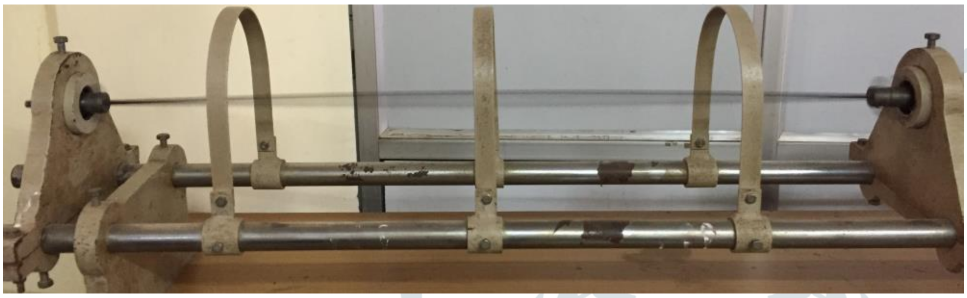

Fig.4 1st Mode Shape

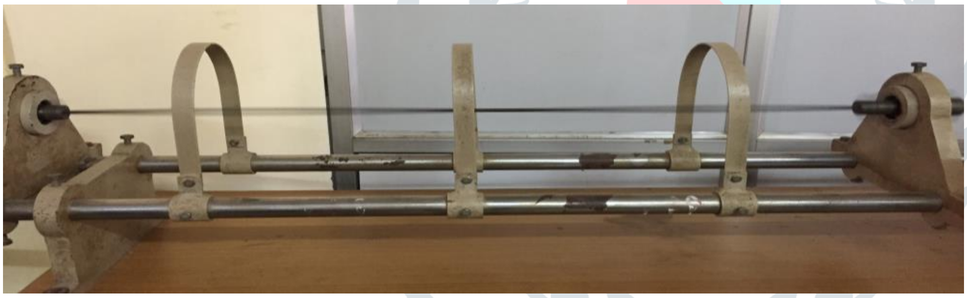

Fig.5 2nd Mode Shape

Table 2 Experimental results

Serial No	Mode Shape	Support – Support (rpm)		Fixed – Support (rpm)	
		N_c (exp)	N_c (theo)	N_c (exp)	N_c (theo)
1	1	730	727.2	1150	1165.2
2	2	2915	2985.6	3765	3772.39

IX. MODAL ANALYSIS

A modal analysis of the shaft is performed using ANSYS software and critical speed of shaft is obtained. The 3D CAD model is imported to workbench .The model is then meshed and the required boundary conditions are applied on the shaft. The modes shapes are extracted and the critical speed is obtained. The Campbell for the end condition is also obtained. Modal analysis was carried out on spring steel material whose properties are as follows:

Table 3 Properties of spring steel material

Serial No	Material Property	Value	Unit
1	Density	7850	Kg m^{-3}
2	Young's Modulus	206	GPa
3	Poisson's Ratio	0.3	-
4	Yield Strength	1200	MPa
5	Ultimate Tensile Strength	1350	MPa

Fig.6 1m Shaft

Fig.7 Meshed Shaft

CONDITION I: FIXED-SUPPORT CONDITION

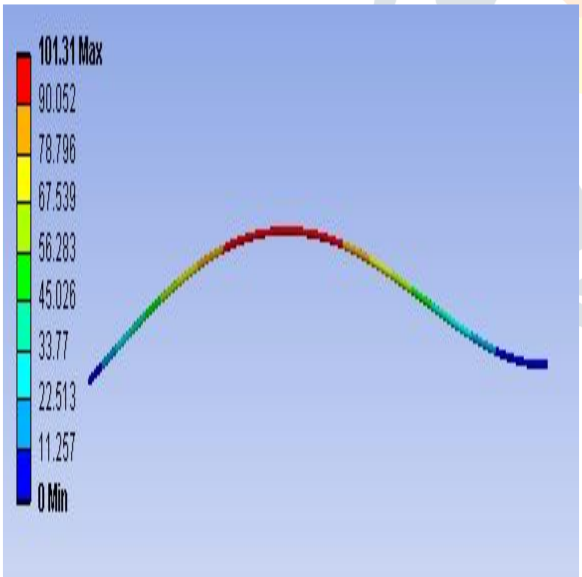

Fig.8 1st Mode Shape

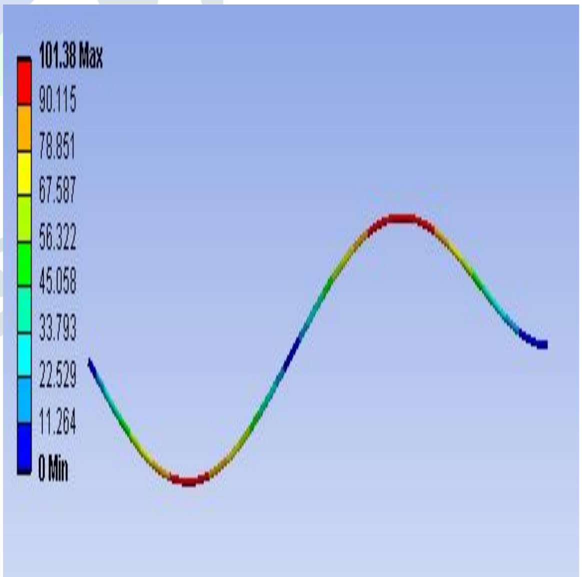

Fig.9 2nd Mode Shape

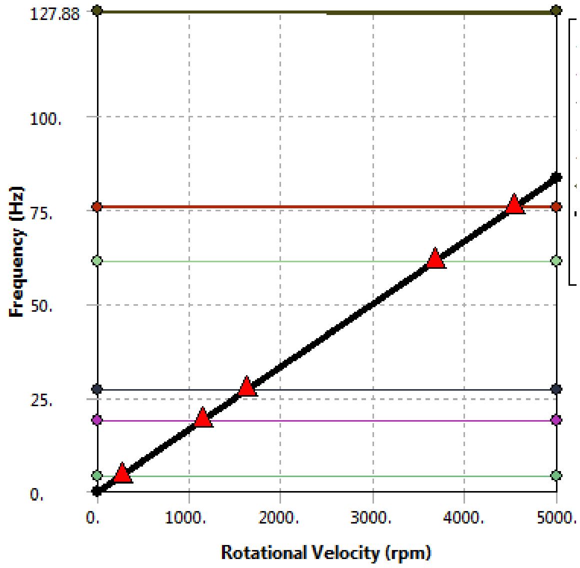

Fig.10 Campbell Diagram

CONDITION II: SUPPORT-SUPPORT

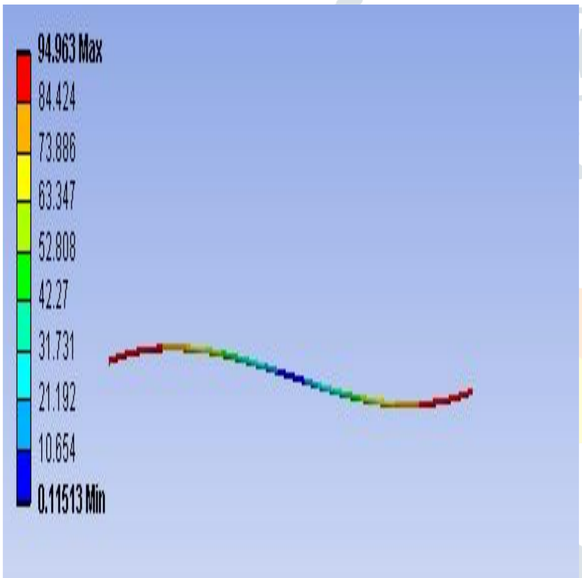

Fig.11 1st Mode Shape

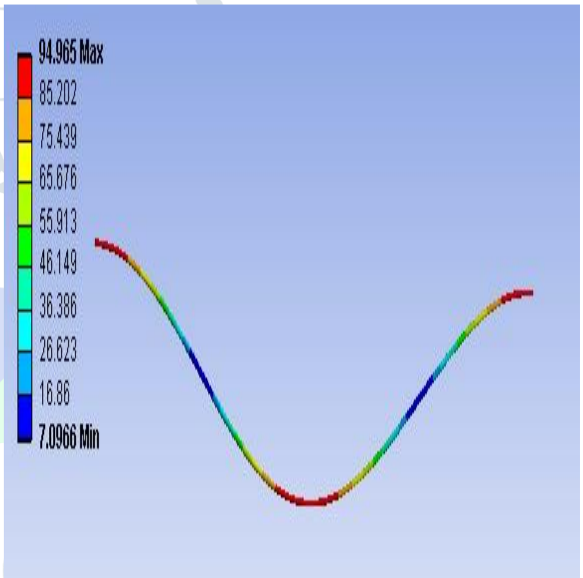

Fig.12 2nd Mode Shape

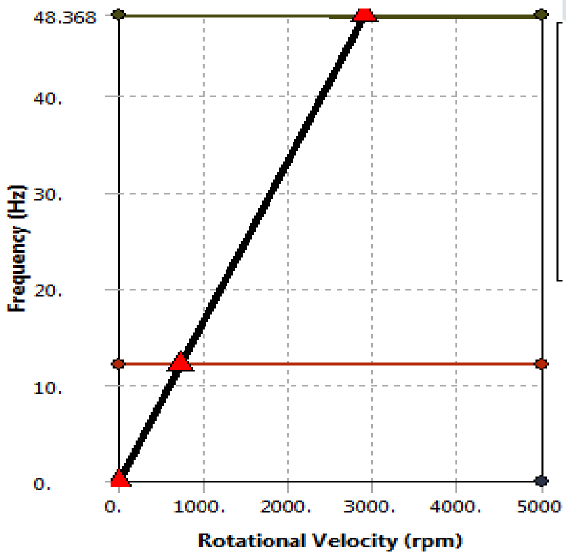

Fig.13 Campbell Diagram

ANSYS Results

Table 4 FIXED – SUPPORT

Mode	Whirl Direction	Stability	Critical Speed (rpm)
1	FW	Stable	1134.9
2	FW	Stable	3677.5

Table 5 SUPPORT – SUPPORT

Mode	Whirl Direction	Stability	Critical Speed (rpm)
1	FW	Stable	752.72
2	FW	Stable	2902.1

X. Results and Discussion

Table 6 Comparison of Results

	Mode Shape	Experimental Speed (rpm)	Theoretical Speed (rpm)	ANSYS Speed (rpm)
Fixed – Support	Mode 1	1150	1165.2	1134.9
	Mode 2	3765	3772.39	3677.5
Support - Support	Mode 1	730	727.2	725.72
	Mode 2	2915	2985.6	2902.1

From table.6 we can observe that the critical speeds obtained by analytical method, experimentation and by ANSYS software are comparatively close. The critical speeds obtained should be evaded while running the shaft to prevent it from failure.

XI. Conclusion

Experimental verification of natural frequencies of shaft for different end conditions is achieved. The critical speed which needs to be avoided is found out theoretically using Dunkerley's equation. The whirling phenomenon and its insight are thus thoroughly described. As the whirling of shaft apparatus is manufactured using conventional arrangements, the difference in theoretical and experimental values is justified. The critical speed of the shaft is also verified by modal analysis using ANSYS software. It was found that theoretical, experimental and ANSYS results are very close. The critical speeds were also obtained from the Campbell diagram by plotting the shaft speed against the vibrating frequency.

References

[1] Ankit J. Desai, Devendra A. Patel, Pranav B. Patel "Analysis of whirling speed and Evaluation of self-excited motion of the rotating shaft", INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY, ISSN: 2277-9655, pp. 784-787,2014.

[2] Mr. Balasaheb Keshav Takle "Experimental Investigation of Shafts on Whirling of Shaft Apparatus", International Journal of Science, Engineering and Technology Research (IJSETR), ISSN: 2278 – 7798, Volume 3, Issue 8, August 2014, pp. 2091-2094.

[3] Shelar Santosh Ashok, Gondkar Suryakant Ashok, Prof. Kadam Abhijit, "DESIGN AND MODAL ANALYSIS TO CALCULATE CRITICAL SPEED OF SHAFT", International Journel of Advance Research in Science and Engineering, ISSN: 2319-8354, Volume No 07, Special Issue 4, April 2018, pp.37-43.

[4] Dr. C. M. Ramesha, Abhijith K G, Abhinav Singh, Abhishek Raj, Chetan S Naik, "Modal Analysis and Harmonic Response Analysis of a Crankshaft", International Journal of Emerging Technology and Advanced Engineering, ISSN 2250-2459, Volume 5, Issue 6, June 2015, pp. 323-327.

[5] Do-Kwan Hong, Byung-Chul Woo, and Dae-Hyun Koo, "Rotordynamics of 120 000 r/min 15 kW Ultra High Speed Motor", IEEE TRANSACTIONS ON MAGNETICS, VOL. 45, NO. 6, JUNE 2009, pp. 2831-28334.