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Dynamic Analysis of Spindle Shaft

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Abstract: High Speed Machines (HSM) play a major role in the production industries, however the premature failure without alarming the hazardous leads to the development of spindle technology. Spindle is the fundamental part of the machines, it dynamic characteristics directly affects the cutting ability and the productivity of machine, machining performance can be remarkably improved by increasing the dynamic stiffness of the spindle. Spindle consists of more number of parts like bearing, motor, cooling jacket, spacers etc. Spindle shaft alone effects more on the dynamics so that here author consider one of the motorized spindle shaft to investigate the inherent dynamic characteristics like natural frequency and mode shapes by using Finite Element Method and Experimental Modal Analysis.
Keywords: Natural Frequencies, Mode shapes, Finite Element Analysis, Experimental Modal Analysis, Spindle shaft.

I. INTRODUCTION

Today High speed machines (HSM) rules the production industries in order to increase the productivity and reduces the machining cost. The premature failure of the spindle leads to the development of spindle technology. The advancement of HSM spindle design consists of configuration comprises of integrating various mechanical functions to increase system performance, accordingly interaction and coupling between various function is significant hence spindle behaviour become very difficult to analyse [1]. Spindle shaft is one of the important part in spindle assembly its dynamic characteristics directly affects the cutting performance of spindle and hence it made more importance on spindle shaft subjected to the dynamic analysis [2]. Reddy and Sharan [3, 4] used a finite-element model to study dynamic behaviour of a lathe spindle and its design consideration. Finite element analysis is the powerful solution technique in many areas like static and dynamics [5]. Experimental Modal Analysis is the important dynamic analysis to understand the inherent characteristics of structure in order to predict the failure and performance of the system and the chatters occurs on the work piece is greatly influenced by the spindle dynamics.

Modal analysis is the foundation for transient and harmonic analysis. In many engineering application the beam is considered as volume, so its cross-sectional area is usually rectangular shape but Spindle shaft is one of the structure consists abrupt change in cross sectional areas in circular shape the theoretical calculation for the stepped spindle shaft is developed by using differential transformation method (DTM). DTM is one of the iterative method to determine the fundamental natural frequency and mode shapes by using Rayleigh beam theory [6]. The response of the system is obtained without giving any initial force to the system is the free-vibration, these response gives the inherent characteristics of structure like natural frequency, mode shapes and damping ratio but in this paper we just consider the natural frequencies and mode shapes, in other words Any structure is deformed elastically and released suddenly then it start to vibrate about its equilibrium position is known as free-vibration. The number of cycles per unit time in free vibration is called the natural frequency of the system. Forced vibration is the response of structure under the influence of external energy like forces are displacement variation. Every natural frequencies have their corresponding mode shapes, while the system vibrate in its mode shapes depends on the material properties like young's modulus, density, damping ratio of material , governing mechanics , and the boundary conditions (cantilever, fixed-free, simply supported etc.). In free-free vibration the starting six frequencies are almost zero or close to zero because the system is free from all the constraints hence it has free three translation and free rotational motions.

II. LITERATURE SURVEY

In manufacturing industries there are different type of machining operation can done by using traditional and non-traditional machines. The metal removal by turning, grinding and milling etc. belongs to traditional type of machining then electro discharge machining, ultrasonic machining, electro-chemical machining etc. belongs to non-traditional machines. The main important parameter in these machining operation is to get accuracy, repeatability, and chatter free surface finishes on the work piece hence it can be achieved by investigating and controlling the vibrations of the structure[7]. Most of the literature survey indicates the importance of spindle dynamics in machine. Dynamics of spindle effects on the cutting ability and performance of the machining operation thus the investigation of spindle dynamics is significant. It can be analysed by using the Finite Element Method using

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analysis software's [8], here we use Solid-works simulation for analysis and verify the obtained results with Experimental Modal Analysis of Impact hammer test.If the natural frequency of the any structure coincide with the same frequency of external energy causes resonance leads to the vibration of the structure hence modal analysis of any rotating systems are significant. Modal analysis is the method that dynamic performance can be analysed, evaluated forecast and optimized by right of its modal parameter.

III. METHODOLOGY

In this study author considered one of the motorized spindle shaft to investigate the inherent dynamic characteristics of the spindle shaft by Experimental Modal analysis and correlate those results with the dynamic frequency obtained by Finite Element Method.

A. Experimental Modal Analysis

Experimental Modal Analysis is the procedure of determining the modal parameters like natural frequencies, mode shapes and damping ratio. With the development of Fast Fourier Transformer (FFT). Experimental Modal Analysis became an interdisciplinary field to bring together the vibrational signals, theory of vibrations etc. Frequency Response Function (FRF) is the ratio of output response of the system to input force due to applied force. Those response can be measured by means of displacement, velocity and acceleration. The obtained results are in time domain, for better understanding purpose these signals are converted to frequency domain by using Fast Fourier Transformer (FFT). Here we use Impact hammer test for analysis.

Considered one of the motorized spindle shaft of maximum diameter 135mm, weight 48kg and length is 950mm then take a proper elastic string and tied at both the ends of spindle shaft and it should hang through the stiff spring. This satisfies the required free-free boundary condition, this means that the spindle is free to rotate and translate in X, Y and Z direction respectively is as shown in the figure 1

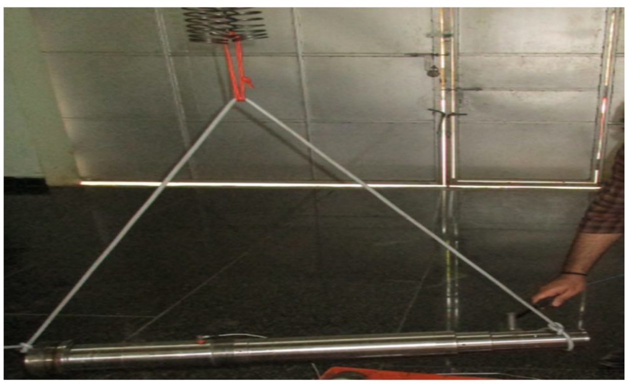

Fig 1 Free-Free boundary condition

Number around 50 points on the spindle shaft consider any one of the reference point which is always excited by the impact hammer. The tri axial accelerometer is placed at all the numbered points for obtaining the output response in X, Y and Z directions to the impulse generated at the driving force. Accelerometer is a device which measures the response as linear or logarithmic plot of transfer function against natural frequencies ("g/N"). The natural frequencies obtained from this free-free boundary condition at all the noted point are taken and measure the average frequencies by using curve fitting technique the resultant Frequency Response Function obtained is as shown in the figure 2

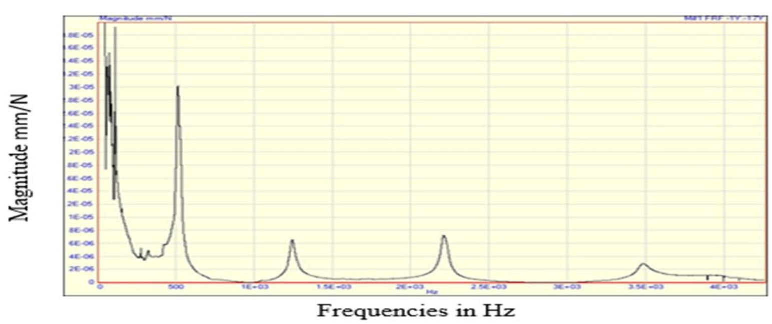

Fig 2 FRF plot by EMA at Free-Free boundary conditions

The starting six fundamental frequencies are equal to zero or close to zero in free-free boundary condition because initially the spindle allowed to three free rotational motion and three free translation motion by hanging the spindle through stiffer spring. The first, second, third and fourth order bending moment obtained from the Experimental Modal analysis are at 517Hz, 1250Hz, 2220Hz and 3500 Hz respectively. From these obtained results the spindle get start to vibrate in its first order bending mode when it runs at 31020 RPM. Similarly the twisting and longitudinal vibration of the spindle at 1803Hz and 2950Hz respectively. The 3D CAD model is to be developed or loaded to the ME Scope software and mark the response point then by using curve fitting technique the frequencies with corresponding mode shapes are obtained. The response of the spindle to the impulse from ME Scope set up is as shown in figure 3

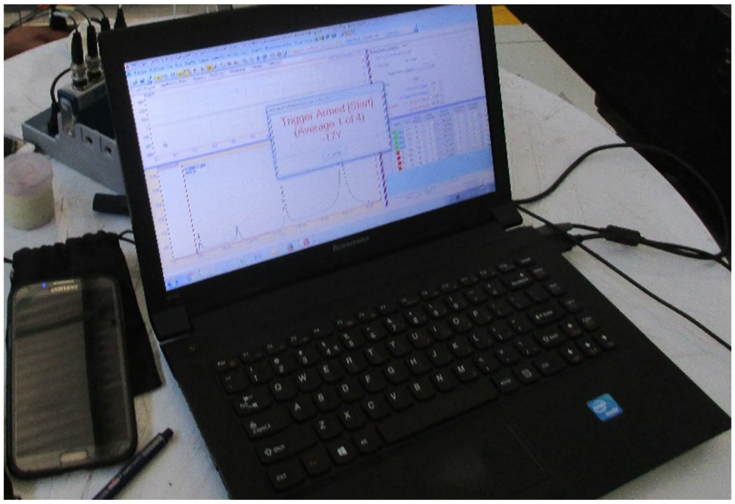

Fig 3 Response of spindle for impulse in ME scope

B. *Finite Element Method*

It is one of the powerful tool for both static and dynamic analysis. Based on the kinetic model of vibration the mathematical model can be developed to achieve the modal analysis. It is difficult for modal analysis to develop mathematical model. A general Kinetic model [5] is as shown below.

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{F(t)\} \qquad (1)$$

Where $[M]$ is the mass matrix, $[C]$ is equivalent damping matrix, $[K]$ is the stiffness matrix, $x(t)$ is the displacement matrix and $F(t)$ is the external load acting on the system, the aim of this analysis is to obtain the resonance frequencies of spindle shaft hence it is not related to any external force acting on the spindle shaft then the equation of motion becomes is as shown below.

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = 0 \qquad (2)$$

Consider the spindle shaft which is created in solid works of weight 48kg and maximum diameter is 135 mm and length is 950mm. The whole spindle material is consider as alloy steel whose density is 7700kg/m^3, material damping ratio is 0.001, poison's ratio 0.28 and young's modulus is 210GPa. The spindle shaft is as shown in the figure 4. As it is modal analysis the spindle is no need to constrain.

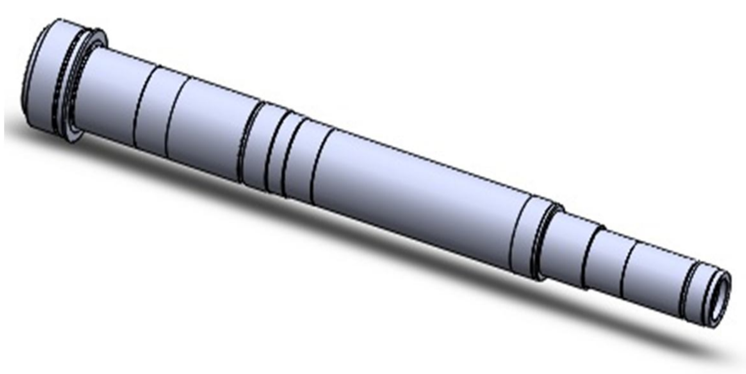

Fig 4 CAD Model of spindle shaft

Modal analysis of spindle shaft from Finite Element Method indicates the starting six frequency are equal to zero and the first, second, third and fourth order bending moment at 513Hz, 1260Hz, 2226Hz and 3443Hz respectively, similarly the twisting mode and longitudinal elongation at 1790Hz and 2952Hz respectively. The obtained first and second order bending mode shapes are shown in the figure 5 & 6

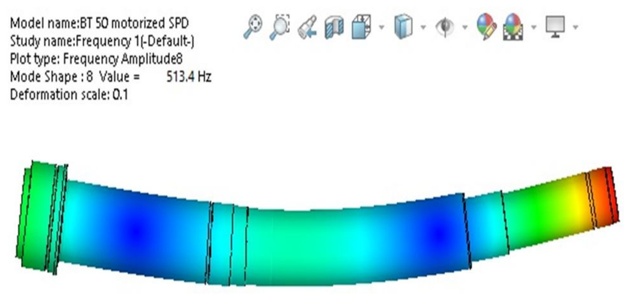

Fig.5 first order bending mode

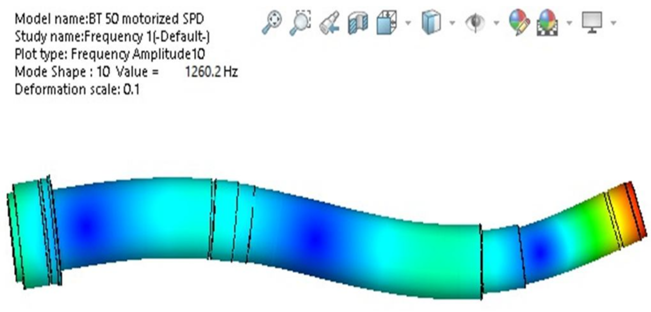

Fig.6 Second order bending mode

IV. RESULTS AND DISCUSSION

The resonant frequencies obtained from the Experimental Modal Analysis and the Finite Element Methods are correlated. The first order bending mode occur at 517 Hz in EMA and 513 Hz in FEM the remaining resonant frequencies are tabulated in below table 1. That the dynamic analysis of any rotating system is significant to avoid resonance.

Sl.No	Experimental Modal Analysis Frequencies (Hz)	Finite Element Method Frequencies (Hz)
01	0	0
02	0	0
03	0	0
04	0	0
05	0	0
06	0	0
07	517	513
08	1250	1260
09	1803	1790
10	2220	2226
11	2950	2952
12	3500	3443

Table 1 Frequencies obtained from EMA and FEA

V. SUMMARY

The above work represents the importance of dynamic analysis to investing the resonant frequencies and mode shapes which are the inherent characteristics of the spindle shaft. If there is any dangerous frequencies occurs at the required operating condition by knowing these fundamental frequencies we can easily shift those frequencies by varying the modal parameters hence the modal analysis of the spindle shaft is significant.

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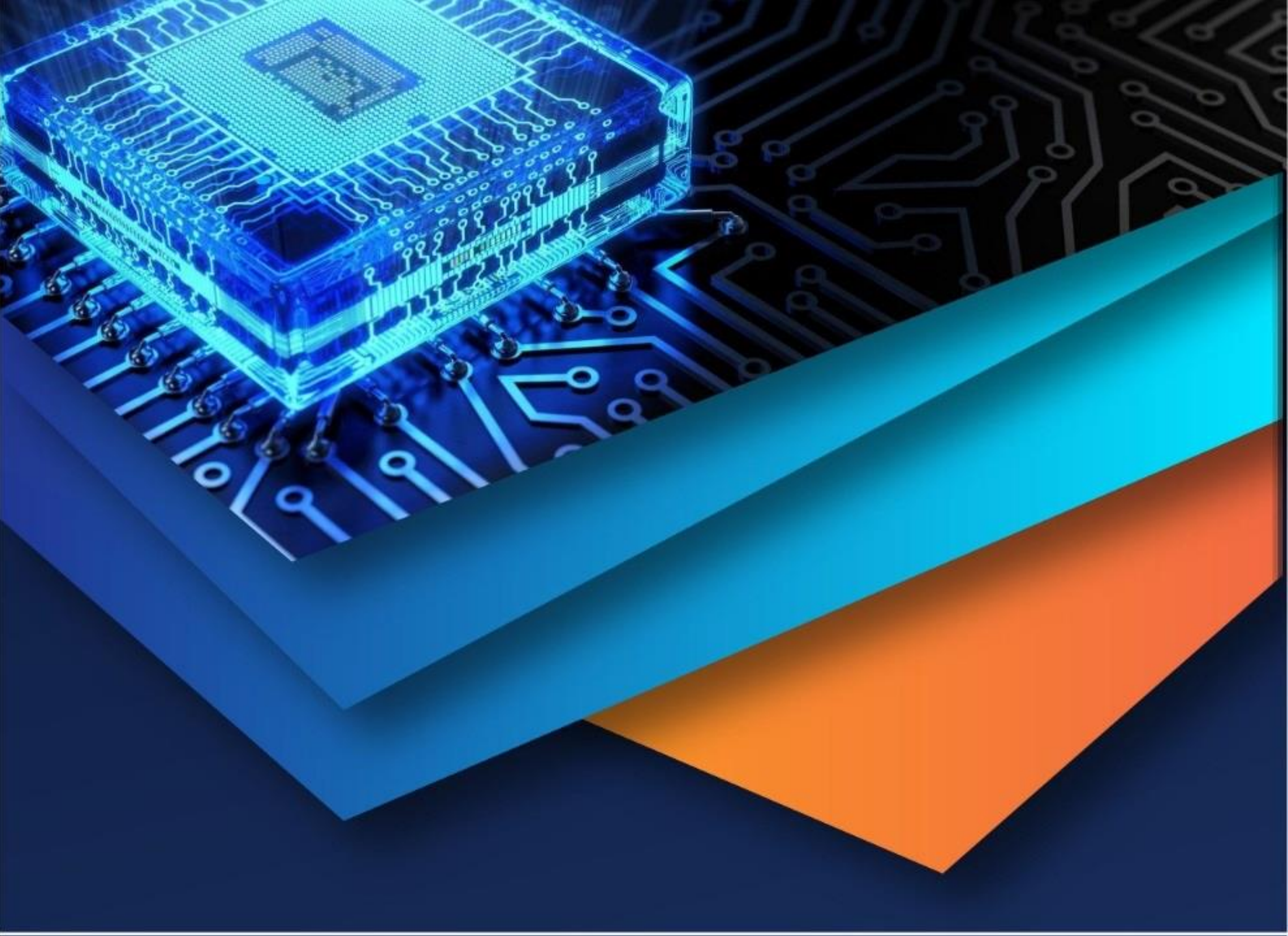

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