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RESEARCH ARTICLE

STATIC AND DYNAMIC ANALYSIS OF HEADSTOCK SPINDLE OF THE LATHE

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ABSTRACT

This paper presents a method of analysis for the prediction of static and dynamic behavior of lathe spindle. The VIBXPERT software kit is used to determine the dynamic characteristics of the spindle and FEM method is used to determine the static parameters of the headstock spindle of the lathe. Analysis of the vibration severity for different spindle speed, feed rate and depth of cut. Static analysis is carried out by determining the forces acting on spindle and deflection and stiffness of the spindle. In this vibration characterization of headstock spindle of the lathe determines the natural frequency, amplitude of vibration, level of vibration, condition of resonance and geometrical stiffness, experimentally. The results show that the maximum rotating speed of spindle is far smaller than the natural resonance region speed and good stiffness, less deflection of the spindle. From the values of vibration at spindle determined from experimental analysis, it is found that the vibration velocity increases with increase in cutting speed, depth of cut and feed rate.

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1. INTRODUCTION

Lathe is one of the most important machine tool in manufacturing industries. The quality of the work piece depends mainly on the condition of the lathe. The headstock plays the most important role in force flow of a machine tool with principal rotating motion. The machining characteristics of a given tool may be governed in many respects by the static and especially the dynamic behavior of its spindle. The spindle unit is an important part of a tool, influencing work piece quality and structural configuration of the headstock. The spindle shaft rotates at different speeds and holds a work piece. The performance of the spindle unit is usually characterized by its static stiffness, accuracy of rotation and general dynamic behavior. The static and dynamic stiffness of the spindle directly affect the machining productivity and finishing quality of the work pieces. The structural properties of the spindle depend on the dimensions of the shaft, motor, tool holder, bearings and the design configuration of the overall spindle assembly. A defect in the spindle and unbalance forces in a lathe will induce more vibration which result in deterioration of the dimensional accuracy and surface finish of the work piece. The spindle bearing system is an important link in the structural chain connecting the work piece to the cutting tool. No matter how dynamically rigid the machine tool frame may be a weak spindle system must always result at best in impaired accuracy and surface finish for the machined components and at worst in severe deterioration of machine performance due to the onset of chatter. The importance of improving the dynamic stiffness in machine tool spindles and the study of the corresponding dynamic characteristics such as mode shapes and natural frequencies are particularly critical when machines with long overhang spindles are considered.

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2. MATERIALS AND METHODS

2.1. Static analysis

The static analysis of the spindle system describes the spindle behavior in a static loading condition.. A static load is the concentrated forces that will be applied on the spindle devices while they are rotating at normal speed condition. Headstock mainly consists of stepped hollow spindle, stepped cone pulley and gears system. The spindle shaft rotates at different speeds and holds the work piece. Static analysis determines the lateral deflection and static stresses on spindle. Static analysis is more useful to determine the static stiffness of the spindle. During normal rotating condition (lathe specified speeds) pulley tension and gear force acting on the spindle. These forces are called as driving force. The lathe is working at 8 different speeds. These speeds are divided in to two categories one is direct drive and other one is back gear drive. Each speed has different belt tension and different gear force, by using basic design formulae we determines the driving force and tabulated in Table 2.1. The stepped hollow spindle is assumed to be simply supported overhang stepped hollow beam and driving forces are considered as point loads. Macaulay's method (the double integration method) is a technique used in structural analysis to determine the deflection of Euler-Bernoulli beams. There are two bush bearings are used in headstock and these two bearings are mounted on the spindle at different distances. Static stiffness is one of the important parameter of machine tools which should be properly designed to improve the performance of the tools even in dynamic conditions. Improvement in overall static stiffness of the spindle system of any machine tool results in improved work piece quality and increased productivity of machine tool. Finite Element Analysis has become one of the most powerful and popular tool for structural analysis of machine tools. Finite Element Modeling allows accurate modeling of the actual structure of the spindle through the use of variety of beam, plate and solid elements to determine the static and dynamic characteristics of the structure under these conditions. By choosing proper shapes, size and number of elements, the Finite Element Model of the spindle structure can be made very close to the actual one. Finite Element Software provides the necessary tools to perform modeling as well as analysis. BEAM188 is an element used for static and dynamic analysis of spindle. BEAM188 element is suitable for analyzing slender to moderately stubby/thick beam structures.

Table 2.1 Driving forces of different speeds

Speed in RPM	Belt Tension in N	Gear Forces in N		
		Gear-1	Gear-2	Gear-3
595	1059	F_t=713.3 F_r=259.6	F_t=410.6 F_r=149.4	F_t=230.8 F_r=84
410	1252	F_t=1035.2 F_r=376.8	F_t=595.8 F_r=216.9	F_t=334.9 F_r=121.9
286	1453.2	F_t=1483.9 F_r=540.1	F_t=854.2 F_r=310.9	F_t=480.13 F_r=174.8
198	1886	F_t=2143.5 F_r=780.2	F_t=1233.7 F_r=449	F_t=693.5 F_r=252.4
94	6690.8	F_t=4515.1 F_r=1643.3	F_t=2583.7 F_r=940.4	F_t=1460.7 F_r=531.6
65	7908.4	F_t= 6529.4 F_r=2376.5	F_t=3758.3 F_r=1367.9	F_t=2112.5 F_r=768.9
45	9235.8	F_t=9431.4 F_r=3432.7	F_t=5428.9 F_r=1975.8	F_t=3051.3 F_r=1110.6
31	12040.8	F_t=13690.7 F_r=4983.1	F_t=7880.1 F_r=2868.1	F_t=4429.1 F_r=1612.2

Figure 2.1. Experimental setup for modal

Figure 2.2. Experimental setup for spindle vibration level measurement in axial direction (X)

Figure 2.3. Experimental setup for spindle vibration level measurement in vertical direction (Y)

Figure 2.4. Experimental setup for spindle vibration level measurement in horizontal direction (Z)

2.2. Dynamic analysis

Dynamic analysis of the spindle describes the dynamic behavior of the spindle during dynamic loading condition. Natural frequency, mode shapes and vibration level of the spindle are used to study the dynamic behavior of the spindle. Numerical and experimental methods are used to determine the dynamic behavior of the spindle. The modal analysis method is used to determine the natural frequency and mode shapes of the spindle. Condition monitoring technique is used to determine the vibration level of the spindle during working condition.

2.3. Experimental Model analysis

In a modal analysis test, vibration force has applied to the structure. Exciter system or impact hammer serves this purpose. Vibration motion is measured by using magnetic transducer. These signals are processed by an analysis system that will digitize them and used them for estimation of frequency response function. The spindle subjected to hinged-hinged condition by using string is tied at both ends of the spindle. Modal analysis was carried out by using FFT analyzer (VIBXPERT), magnetic transducer, exciter or hammer and OMNITREND PC software. OMNITREND PC software is required to create the route in VIBXPERT in order to save and analyze the results. Experimentation is carried out by mounting the magnetic transducer at the middle of the spindle then the spindle is impacted by the hammer. The experiment is carried out on lathe by selecting three measuring points that is horizontal, vertical and axial measuring points on front end of the spindle. Vibration level measurement of the spindle was carried out by using FFT analyzer (VIBXPERT), magnetic transducer and OMNITREND PC software. OMNITREND PC software is required to create the route in VIBXPERT in order to save and analyze the results. Experimental work has been conducted by mounting the magnetic transducer in axial (X) vertical (Y) and horizontal (Z) measuring points on front end of the spindle for different cutting speed and depth of cut by keeping feed rate constant. During the experiment cutting speed and depth of cut varied from 31rpm to 595rpm and 0.25mm to 1mm. Cutting speed has varied based on lathe design.

3. RESULTS AND DISCUSSION

3.1. Static Analysis

The static analysis of the headstock spindle of lathe carried out by using finite element method(ANSYS) and these values are compared with the numerical method(basic design formula). The results shows that maximum deflection of 0.2532 mm at a distance 413 mm from the small end of spindle and which is supported at distance of 107 mm and 662 mm at the bearing position can be seen from the ANSYS results. The deflection of the spindle varies throughout the length due to driving forces. Fig-3.2 it can be seen that, the variation of deflection with respect to spindle length is obtained from both FEM and theoretical calculation.

Theoretical results

Due to maximum bending moment, maximum bending normal stress of 78 N/mm^2 obtainedat a distance of 419 mm from small end of the spindle. Minimum bending normal stress -43 N/mm^2 is obtained at a distance of 107 mm from small end of the spindle. These results are compared with theoretical results.From Fig-3.3 it can be seen that the variation of bending normal stress with respect to spindle length is obtained from both FEM and theoretical calculation. Maximum shear force 13690 Nis obtainedat a distance of 37 mm from small end of the spindle and minimum shear force -12780 N is obtainedat a distance of 107 mm from small end of the spindle. This shear force is used to determine the shear stress at different length of the spindle. From Fig-3.4 it can be seen that, the variation of bending shear stress with respect to spindle length is obtained from both FEM and theoretical calculation. Both bending moment and torque are acting on the spindle due to the the power being transmitted through gears and pulleys, which induces combined bending and shear stresess on the spindle. In such situations it is preferrable to calculate VonMises stress based on distorsion energy theory. Von Mises stress also varies along with the spindle length. Maximum vonMises stress of 82 N/mm^2 is observed at a distance of 491 mm from small end of the spindle. From Fig-3.5 it can be seen that, the variation of VonMises stress with respect to spindle length is obtained from both FEM and theoretical calculation.

3.2. Dynamic analysis

Natural frequency, resonance condition and vibration level is used to study the dynamic behavior of the spindle. Numerical and experimental methods are used to determine the natural frequency of the spindle. Numerical work has done by using ANSYS package and experimental work is carried out by using VIBXPERT. The first four natural frequencies and mode shapes were computed. Figure.3.6shows that Fast Fourier transformation (FFT) experimental results of the spindle it was observed that resonance is occurring at the first natural frequency that is at the 22 Hz. The second, third, and fourth natural frequencies are 54 Hz, 95Hz and 125 Hz respectively. These experimental results are compared with numerical results and computed in Table 3.1.

The viration for various cutting condition has been analysed by plotting the graph for different cutting speed and depth of cut. During working condition the vibration level of the spindle increases. Experiment is carried out on spindle using VIBXPERT kit. During turning operation the vibartion level of the spindle is influenced by three parameters such as cutting speed,depth of cut and feed rate . Experimental work has been carried out by varying cutting speed and depth of cut keeping feed rate constant.

By varying cutting speed and depth of cut, root mean square value (RMS) of velocity of vibration has been measured in three different directions of the spindle such as axial (X), vertical (Y) and horizontal (Z), directons. The RMS value of velocity of vibration variation with respect to depth of cut in axial, horizontal and vertical directions. Table 3.2. shows the experimental result of vibration in axial, horizantal and vertical direction of spindle. Figure 3.6,3.7 and 3.8 shows the comparison of vibration level in axial, horizantal and vertical directons for different depth of cut and cutting speed.

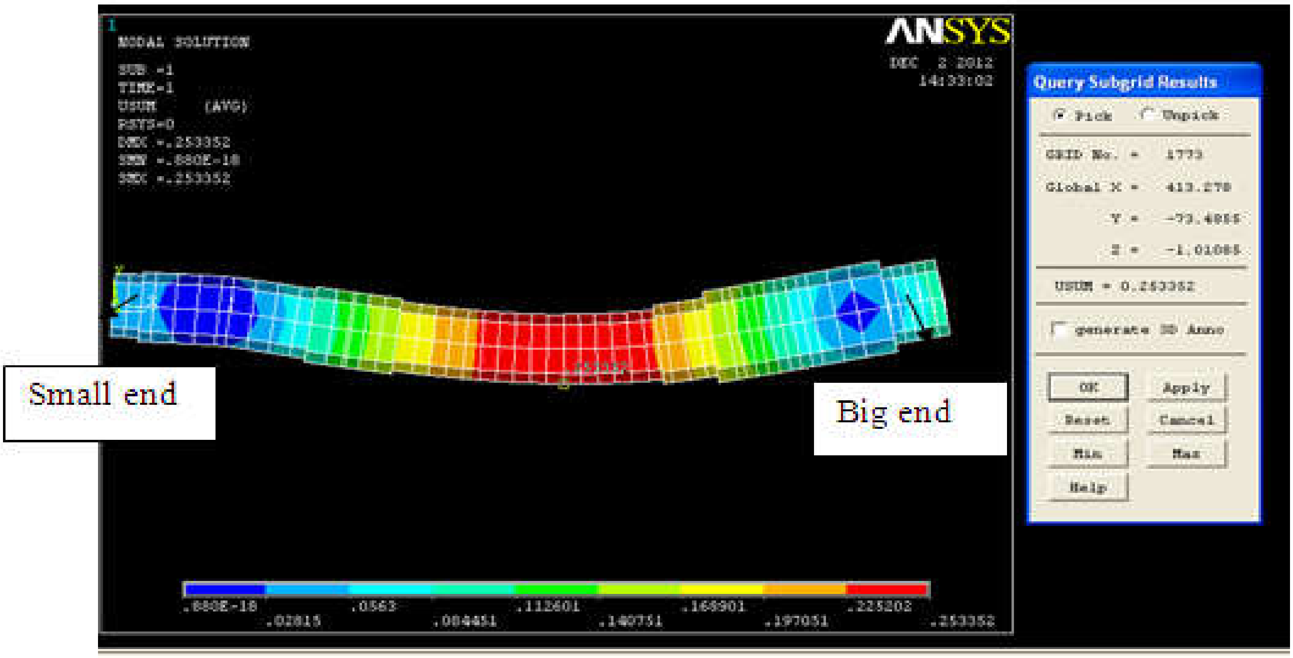

Figure 3.1. Deflection of the spindle

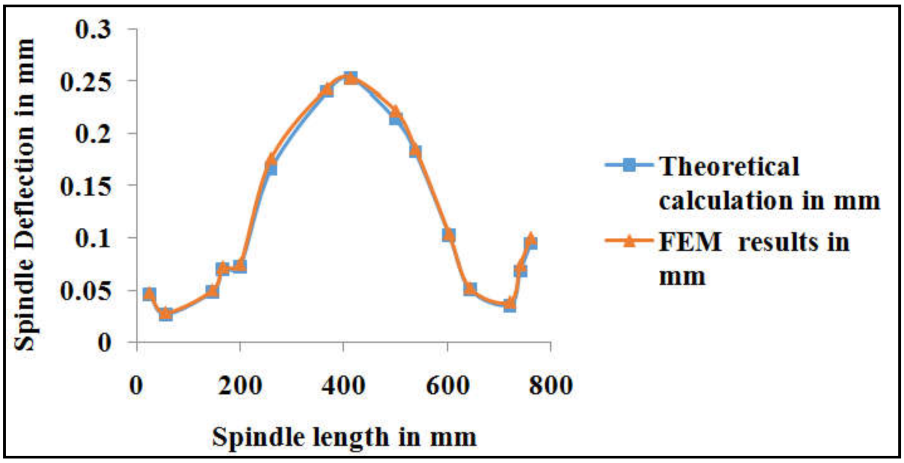

Figure 3.2. Variation of spindle deflection with respect to spindle length from both numerical and theoretical results

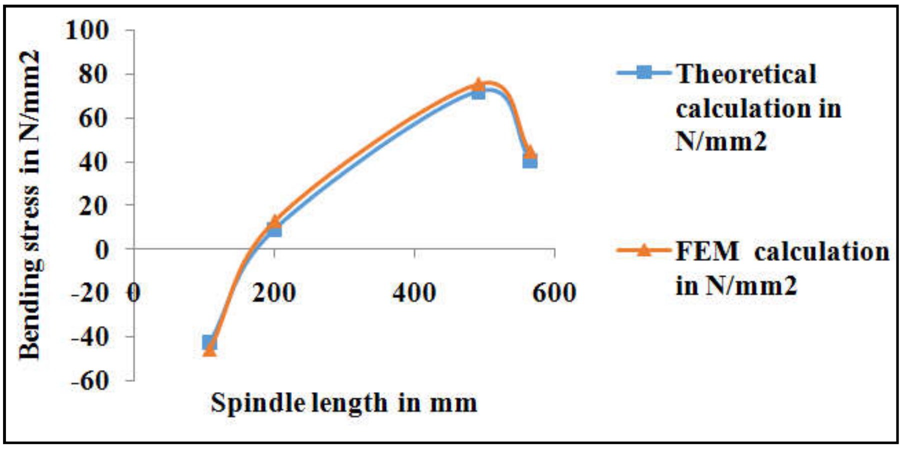

Figure 3.3. Variation of Bending normal stress with respect to spindle length from both numerical and theoretical results

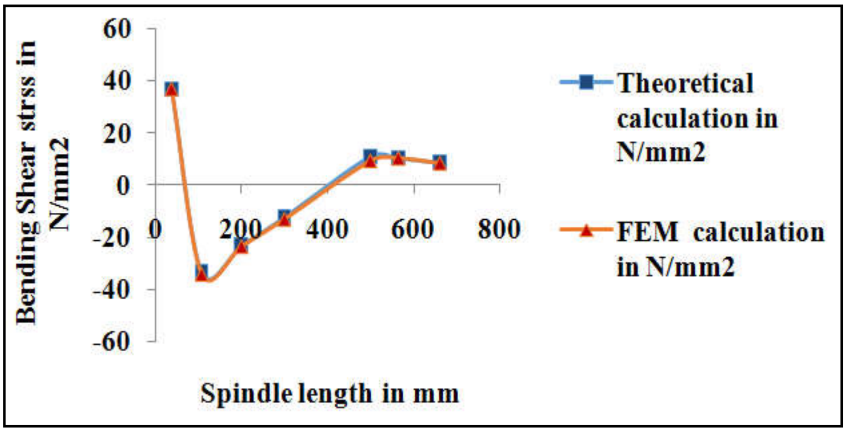

Figure-3.4 Variation of bending Shear stress with respect to spindle length from both numerical and theoretical results

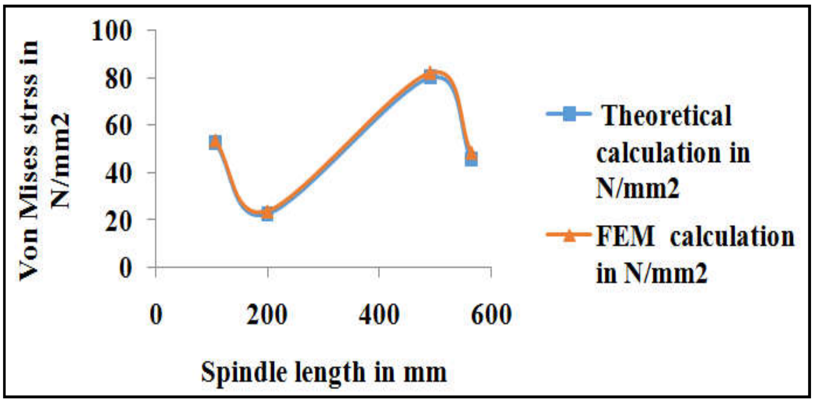

Figure-3.5Variation of VonMises stress with respect to spindle length from both numerical and theoretical results

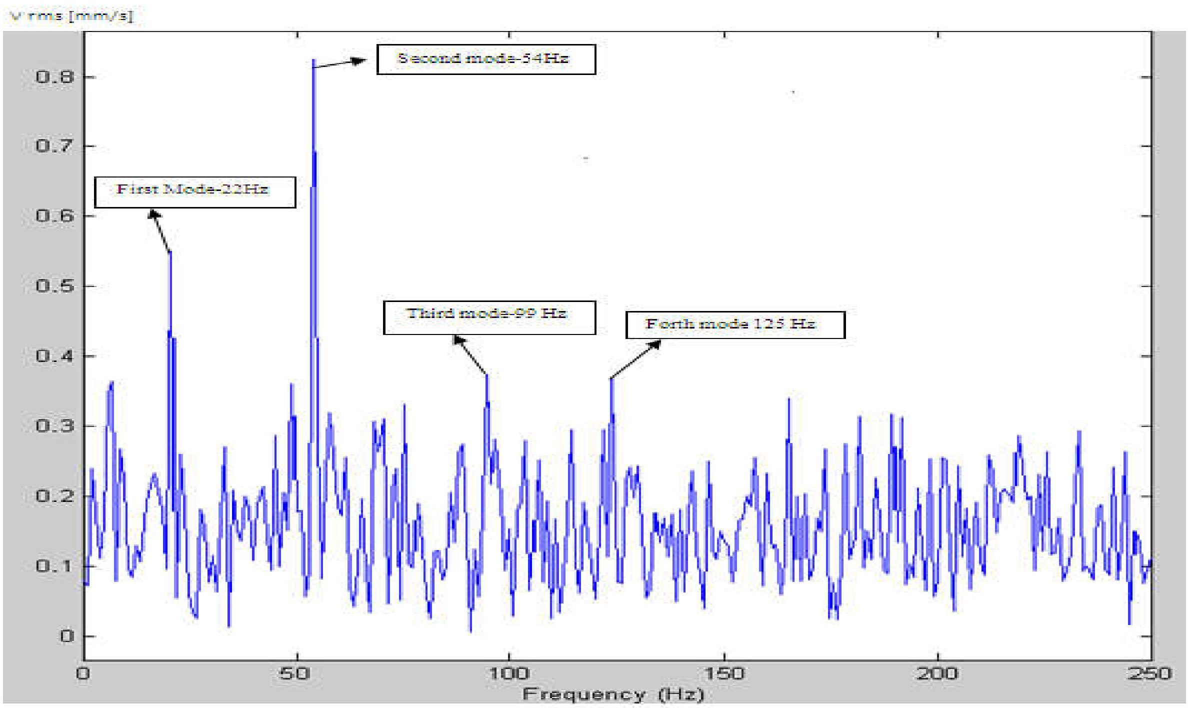

Figure 3.6. Fast fourier transformer(FFT) result

Table 3.1. Natural frequency of the Spindle

Mode number	Numerical results in Hz	Experimental results in Hz	Percentage Error
Bending mode-1	21.7	22	1.64
Bending mode-2	57.7	54	6.31
Axial mode-3	97.8	99	1.18
Bending mode-4	117.1	125	6.33

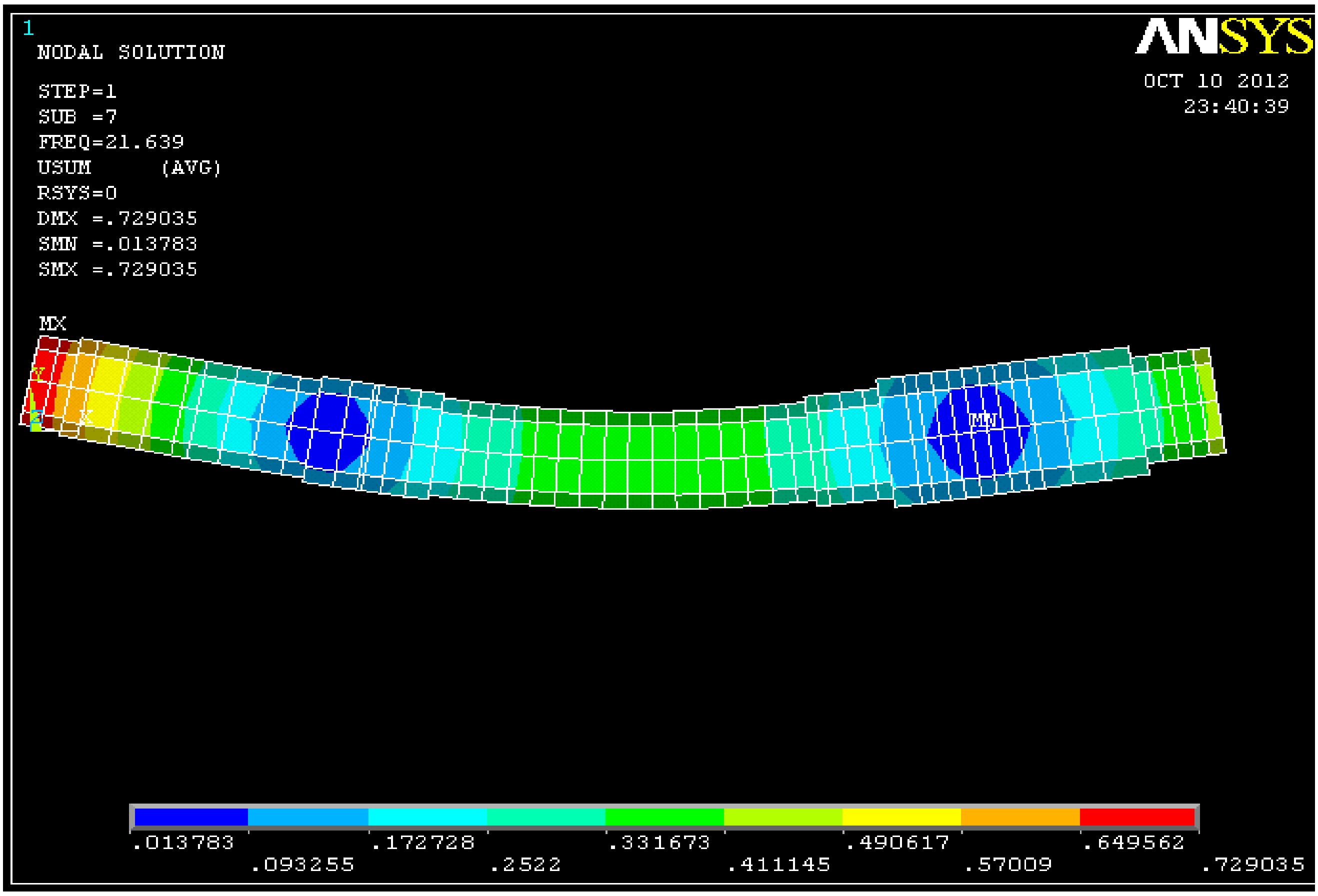

Figure 3.2. Mode shape at natural frequency 21.7 Hz (Bending mode)

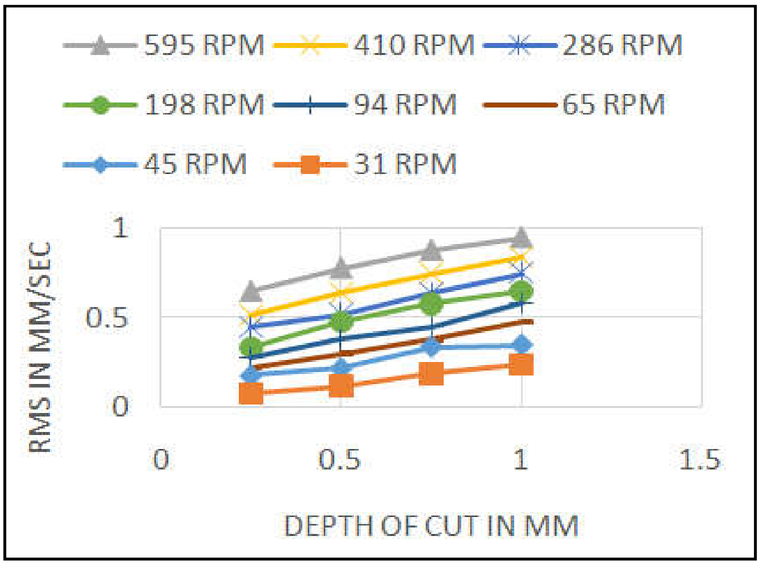

Figure 3.6 Variation of vibration level of the spindle in axial direction

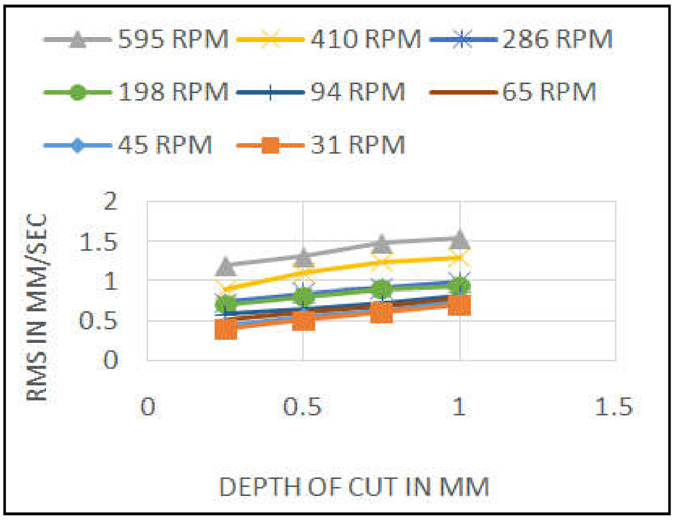

Figure 3.7. Variation of vibration level of the spindle in Horizantal direction

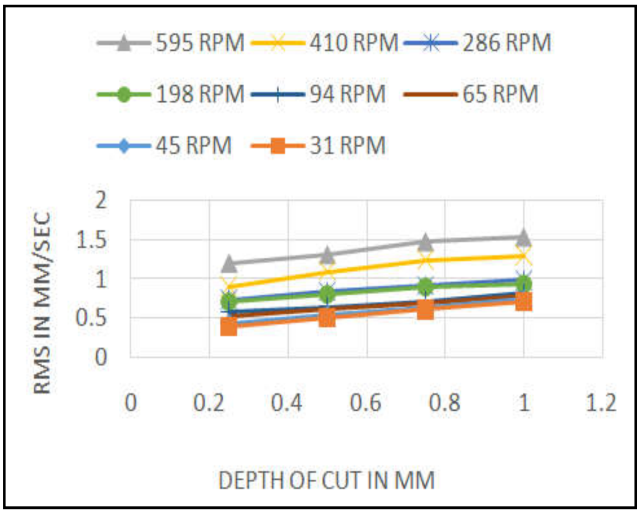

Figure 3.8. Variation of vibration level of the spindle in vertical direction

Table 3.2. Input parameters and dynamic response of accelerometers

EXP No	C.S in RPM	DOC in mm	F.R in mm/rev	Amplitude of velocity level of spindle					
				Axial		Horizontal		Vertical	
				RMS	Peak	RMS	Peak	RMS	Peak
1	595	0.25	0.06	0.65	0.09	1.2	0.7	0.35	0.08
2	595	0.5	0.06	0.78	0.1	1.31	0.89	0.48	0.12
3	595	0.75	0.06	0.88	0.13	1.48	0.99	0.59	0.15
4	595	1	0.06	0.95	0.15	1.54	1.08	0.63	0.18
5	410	0.25	0.06	0.52	0.07	0.9	0.5	0.31	0.06
6	410	0.5	0.06	0.64	0.09	1.1	0.8	0.39	0.1
7	410	0.75	0.06	0.75	0.12	1.24	0.91	0.41	0.13
8	410	1	0.06	0.84	0.14	1.3	1.01	0.51	0.15
9	286	0.25	0.06	0.45	0.05	0.74	0.45	0.28	0.04
10	286	0.5	0.06	0.52	0.09	0.85	0.72	0.34	0.09
11	286	0.75	0.06	0.64	0.1	0.92	0.88	0.38	0.11
12	286	1	0.06	0.75	0.12	0.99	0.95	0.45	0.13
13	198	0.25	0.06	0.34	0.06	0.71	0.37	0.21	0.03
14	198	0.5	0.06	0.48	0.08	0.81	0.66	0.24	0.06
15	198	0.75	0.06	0.58	0.1	0.9	0.78	0.32	0.09
16	198	1	0.06	0.65	0.11	0.94	0.89	0.4	0.1
17	94	0.25	0.06	0.28	0.04	0.59	0.28	0.18	0.01
18	94	0.5	0.06	0.38	0.06	0.65	0.54	0.21	0.04
19	94	0.75	0.06	0.45	0.09	0.72	0.69	0.24	0.06
20	94	1	0.06	0.58	0.1	0.82	0.81	0.3	0.09
21	65	0.25	0.06	0.22	0.02	0.52	0.17	0.12	0.008
22	65	0.5	0.06	0.3	0.04	0.61	0.36	0.17	0.02
23	65	0.75	0.06	0.38	0.07	0.69	0.62	0.19	0.04
24	65	1	0.06	0.48	0.09	0.79	0.79	0.21	0.07
25	45	0.25	0.06	0.18	0.01	0.44	0.11	0.1	0.006
26	45	0.5	0.06	0.22	0.03	0.55	0.24	0.12	0.009
27	45	0.75	0.06	0.34	0.06	0.64	0.54	0.16	0.01
28	45	1	0.06	0.35	0.08	0.75	0.61	0.19	0.05
29	31	0.25	0.06	0.08	0.009	0.4	0.09	0.09	0.002
30	31	0.5	0.06	0.12	0.01	0.51	0.13	0.1	0.006
31	31	0.75	0.06	0.19	004	0.61	0.34	0.14	0.009
32	31	1	0.06	0.24	0.06	0.71	0.56	0.16	0.04

Conclusion

In this work, the static and dynamic analysis of a typical geared lathe spindle is presented. Numerical and experimental methods are used to determine the static and dynamic behavior of the lathe spindle and also there values are compared with theoretical results wherever possible. It can be seen from the static analysis results that the maximum deflection of spindle is found to be 0.2532 mm at a distance of 413 mm from the small end of the spindle. The maximum bending stress of 75 N/mm^2 is obtained at a distance of 491 mm from small end of the spindle. Maximum shear stress 37 N/mm^2 obtained at a distance of 37 mm from smaller end of the spindle. The maximum Von Mises stress of 82 N/mm^2 is obtained at a distance of 491 mm from small end of the spindle. Stiffness of the spindle obtained is 150 KN/mm. The dynamic analysis of the spindle system describes the dynamic behavior of the spindle in a dynamic loading condition. Natural frequency, resonance condition and velocity /amplitude of vibration of the spindle is used to study the dynamic behavior of the spindle.

Modal analysis results show that the lowest natural frequency of the spindle is 22 Hz which is bending in nature from both FEM and experimental results. The first critical speed of the spindle happens to be at 1298 rpm which is very much away from the maximum rotating speed of the lathe spindle which is 595 rpm. Experiments are conducted on lathe machine and machining variables such as vibration velocity in horizontal, vertical and axial direction of spindle is measured based on the vibration signal collected through a VIBXPERT data acquisition system. The effect of parameters such as cutting speed and depth of cut on machining variables is evaluated. Results indicate that the vibration velocity level increases as the cutting speed, depth of cut and feed rate increase. Also it can be seen that at lower cutting speed, vibration level of the spindle remains almost constant, but as the cutting speed increases vibration level also increases steadily. Hence it is found that cutting speed and depth of cut influence the vibration character of spindle and have to be judiciously chosen for a given material to minimize the vibration level.

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