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Static & Modal Analysis of Lathe Spindle using ANSYS

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ABSTRACT

The machine tool spindle provides the relative motion between the cutting tool and the workpiece which is necessary to perform a material removal operation. The present machine tool structures consist of spindle system which plays a vital role in the quality of the final product and enhances the overall productivity and efficiency of the machine tool itself. During its operationthe spindle undergoes many vibrations due to various factors like bearing defects, incorrect bearing alignment, out-of-balance assembly, incorrect lubrication and high critical speeds. The major force acted on spindle is due to cutting force. The distance between the bearing supports of spindle plays an important role in reduction of deformation in spindle. It is very important to analyze the vibration effect on a spindle to avoid the damage occur due to resonance. Herestatic structural analysis is carried out on spindle to decide the better span and then modal analysis is done using the ANSYS software.

KEYWORDS: Lathe spindle, static analysis, modal analysis, ANSYS, bearing span, resonance, cutting force.

1. INTRODUCTION

In machine tools, a spindle is a rotating element of the machine,which is responsible for the rotations of chuck(workpiece holder) to carry out various operations, which often has a shaft at its heart. In shop-floor the word spindle is used metonymically to refer to the entire rotating unit, including the shaft itself, its bearings and any other items attached to it (chuck). On the other hand, a machine tool may have several spindles, like the headstock and tailstock spindles on a bench lathe. Among the several ones,the biggest one is the main spindle. In industrial areas, the specialized tasks require the specialized machine tools in order to satisfy the high-volume mass production. These tools may have a group of 4, 6, or even more main spindles. These tools are called multispindle machines. For instance, gang drills and many screw machines etc, can be considered as multispindle machines. On the other hand, even a bench lathe possesses more than one spindle (including the tailstock), it is not a multispindle machine, because it has only one main spindle.

Examples of spindles include

- On a lathe (whether wood lathe or metal lathe), the spindle is the main component of the headstock.
- In the machinery of rotating-cutter woodworking,shaped milling cutters are seated on the spindle for cutting features (such as rebates, beads, and curves) into moldings and similar millwork.
- Similarly, in the machine tools for rotating-cutter metalworking (such as the drill presses and milling machines), the tool is fixed to mounted on the spindle (example, via a chuck).

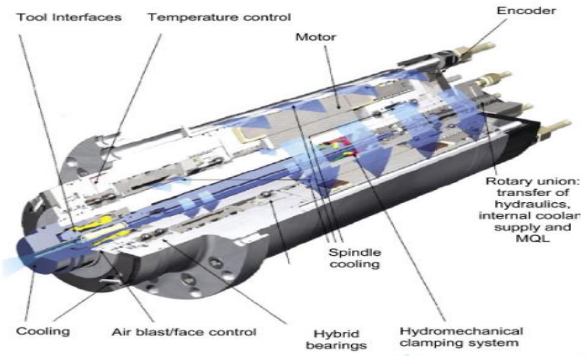


Fig 1: Spindle arrangement

Varieties of spindles include grinding spindles, electric spindles, machine tool spindles, low-speed spindles, high speed spindles, High speed spindle, belt-driven spindle and more.

2. PROPOSED WORK

The performance of the spindle depends on various parameters like material properties, span of bearing supports, the forces applying on it, the speed at which it is being operated and many more. Here in this paper the spindle is tested for various materials at different span distances. One better span is decided for a material on the basis of its deformation. Then modal analysis is done on the spindle at the decided better span. Based on the modal results and the static structural results, the better material and the better span is determined.

3. MATERIALS USED

Titanium is the material widely used in various industries like aircraft, aero-engines, bio medical devices and components in chemical processing equipment [1]. Hence Ti-6Al-4V is the considered workpiece material in the turning operation. The quality of the machined surface depends on the workpiece, process carried out and tool related parameters such as feed-rate, cutting fluid,cutting speed and depth of cut used while machining the workpiece [2].

Table 1 : Chemical composition

Material	Ti	Al	V	Fe	C	Ni	Zn
Ti-6Al-V	90.00	6	4.00	<0.3	<0.10	--	--
WC-Co	0.12	--	--	0.14	5.45-5.65	0.04	0.002

The strength of the material can be defined by several parameters including Tensile Strength and Yield Strength [3].So, in order to machine the high strength material (Ti-6Al-4V) the cutting material is to be stronger than this.So, the cutting material considered is Tungsten -carbide cobalt alloy. It has high Tensile strength, hardness, Yield strength and also it possesses high thermal conductivity comparing to workpiece material(Ti-6Al-4V) [4].

For spindle, the material has been chosen based on various parameters like, bending resistant,high shear strength, staticstrength,fatigue strength, good machinability, Ductility, thermal resisting properties, lower brittleness etc.

Table 2: Mechanical Properties

Property	Ti-6Al-4V	WC-Co
Tensile Strength	1170 Mpa	1440 MPa
Tensile Yield Strength	1100 Mpa	1100 MPa
Modulus of Elasticity	114 Gpa	570-700 GPa
Density	4.42 gm/cc	14.95 gm/cc
Thermal conductivity	7.2 W/m.k	110 W/m.k

Some of the commonly used materials for spindle manufacturing are, High-carbon chromium bearing steel, Martensitic stainless steel, Steel alloys and carbon steel for tools and machinery,Aluminium chrome molybdenum steel. Based on the properties of above said materials, spindle materials are selected in such a way that they exhibit the similar properties of above said materials commonly used for spindle [5].The materials used in this work for spindle are 45C8, C35Mn75 (Indian steel) and GS-17CrMo5-5. The chemical composition of the materials is given in the table below.

Table 3:Chemical composition of spindle materials

Material	C	Mn	Si	S	P	Cr	Mo
45 C8	0.40-0.50	0.60-0.90	0.10-0.35	0.040	0.040	-	-
GS-17Cr Mo 5-5	0.15-0.20	0.5-0.100	<=0.60	0.02	0.025	1.0-1.5	0.45-0.65
C35Mn75	--	1.2	0.4	--	--	0.04-0.08	< 0.05

The various properties of the materials selected for the spindle are tabulated below,

Table 4: Properties of materials

4. CUTTING FORCE CALCULATIONS

A chip removal force is applied to the workpiece through cutting tool for the metal removal to happen during the machining process. The applied force acts against thereaction forces generated in the plane of cutting action. The cutting plane is nothing but, a theoretical plane in which the material is broken away from the workpiece by the tool turns into chips .

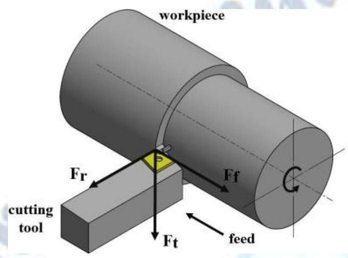
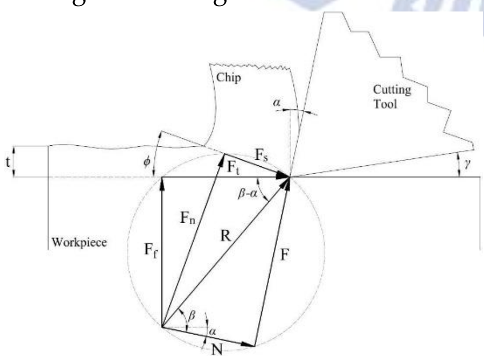


Fig 2: Cutting forces generated in turning operation

The various forces acting on the workpiece in the cutting plane are cutting force , friction forces between the chip and the tool , the workpiece and the tool. In general, analyzing the cutting forces and mechanics in cutting operations is a difficult task due to the complexity in workpiece and cutting tool geometries.So, in order to simplify the process and make simpler estimations for the forcecalculations, the turning operation is assumed to be the Orthogonal cutting. The spindle removal is to be done carefully and neatly.The cutting edge of the tool in orthogonal cutting is perpendicular to feed direction. Hence no cutting forces are generated on the tool in radial direction, which makes the operation a two-dimensional cutting process.In calculations, the cutting force and its components are calculated using the orthogonal cutting basics. According to Merchant, the cutting forces are shown as point forces acting on the tip of tool although they are actually distributed over the plane in orthogonal cutting.



Material	45C8	C35Mn75	GS-17CrMo 5-5
Young's Modulus (GPa)	190-210	190-200	211
Poisson's Ratio	0.27-0.3	0.27-0.3	0.29
Density (g/cm3)	7.85	7.85	7.85
Ultimate strength (MPa)	660	600-750	490-640
Yield strength (MPa)	560	400-500	315

Fig 3: Merchant circle representation of cutting forces.

The forces in this figure are described as follows,

R	Resultant cutting force [N]
F_f	Cutting force(feed) component perpendicular to cutting direction [N]
F_t	Tangential force on the tool [N]
F	Friction force [N]
N	Normal force generating the friction F [N]

βangle can be defined as the friction angle between cutting force R and normal force N, and this angle can be defined in terms of m , the friction coefficient.

$$\mu = \frac{F}{N}$$
$$\mu = \tan\beta$$
$$\beta = \tan^{-1}(\mu) \qquad (1)$$

consider, b_c is the width of the cut in radial direction and angleΦ is defined as the cutting angle,which is the angle between the cutting plane and the cutting direction. Hence the geometry in the Merchant circle, the component of R can be obtained as,

$$F_t = tb_c\tau_s \frac{\cos(\beta-\alpha)}{\sin\phi\ \cos(\phi+\beta-\alpha)} \qquad (2)$$

$$F_f = tb_c\tau_s \frac{\sin(\beta-\alpha)}{\sin\phi\ \cos(\phi+\beta-\alpha)} \qquad (3)$$

And the parameter formula necessary to find the material specific K_t and K_f values is ,

$$\phi = tan^{-1}\frac{r\cos\alpha}{1-r\ sin\alpha} \qquad (4)$$

So, from above equations we can say that the cutting forces can be obtained from process parameters. However, it is difficult to predict these specific parameters, therefore these formulas are used differently in practical situations.So, new parameters K_t and K_f

known as specific cutting and tangential forces factors are introduced [6] as ;

$$K_t = \tau_s \frac{\cos(\beta-\alpha)}{\sin\phi \cos(\phi+\beta-\alpha)} \quad (5)$$

$$K_f = \tau_s \frac{\sin(\beta-\alpha)}{\sin\phi \cos(\phi+\beta-\alpha)} \quad (6)$$

Using these new coefficients in equations in (2) and (3) , the cutting forces can be rewritten as;

$$F_t = tb_c K_t \quad (7)$$

$$F_f = tb_c K_f \quad (8)$$

So now the Resultant cutting force R,

$$R = \sqrt{{F_t}^2 + {F_f}^2} \quad (9)$$

The possible worst-case scenario is needed to begenerated to estimate the cutting forces. Hence, the sample case is Ti-6Al-4V workpiece of diameter D = φ110 mm, length L = 50 mm is to be turned at the rate of f = 0.35 mm/rev feed , depth of cut b_c = 6 mm and speed N = 217 rpm, t= 0.2 mm and the cutting ratio r = 0.8.

Assuming $\alpha = 5°$ for the turning operation. The coefficient of friction between the workpiece and tool is taken as [7]

μ = 0.39

from eq (1) ,

$\beta = \tan^{-1}(0.39) = 21.36°$

for the cutting ratio r = 0.8, from eq (4)

φ = 40.58 °

since the shear stress for workpiece material (Ti-6Al-4V) is τ_s = 760 MPa, from eq (5) and (6)

K_t= 2054.95 N/mm²

K_f = 603. 24 N/mm²

Now from eq(7) and (8)

F_t = 2465.94 N

F_f = 723.88 N

Hence from eq(9) ,

Resultant force , R = 25699.99 = 2570 N

Assuming, the extension distance of spindle b =120 mm.

So, then the moment , $M =$ R b

= 2570 x 120 = 308400 N-mm

5. STATIC ANALYSIS IN FEM

The test model is designed in Design modeler and the analysis of test model is made in ANSYS workbench 2021 R2 student version**. The** spindle is designed with inner diameter D_i = 60 mm, outer diameter D_o = 100 mm, Length L = 650 mm.

The geometry of the spindle is made in Ansys Design Modeler. The spindle is represented as one-dimensional longitudinal body which has the moment of inertia I. Thespindle is tested in two cases as per the superposition method of analysis.

Case 1:Rigid body and Flexible bearing supports

Case 2: Rigid bearing supportsand Flexible body

In case-1 the spindle body is made rigid by applying the high value of Elastic Modulus (E = 10^{12} MPa) and original bearing stiffness value. In the second case of superposition the bearings are made rigid by applying the original value of Elastic Modulus of spindle material and high stiffness values (K_{11}& K_{22}) in the bearing constraints in Ansys workbench as per the COMBI-214 elements.

The Directional deformations for various materials at various spans are tabulated below,

Table 5: Deformations for GS-17CrMo 5-5

GS17CrMo5-5	Case -1	Case-2	Combined
300	-0.11902	-0.019015	-0.13803
350	-0.090626	-0.013558	-0.073304
400	-0.071657	-0.010106	-0.056312
450	-0.049928	-0.0081055	-0.034533

Table 6: Deformations for C 35 Mn 75

C 35 Mn 75	Case -1	Case-2	Combined
300	-0.1254	-0.019015	-0.14441
350	-0.095488	-0.013558	-0.076612
400	-0.075506	-0.010106	-0.058618
450	-0.052608	-0.0081055	-0.036022

Table 7 : Deformations for 45 C 8

45 C 8	Case -1	Case-2	Combined
300	-0.11943	-0.019015	-0.13844
350	-0.090941	-0.013558	-0.073501
400	-0.07191	-0.010106	-0.056446
450	-0.050103	-0.0081055	-0.034616

The above tables depict that the better material we can choose is GS-17CrMo 5-5 as it exhibits the lower deformation at every corresponding span compared to the remaining materials.

On the other hand, the better span for the spindle can be decide based on the deformation the spindle exhibits under the given conditions. From the abovetables, it can be decided that the better or optimized span distance for the spindle is 450 mm as it exhibits the lower deformations for the chosen material (GS-17CrMo 5-5) among all the spans.

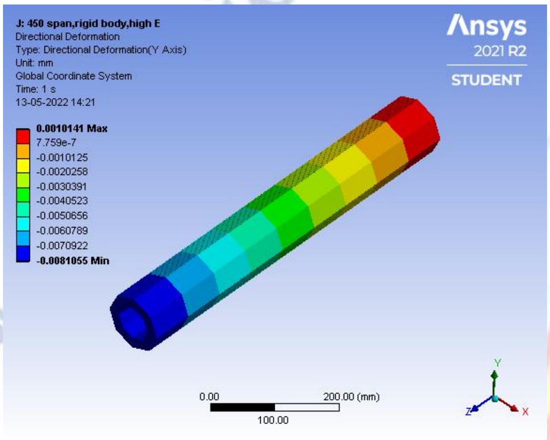


Fig 4: Case -1 deformation at 450 mm span

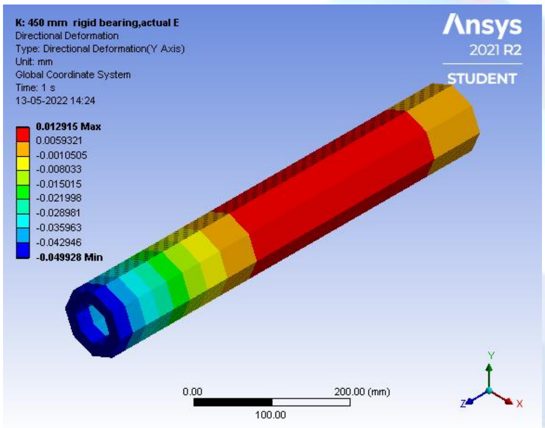


Fig 5: Case -2 deformation at 450 mm span

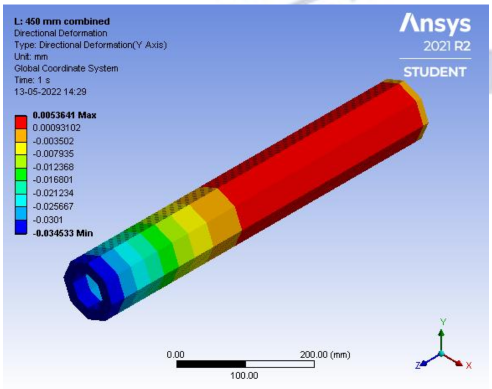


Fig 6: Combined deformation at 450 mm span

Now for this better fixed span the stresses are determined using the ANSYSworkbench 2021 R2. The maximum combined stress for the material GS-17CrMo 5-5 is found to be 6.0276 MPa which is developed near the overhung part of the spindle.

Table 8 :Stresses of various materials at 450 mm span

Material	Maximum combined stress (MPa)	Minimum combined stress(MPa)
GS-17CrMo 5-5	6.0276	-6.0276
C35Mn75	6.7141e-014	-6.7141e-014
45C8	7.2252e-015	-7.2252e-015

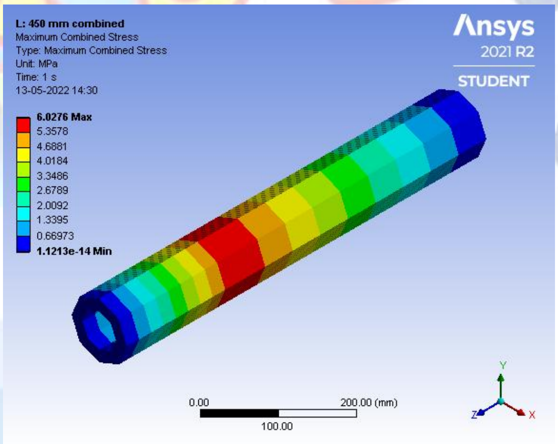


Fig 7: Maximum combined stress at 450 mm

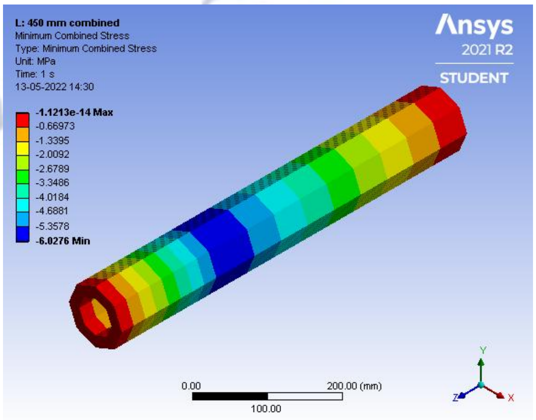


Fig 8 : Minimum combined stress at 450 mm

6. STATIC ANALYSIS IN ANALYTIC

The spindle is considered as one-dimensional beam which is supported on two bearings at A and B at a distance of span S.The beam experiences a vertical cutting force and the moment at the overhung part of the spindle. As per the superposition method of analysis, the spindle can be tested in two cases as discussed earlier.

Case 1:

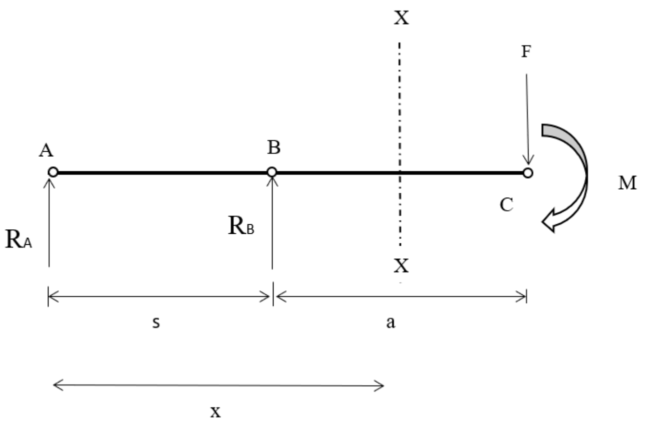


Fig 9: Free-body diagram representing the spindle

Here,

S = span distance between bearing supports

a = overhung distance

x = section distance from support A

From the above figure (Fig:9) the reaction forces generated at bearings can be determined as

Taking the algebraic sum of vertical loads

$$R_A + R_B = F$$

Taking the moment about support A,

$$R_B = \frac{F(s+a)+M}{S}$$

$$\text{EIy} = \frac{R_A x^3}{6} + \frac{R_B (x-s)^3}{6} - \frac{(R_A+R_B)S^2 x}{6} + \frac{R_B S^3}{6} \qquad (10)$$

Case 2:

In this case the body is assumed to be rigid (E = 10^{12}MPa) and original stiffness values of the bearings. For the bearing at support B (7020A5-TRS-DB-EL-P3) radial stiffness is 8.6×10^5 N/mm and for the bearing at support A is 1.96×10^6N/mm.

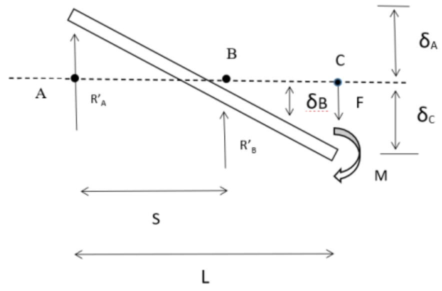


Fig 10 : Rigid body flexible bearing

Taking algebraic sum of vertical forces,

$$R_A' + R_B' = F$$

Taking the moment about A,

$$R'_B = \frac{F(s+a)+M}{S}$$

Now the deformations at supports,

$$\delta_A = \frac{R_A'}{K_A}$$

$$\delta_B = \frac{R_B'}{K_B}$$

Then the maximum deformation is given by,

$$\delta_C = -\delta_A + \frac{L(\delta_A + \delta_B}{S}$$

From eq (10) and eq (11), the combined case deformation as per superposition method is,

$$Combined = \delta_c + y$$

The results of the static analysis decide the optimal span distance of 450 mm among the taken ones. Then further analysis is performed on the spindle [including static and modal]. The obtained results are tabulated below.

Table 9: Results for GS-17CrMo -5

Span	Case 1		Case 2		Combined	
	FEM	Analytic	FEM	Analytic	FEM	Analytic
300	-0.11902	-0.06486	-0.019015	0.015255	-0.13803	-0.0496
350	-0.090626	-0.05784	-0.013558	0.011491	-0.073304	-0.04635
400	-0.071657	-0.04864	-0.010106	0.008974	-0.056312	-0.03967
450	-0.049928	-0.0385	-0.0081055	0.007198	-0.034533	-0.0313

Table 10: Results for C35Mn75

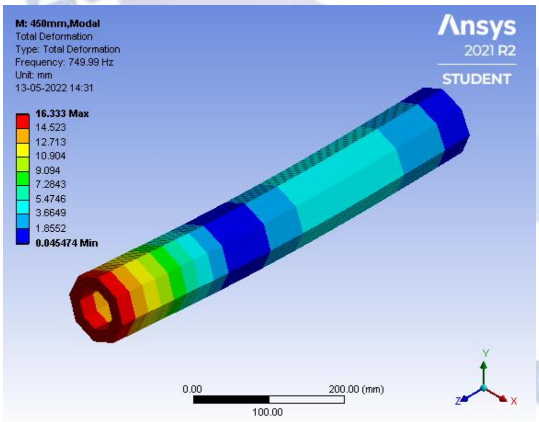
Span	Case 1		Case 2		Combined	
	FEM	Analytic	FEM	Analytic	FEM	Analytic
300	-0.1254	-0.06842	-0.019015	0.015255	-0.14441	-0.05317
350	-0.095488	-0.06102	-0.013558	0.011491	-0.076612	-0.04953
400	-0.075506	-0.05132	-0.010106	0.008974	-0.058618	-0.04234
450	-0.052608	-0.04062	-0.0081055	0.007198	-0.036022	-0.03342

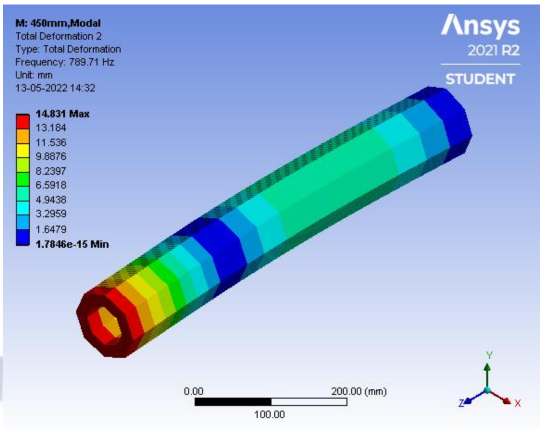
Table 11: Results for 45C8 steel

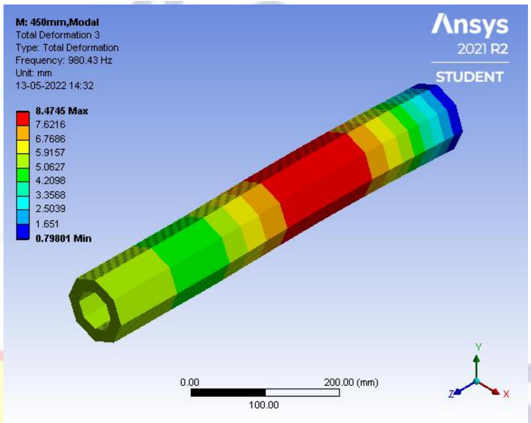
Span	Case 1		Case 2		Combined	
	FEM	Analytic	FEM		FEM	Analytic
300	-0.11943	-0.06516	-0.019015	0.015255	-0.13844	-0.04991
350	-0.090941	-0.05812	-0.013558	0.011491	-0.073501	-0.04662
400	-0.07191	-0.04887	-0.010106	0.008974	-0.056446	-0.0399
450	-0.050103	-0.03868	-0.0081055	0.007198	-0.034616	-0.03149

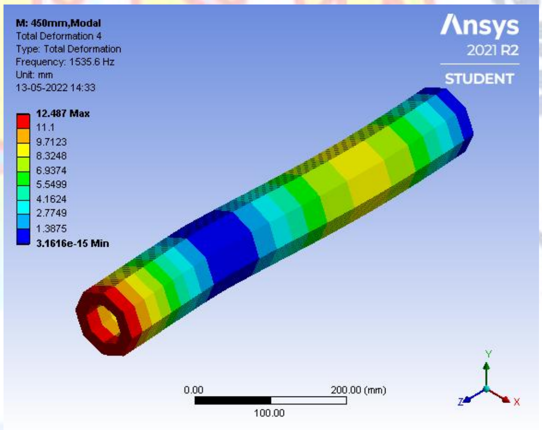
7. MODAL ANALYSIS

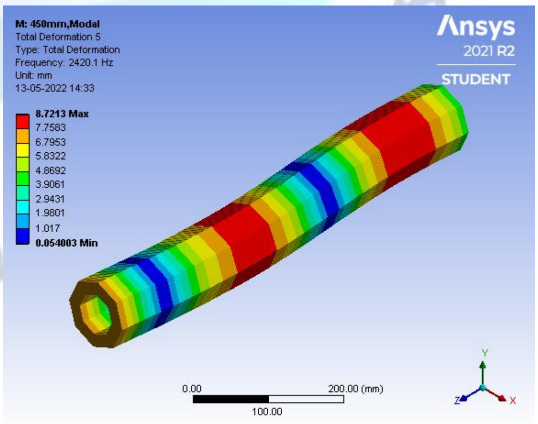
The spindle is tested for the modal behavior in ANSYS workbench. The analysis is carried out for the same test model on which the static analysis is done. Here the Eigen frequencies are determined for the first 6 modes and the behavior is demonstrated below.











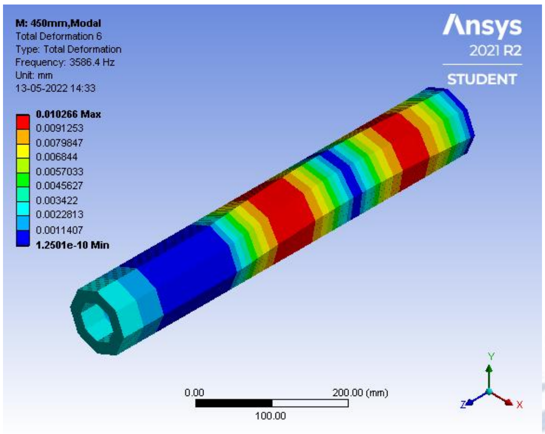


Fig 11: The first 6 mode shapes.

The above figure, depicts the first six modes of the spindle for the material GS-17CrMo 5-5.Further the, modal behavior of the spindle with other materials is tabulated below.

Table 12: Modal shapes of various materials

Materi al / mode	GS-17CrMo5-5	C35Mn75	45C8
1	749.99	733.4	748.95
2	789.71	769.38	788.38
3	980.43	970.47	980.42
4	1535.6	1498.9	1535.9
5	2420.1	2380.6	2419.7
6	3586.4	3519.	3605.9

8. CONCLUSIONS

- From the Tables-(9, 10 & 11) it is observed that the deformation is very low at the span of 450 mm for the three materials also. So, it is concluded that the better span is 450 mm among the considered ones.
- From the obtained results [Tables-(9, 10 & 11) it is concluded that the better and optimal material is GS-17CrMo 5-5 steel as it exhibits lower deformation, lower stresses are developed.
- In the worst case of loading the spindle the generated stresses are much lower than the yield limit 415 MPa of the material (GS-17CrMo 5-5). Hence the plastic deformation can't be expected during the operation.
- Its frequency for the sixth mode (3586.4 Hz) is far above the speed range of working, 0-6000 rpm (100 Hz) proves that the spindle avoids any resonance during the operation.

9. FUTURE WORK

- Transfer matrix method can be used for analytical purpose.
- The various lathe operations like facing, drilling, tapered-turning can also be performed and analyzed.
- Thermal analysis can be carried out in order to detect the effect of temperatures due to friction, high depths of cut, heavy forces those may act from various external sources and any possible cases.
- In order to determine more accurate behavior of spindle, the bearing stiffness values can be considered by finding the values experimentally.
- One can develop the prototype manufacturing of spindle and the experimental testing can be made.
- Based on the spindle behavior during operation and the efficiency required, the bearings and the motor power can be predicted.
- The compact and high-power motor systems that produce low heat will be provided by the superconducting materials and new motor technologies.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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