Selection of Lathe Spindle Material Based on Static and Dynamic Analyses Using Finite Element Method

A REPORT BY

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1.INTRODUCTION

Lathe is the conventional machine tool and is one of the most fundamental and versatile machine with large variants to be used in all manufacturing shops. Spindle is a rotational component of the machines used in different spheres of industrial operations, especially, in metal cutting process. A spindle shaft, similar to the housing, holds the components together and located on the spindle bearings. Spindle shaft is the main rotating component of the system and one of the first components subjected to loads during cutting. Its stiffness and robustness greatly affect both static and dynamic behavior of the spindle system, ultimately the performance of the machine tool. The purpose of this paper is to study the static and dynamic behavior of lathe spindle (shaft) under turning operation using FEM to determine the deformations and various stresses under the same boundary conditions. Also, it is important to observe change in deformation, von-Mises stress with change in cutting force and RPM.

C.W. Lin et al. [1] in the paper stated that the FEM analysis approach is the most popular approach for the dynamic analysis of the spindle bearing system because of its capacity to solve the complex model and boundary conditions along with less time calculation. Earlier, Kang et al. [2] hinted about the integrated computer aided strategies for designing machine tool spindle-bearing systems. In this study, the influence of design parameters on static and dynamic performance of spindle-bearing systems were investigated for instituting the necessary design modifications.

Table 1. Mechanical properties.

Material properties	AISI 1045 carbon steel	AISI 4140 alloy steel	AISI 304 stainless steel	Grey cast iron
Ultimate tensile strength	515 MPa	655 MPa	586 MPa	240 MPa
Yield strength	485 MPa	415 MPa	207 MPa	124 MPa
Modulus of Elasticity	200 GPa	198 GPa	193 GPa	110 GPa
Shear modulus	80 GPa	80 GPa	86 GPa	42.9 GPa
Poisson's ratio	0.29	0.27-0.30	0.31	0.28
Density	7.87 g/cm^3	7.85 g/cm^3	7.75 g/cm^3	7.20 g/cm^3
Hardness, Brinell	170 HB	197 HB	123 HB	120-550 HB

Thorough investigation of deformation, stress and strain distribution of each material towards the suitability as lathe spindle is made here.

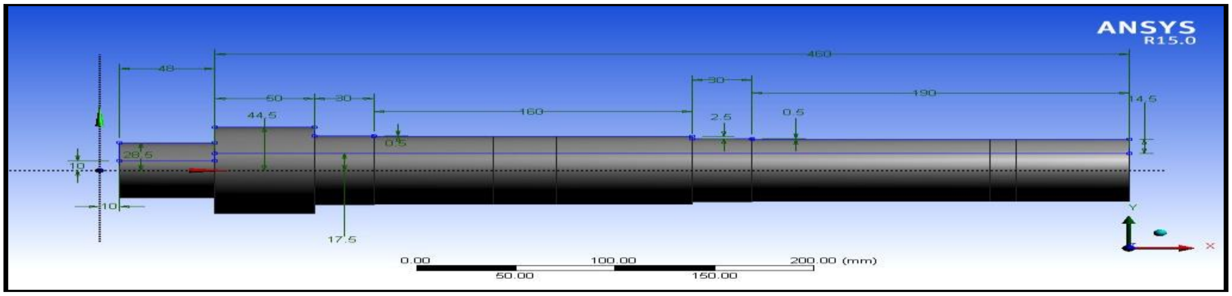

Fig :1

2. Modeling and meshing of spindle.

In this study, a model of lathe spindle shaft is designed. The preliminary design of the spindle contains angular contact ball bearings mounted on the shaft with DBB configuration. The spindle shaft is developed using "design modeler" in ANSYS 23 workbench. The shaft is made similar to the spindle, the test model is a straight steel shaft with an inner diameter of 35 mm and outer diameter of 65 mm. Total shaft length is 508 mm. The shaft is supported and fixed at two points by ball bearings. A three-dimensional model developed is presented in Fig. 1. In any computer simulation, meshing is the most important part. Meshing by means of dividing a large structure into small grid points called nodes is done. Elements are connected to the nodes in sequence. Solid elements of tetrahedral shape geometry allow uniform meshing, but hexahedral shape provides more accurate result. The meshed geometry is as shown in Fig. 2. Both mesh types are considered and after studying the beneficial aspects, hexahedral mesh is chosen.Close view of the mesh elements is also shown for better understanding of the grid pattern. Appropriate mesh size is obtained based on the results. Element size is taken as 2 mm. Relevance is kept as 100. Span angle and relevance centre are kept as fine. The model consists of total 110712 nodes and 22904 elements. The properties of the materials used are listed in Table 1.

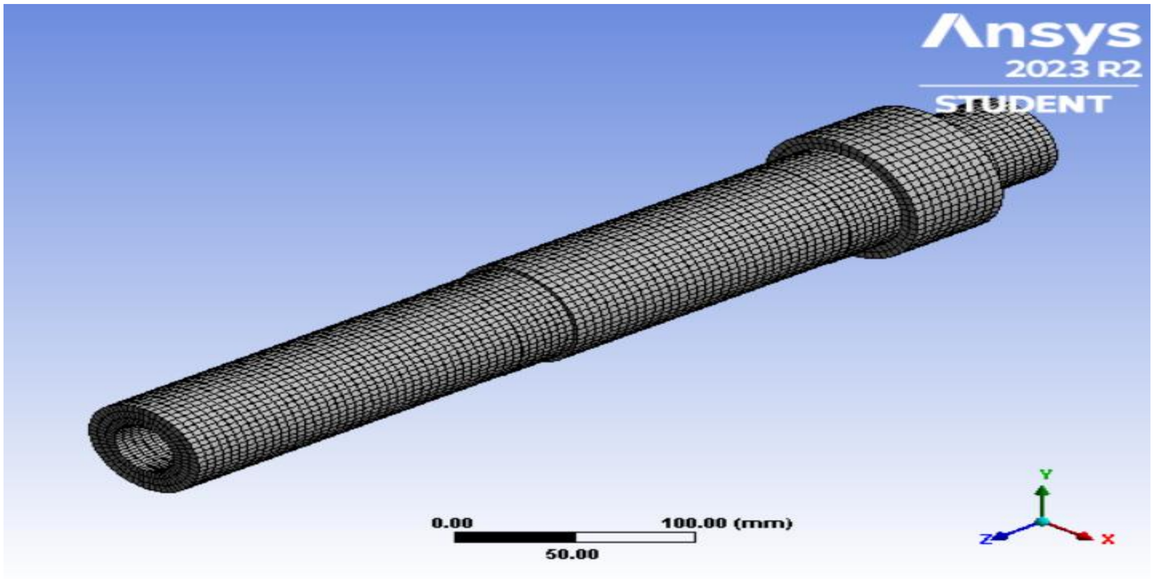

Fig :2

One load is applied on the spindle end. The other one is cutting force during machining operation. Torque is applied on one end of the spindle. RPM is applied on one end of spindle in clockwise direction. Cylindrical supports are added in spindle to restrict its radial and axial movement.

Cutting Force(N)	AISI 1045 Carbon Steel	AISI 4140 alloy Steel	AISI 304 Stainless steel	Grey cast iron
610	.0013768	.0013954	.0013428	.0025055
660	.0014896	.0015098	.0014529	.0027108
720	.0016256	.0018072	.0016804	.0029573
790	.0017388	.0018072	.0018438	.0032776

Table.2. Maximum total deformation(mm) variation with cutting force

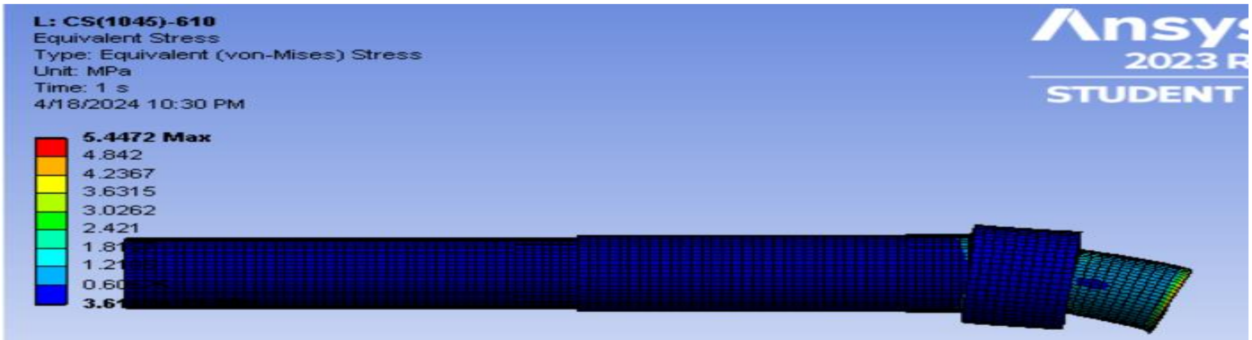

Fig :3

3. Results and Discussion

Static structure analysis is useful in identifying and measuring the deformation and stress induced in the lathe spindle based on the conditions applied. The resulting lateral deflection of the spindle due to loading is determined by the elastic behaviors of both the shaft and bearings. As the cutting force increases, deformation tends to increase. In this work, deformation and stress are plotted and analyzed.

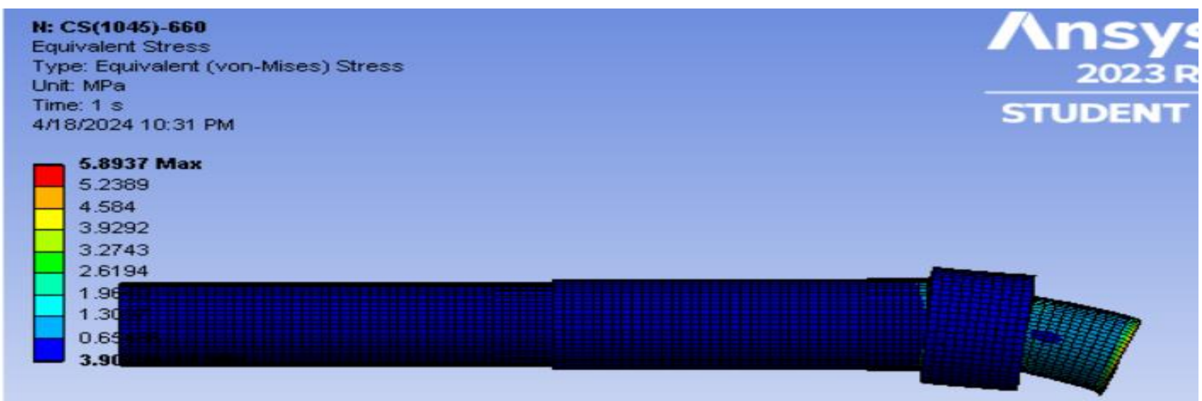

Fig :4

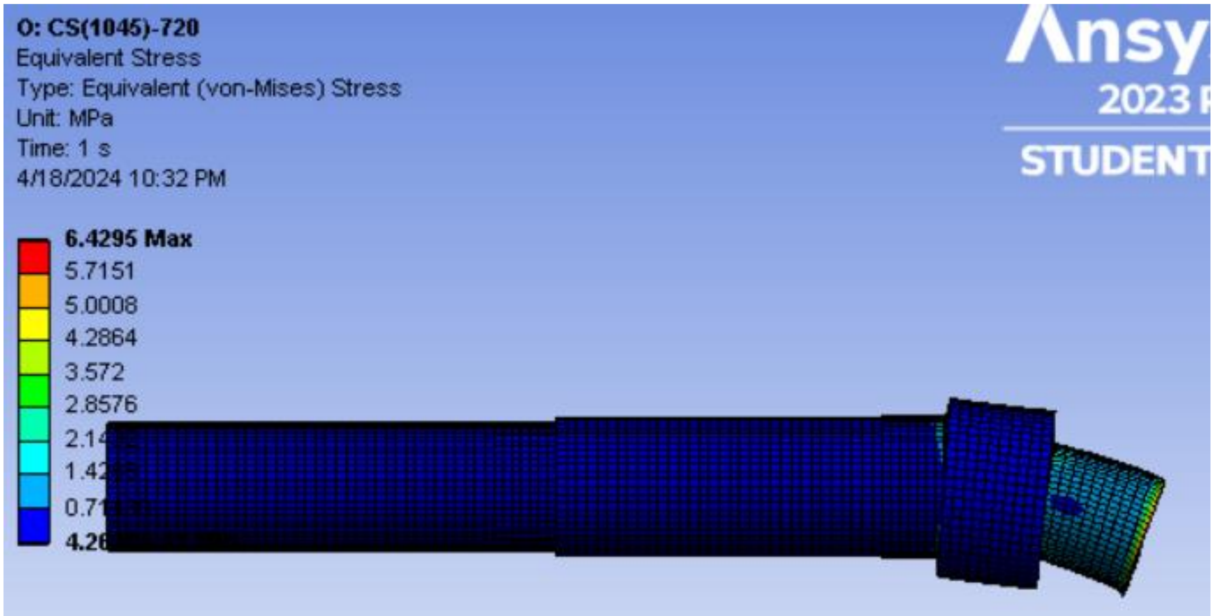

Fig :5

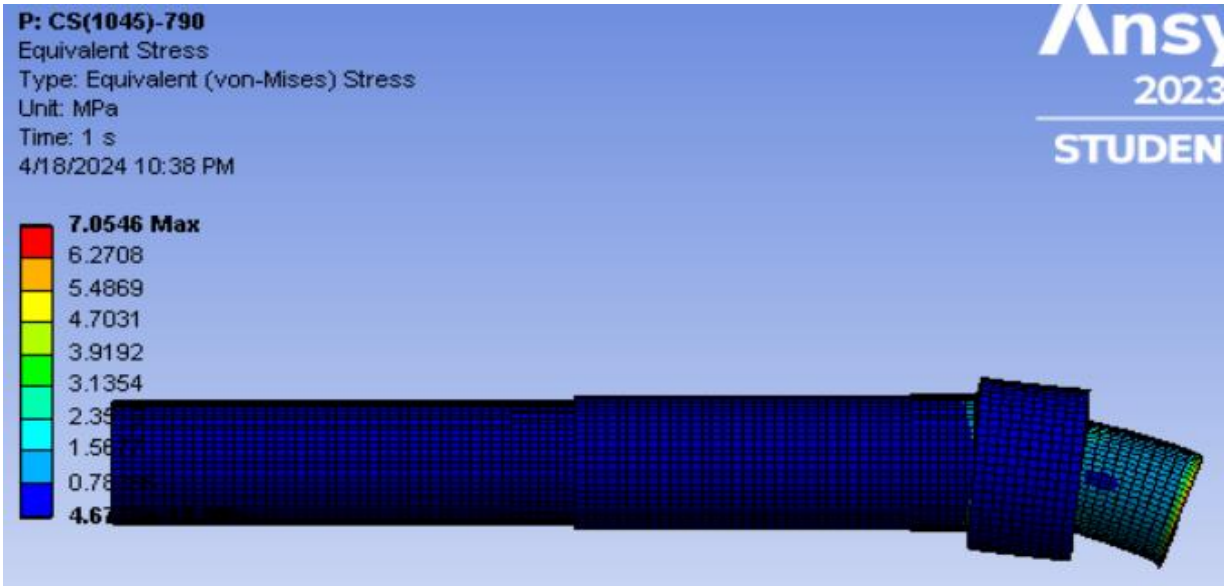

Fig :6

Total deformations of different materials under varied cutting forces are studied. Different cutting forces are applied on one end and load due to tension in belt is applied on the spindle end. Total deformation for all four materials at different cutting forces is presented in Table 2. Maximum total deformation is increasing with increment in cutting force. For the cutting force of 790N, maximum deformation of 0.0032776 mm is observed in grey cast iron and minimum deformation of 0.0017388 mm is in AISI 1045 carbon steel. AISI 304 steel has deformation more than AISI 4140 steel and less than grey cast iron for all the cases. Also, AISI 4140 steel has intermediate values of AISI 1045 carbon steel and AISI 304 steel. Distribution of total deformation across the spindle are shown in in Figs. 3, 4, 5 and 6. These contours are also drawn for the highest cutting force. It is observed from that maximum deformation occurs at the face area of the spindle and minimum at the spindle bearing part for all materials. Deformation values are less in AISI 1045 carbon steel for most of the spindle area. From Fig. 3, it can be observed that under the same loading condition, the total deformation pattern for the material AISI 1045 carbon steel is different and has the lowest value than other three materials.

Cutting Force(N)	AISI 1045 Carbon Steel	AISI 4140 alloy Steel	AISI 304 Stainless steel	Grey cast iron
610	5.4472	5.4441	2.1621	5.4466
660	5.8937	5.8903	2.3393	5.8931
720	6.4295	7.0505	6.431	6.4288
790	7.0546	7.0505	7.0562	7.1253

Table.3. Maximum equivalent stress (Mpa) variation with cutting force

Equivalent alternating stresses for all four materials at different cutting forces are presented in Table 3. In spindle, as the cutting force is increased, the equivalent stress also increased. If the stress value is under material yield strength, the material is expected to be safe. Maximum equivalent stress of 7.1253 MPa observed for grey cast iron and the minimum stress of 7.0546 MPa observed on AISI 1045 carbon steel with 790 N cutting force. AISI 1045 carbon steel has the low stress values among all the materials considered here. Similar stress pattern is observed in all the cases with the position of the maximum stress also being same with varied magnitude. Contours of the equivalent stress distribution of spindle are presented in Figs. 6-8. The maximum stress generated in AISI 1045 carbon steel is 7.0546 MPa as shown in Fig.6. The maximum equivalent stress generated in AISI 4140 alloy steel is 7.0505 MPa as shown in Fig.7. The maximum equivalent stress generated in AISI 304 Stainless steel is 7.0562 MPa as shown in Fig.8. The maximum equivalent stress generated in Grey cast iron is 7.1253 MPa. It is observed that maximum equivalent stress occurs at spindle rotor part and minimum at spindle body nearest to bearing part. AISI 1045 carbon steel is showing less deformation and stresses, which may be due to its high yield and ultimate tensile strengths. Also, the values are changing less with the change of material.

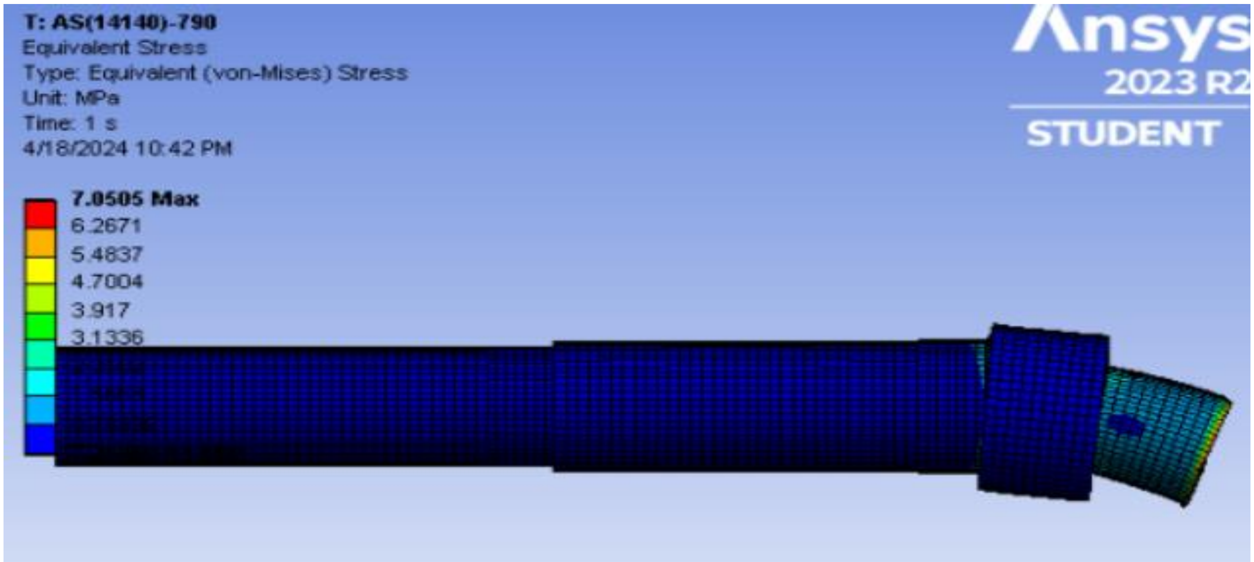

Fig :7

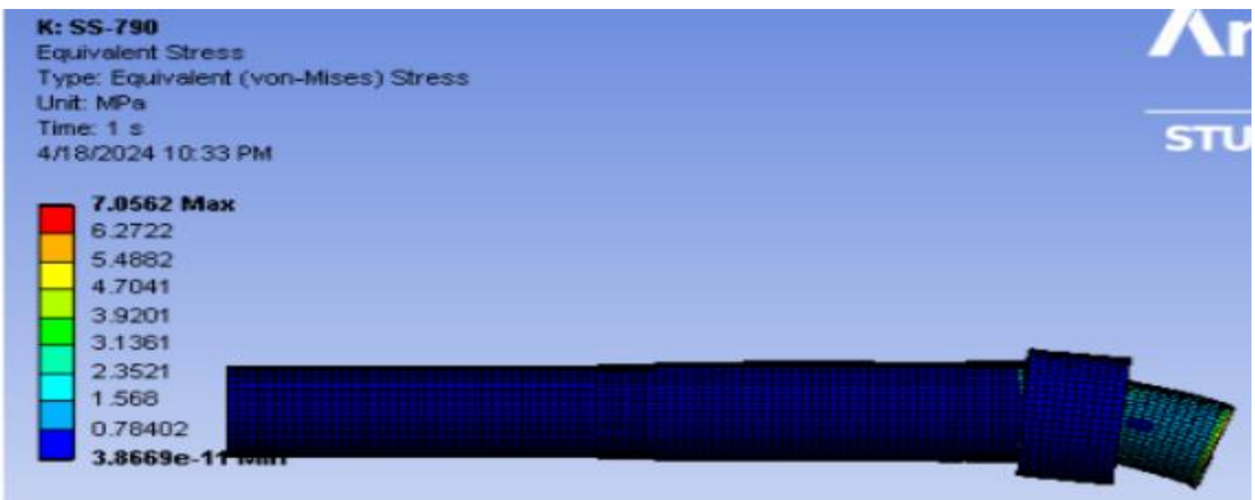

Fig :8

Usually, spindle rotates at the speed ranging from 1500 to 6000 rpm. The rotational speed also has an effect on stress development in the spindle. The values of strains and stresses for all four materials at different rotational speeds are presented in Table 4 and Table 5 respectively. A very less variation in stress is observed and stresses are increasing with speed. Maximum stress development is seen in 6000 rpm for Grey cast iron. AISI 1045 showed less stresses for all the speed cases. It can be confirmed that the effect of speed is less in development of stresses in spindle. For the speed increment from 1800 to 6000 rpm, only 1% increase in stress is observed. Also, as the rotation speed is increased, the equivalent strain also increases. The values of strains for all the four materials at different rotational velocities are presented in Table 4. Similar to stresses, less variation is observed in the values of strain in lathe spindle with speed. AISI 1045 showed less strain for all the speed cases. Maximum strain development is seen in 6000 rpm for Grey cast iron.

Rotational Speed (Rpm)	AISI 1045 Carbon Steel	AISI 4140 alloy Steel	AISI 304 Stainless steel	Grey cast iron
1800	4.5888e-7	5.231e-7	4.401e-7	7.8369e-7
3500	1.735e-6	1.9778e-6	1.6712e-6	2.6429e-6
4500	2.868e-6	3.2694e-6	2.7625e-6	4.898e-6
6000	5.0986e-6	5.8122e-6	4.9112e-6	8.7075e-6

Table 4 -Maximum total strain variation with rpm

Rotational Speed (Rpm)	AISI 1045 Carbon Steel	AISI 4140 alloy Steel	AISI 304 Stainless steel	Grey cast iron
1800	·072021	.081441	.067405	.067418
3500	.2723	.30792	.25485	.2549
4500	.45013	.509	.42128	.42136
6000	.80023	.9049	.74894	.74909

Table 5 -Maximum total stress variation with rpm

Now the dynamic behavior of spindle with rotational speed is also analyzed with Campbell diagram. Since the spindle working speed range is between 0 to 6000 rpm, it is expected that the critical speeds are much above this range. The analysis is conducted for the speeds between 0 to 100000 rpm with multiple load steps in order to find the critical speeds. With the Campbell diagram as shown in Fig. 9, it is also possible to obtain the natural frequency of the spindle at any working speed within the conducted speed range of analysis. The critical speeds of the spindle are marked on the Campbell diagram. It is found that within the working speed range of the spindle (0-6000 rpm), the critical speeds stay above 1000 Hz.

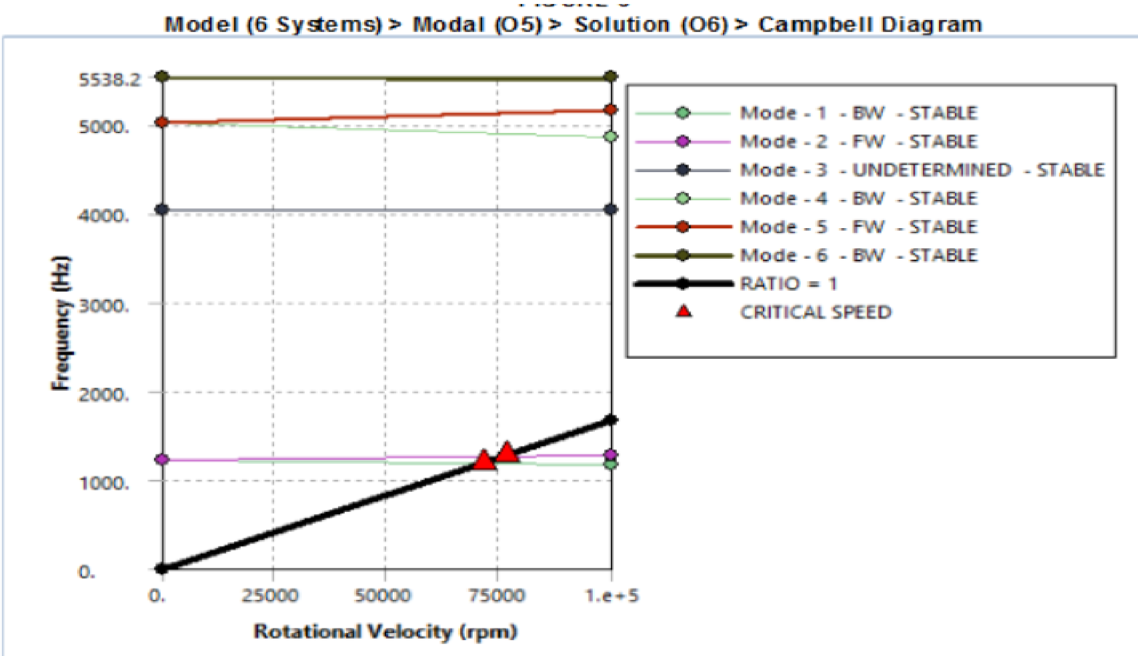

Fig :9 Campbell diagram of the spindle.

Mode	Whirl Direction	Mode Stability	Critical Speed (rpm)
1	BW	STABLE	71729
2	FW	STABLE	76537

4. CONCLUSIONS

A lathe spindle is modeled and AISI 1045 carbon steel, AISI 4140 alloy steel, AISI 304 stainless steel and grey cast iron are used as spindle materials. The computational model is generated with the reference scale using ANSYS 23.0 workbench and static structural analysis is performed with varied cutting force. Deformations and Equivalent stresses are analyzed with the cutting force ranging from 600 to 800 N. Values are tabulated and contours are drawn for the case of the highest force. AISI 1045 carbon steel shows the minimum value of maximum total deformation in 790N case, which is 0.0017388 mm. The maximum deformation in grey cast iron is thus high at 790N force (0.0032776 mm), which is not desirable. Maximum equivalent stress of 7.1253 MPa is observed in grey cast iron and the minimum stress of 7.0546 MPa is observed in AISI 1045 carbon steel. AISI 4140 alloy steel has stresses and deformation less than AISI 304 stainless steel. Overall, AISI 1045 carbon steel showed good results as less stresses and deformation are observed for all the cases of cutting forces. Changes in the values of stresses and strains are less with the change of material. Change of deformation is significant with change of material. Also, the rotational speed has an effect on the development of stresses and strains in the spindle. Similar to stresses, less variation is observed in the values of strain in lathe spindle with speed. Using Campbell diagram, it is found that within the speed range of the spindle (0-6000 rpm), the critical speeds stay above 1000 Hz. Results thus give better understanding of the materials suitable for lathe spindle, which is the main rotational component of the machines used in any metal cutting process. This work can be easily applied for any specific spindle with varied parameters like speed and force, as per the application.

REFERENCES

[1] C.W.Lin , Y.K. Lin, C.H. Chu, “Dynamic models and design of spindle-bearing system of machine tools”: A review, International Journal of Precision Engineering and Manufacturing 14 (2013) 513-521.

[2] Y. Kang, Y.P. Chang, J.W. Tsai, S.C. Chen, L.K. Yang, Integrated CAE strategies for the design of machine tool spindle-bearing systems, Finite Elements in Analysis and Design, 37 (2001) 485-511.