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Static and Dynamic Analysis of a Deep Hole Internal Grinding Shaft Tool

Muhammad Jawad Ahmad[1], Zhu Xianglong[1,] Kangrenke*[1,] and Dongzhigang[1]

[1] Key Laboratory for Precision and Non-traditional Machining Technology of Ministry of Education,
Dalian University of Technology, Dalian 116024, China.

Abstract:

Cylindrical parts with deep holes and thin-wall structures are the backbone in aerospace, such as sleeves, actuators, and landing gears of aircraft. However, in precise, the precision machining of inner holes of cylindrical parts with small bores, large depth to diameter ratios (>7-8) is more problematic, which realized the significance of the grinding of such deep holes.

In this article, an optimized structure of a deep hole internal grinding shaft tool is introduced. The vital structure of this grinding machine is the internal grinding shaft tool structure and one of the decisive factors distressing the surface grinding quality because of the length and complexity of the structure with a limited exterior dimension. First, the modal of the grinding shaft tool structure is designed in CREO-Parametric software. Then the designed modal is carried through the static and dynamic analyses employing ANSYS FEA software to authenticate and assure the structural stiffness and behavior to attain high precision machining of deep holes. In static analysis, various parameters such as materials of internal grinding shaft and various structural designs of the shaft took under research consideration. Next, the dynamic analysis has been performed against the optimized structure. Finally, harmonic analysis is performed to verify the internal grinding shaft tool design. Consequently, quite a few developments have been made in the structure and also provide a motorized spindle to segregate the effects of vibrations and forces on machining quality due to the driving mechanism.

Keywords: Deep hole internal grinding shaft tool, FEM, static analysis, dynamic analysis, Harmonic response.

INTRODUCTION

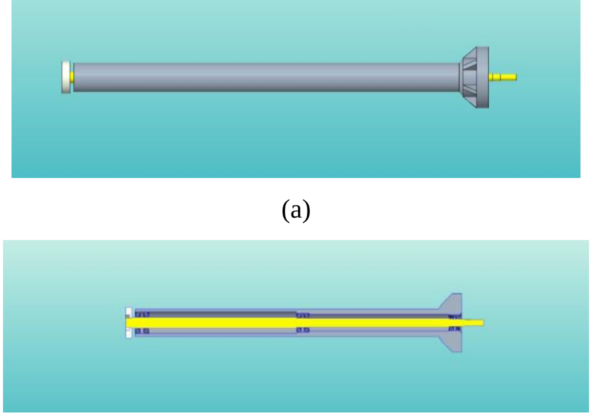
Cylindrical parts with deep holes are the aerospace field's backbone, highlighting the significance of high precision machining of deep holes. In precision machining, static and dynamic characteristics of the internal grinding shaft tool's structure play an intensive role in the quality of the product and overall productivity and efficiency of its performance. Hence it is of great significance to analyze the internal grinding shaft tool statically and dynamically.

P. Xia et al. [1] in this paper presented the static analysis of the deep hole internal grinding shaft tool and provided a compensation method to improve the design. X. Zhou et al. [2] introduced the precise modeling and modal analysis of the deep hole internal grinding shaft tool. Then stated that the finite element analysis is the most significant methodology for the dynamic analysis of grinding shaft tool because of its ability to resolve the complex model and boundary conditions accompanied by less time calculation. [3] In this article, the model of internal grinding force is derived beneath the fundamental mechanical laws concerning plastic deformation of the specimen in the contact zone and parameters of the wheel. P. P. Pereverzev et al. [4] have made a mathematical model to compute the grinding force with the influence of the degree of dulling. A. Anand and H. Roy [5] have computed the static stiffness and performed dynamic analysis on the optimized design of the spindle. C. Guo et al. [6] have provided the study of static and modal analyses to measure the characteristics; static stiffness, natural frequency, and their shape modes and acquired the resonance-free structure of spindle. J. Feng et al. [7] have performed the optimization of the came shaft grinding machine spindle structure. The results are validated by comparing theoretical measurements. D. Liu et al. [8] studied the influence of the stiffness with load aptitude and vibration resistance.

This research study aims to carry out the static structural analysis and acquired the most optimized structural design of deep hole internal grinding shaft tool against the most suitable material. Modal analysis has been performed against the most appropriate optimized design and modal shapes against their natural frequency attained for a dynamic behavior assessment. After that, the harmonic analysis is performed to validate the design against critical frequencies for the operating speed range of 6000 rpm to 8000 rpm.

STRUCTURE

Deep hole internal grinding shaft tool consists of a grinding wheel, a long shaft, six angular contact ball bearings, and an arm bracket in a complex design due to the restricted external dimension. The length of the grinding shaft is 1000 mm with an outer diameter of 90 mm. The arm bracket has six ribs at the support side. The structure of the deep hole internal grinding shaft tool is show in Figure 1.



(a)

(b)

Figure 1: Structure of the deep hole internal grinding shaft tool (a) and (b).

Boundary condition:

For modal analysis, it is essential to initiate the dynamic equation of the deep hole internal grinding shaft tool. The dynamic equation of the deep hole internal grinding shaft tool is presented below: -

i) Forced vibration equation

$$M\,d\ddot{x} + C\,d\dot{x} + k\,dx = F(x),$$

Where $F(x) = F_o \cos\omega t$

Where,

M - the mass of the grinding shaft system (kg)

C - damping coefficient (Nsec/mm)

K - stiffness (N/mm)

F(x) - the excitation vector

F_o - constant excitation force

x - displacement vector (mm)

In this analysis, the natural frequency of the internal grinding shaft tool computed by the material properties, structure, and the damping will have a minute influence on the natural frequency of the Internal grinding shaft system, thus F(x) = 0,

ii) Free vibration equation

$$M\,d\ddot{x} + C\,d\dot{x} + k\,dx = 0,$$

Supposing the Internal grinding shaft system is experiencing simple harmonic vibration,

iii) $$x(t) = \phi \sin(\omega t + \rho)$$

Where: ϕ – Amplitude, ω – Angular frequency, and ρ – Phase angle. By substituting (iii) in (ii):

iv) $$(k - \omega^2 M)\,\phi = 0$$

The Formula (iv) is used to compute the Internal grinding shaft system modes where ϕ_i (i = 1,2,3, …., n).

For frequency:

$$f = \frac{\omega}{2\pi} \qquad \text{(v)}$$

f is the natural frequency of the system.

FE MODEL:

For the structural analysis, a comprehensive Internal grinding shaft tool model is made. Then the model is imported in ANSYS. The Finite Element Method was employed to appraise the specific structure performance and the comprehensive dynamic behavior of the grinding shaft with concerned allotted material and load conditions. Element with relatively fine mesh is applied to each component of the structure in three different mesh sizes of 4mm 6mm, and 10mm with 71556 elements alongside 144994 nodes in total. Three different types of materials were applied for the grinding shaft rod and arm bracket analysis one by one, and the material of bearing used is stainless steel.

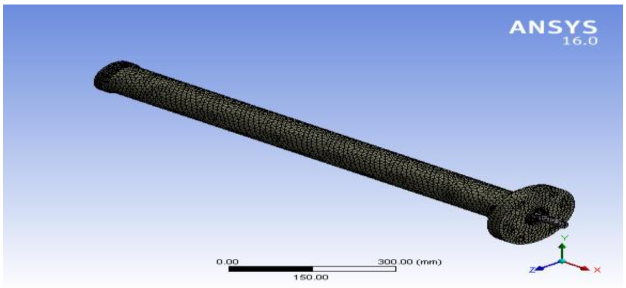


Figure 2: FE model.

SPECIFICATION:

Properties of material:

The properties of different material are used is presented below in the table 1.

Table 1: Mechanical properties of materials

Material	40Cr Steel	Steel 45	Alloy 4140
Young's Modulus (GPa)	205	205	200
Poisson Ratio	0.29	0.28	0.27
Density (g/cm^3)	7.85	7.86	7.85
Ultimate Strength (MPa)	972	565	655
Yield Strength (MPa)	841	310	415

Boundary condition:

Calculation of grinding force:

Deep holes grinding is based on internal grinding; the grinding force can divide into three axial, tangential, and radial components. The axial force has a very subtle effect, and the axial stiffness is much higher in comparison. Radial and tangential forces for the insertion stage of internal grinding are given below.

Radial force;

$$F_r = \frac{1.9\,\sigma_i v_{wo}\,T\,v_s}{v_{wh} n_{wo}} + \frac{\eta T \sigma_i}{3}\sqrt{\frac{dDv_s}{n_{wo}(d-D)}} = 98.05N \quad \text{(vi)}$$

Tangential force;

$$F_t = \frac{2.8\,\sigma_i v_{wo}\,T\,v_s}{v_{wh} n_{wo}} + \frac{\mu\eta T \sigma_i}{3}\sqrt{\frac{dDv_s}{n_{wo}(d-D)}} = 90.22N \quad \text{(vii)}$$

σ_i = Stress intensity N/ m^2 (machined material 30CrMnSi2A)

T = Height of wheel in m.

v_s = Radial supply velocity in m/s.

d = Internal diameter of work surface in m.

D = External diameter of grinding wheel in m.

v_{wh} = Grinding wheel speed in m/s

v_{wo} = Workpiece speed in m/s

n_{wo} = Rotary speed of workpiece in rpm.

μ = Coefficient of friction.

η = Degree of dulling.

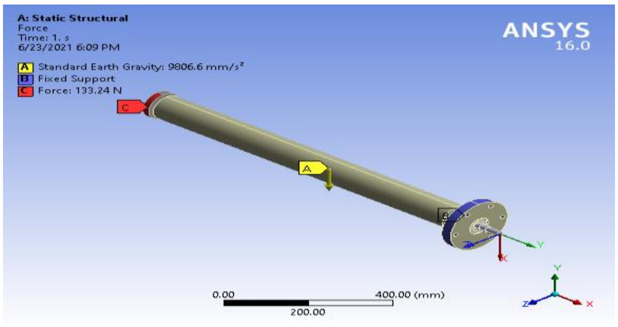


Figure 3: Applied boundary conditions and loads.

STATIC STRUCTURAL ANALYSIS:

The grinding shaft tool is the phenomenal central part of the deep hole internal grinding machine, which passes through different types of forces and moments during the process. That could be caused by high deformation and stress in structure, leading to failure of bearings or shaft structure and extensively affects the precision of grinding quality. Hence, it is significant to carry out the shaft through static and dynamic analysis to verify the structure.

Static structural analysis depends on the structure design, shaft material, numbers and type of bearing. The ability of the grinding shaft tool against the static loads is the actual representation of static structural characteristics of the shaft, which directly implicates the ability to hold loads and stand against the vibration. The grinding force acts in tangential, radial, and axial directions. Nevertheless, the load impact in the radial and tangential direction is much more than the axial one, and the bending stiffness of the shaft is much lower than the axial stiffness. The grinding shaft is made to aim the deep holes; because of extra length, gravity is also taken into account. Therefore, the static structural analysis involves the effect of radial, tangential, and gravity force as well.

Structure designs:

The deep hole internal grinding machine shaft tool carry through analysis with four different structure designs against steel 45 material. Results are given below:

1) 3 Ribs with thin back structure

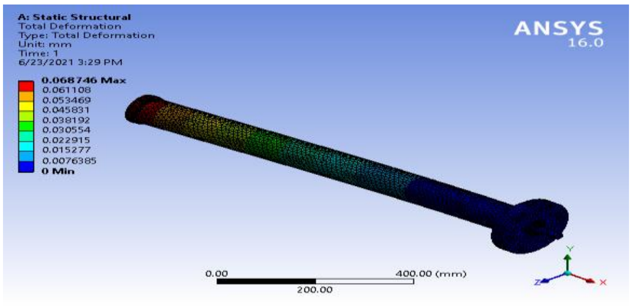


Figure 4: Deformation of three ribs with thin back tool structure

2) 3 Ribs with thick back structure

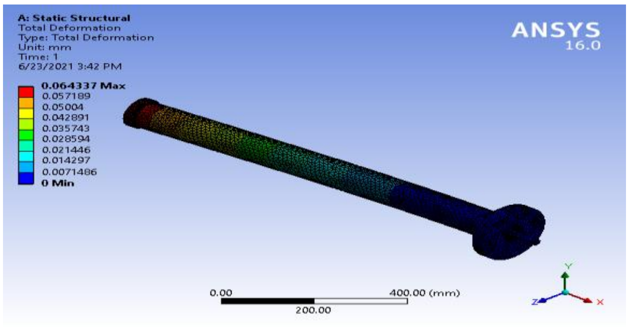


Figure 5: Deformation of three ribs with thick back tool structure

3) 6 Ribs with thin back structure

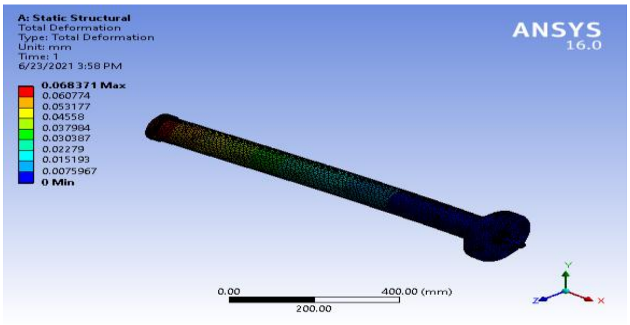


Figure 6: Deformation of six ribs with thin back tool structure

4) 6 Ribs with thick back structure

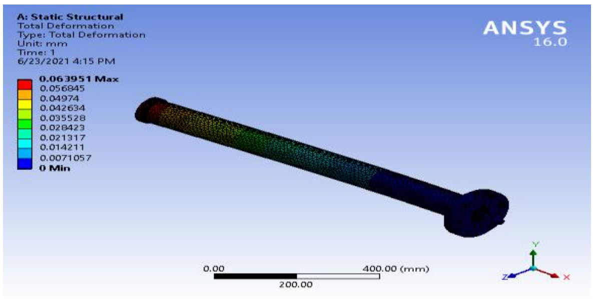


Figure 7: Deformation of six ribs with thick back tool structure

Effect of materials on internal grinding tool deformation:

The analysis of the best internal grinding shaft tool design against three different materials performed. Results are presented below:

1) 40Cr steel

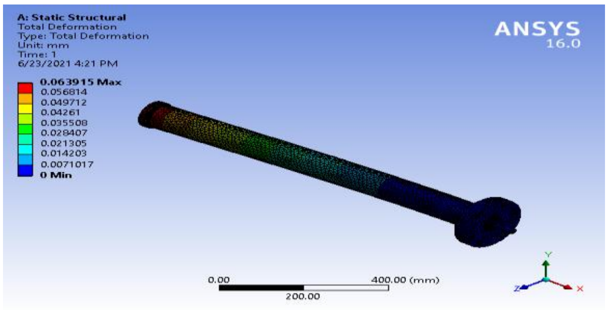


Figure 8: 40Cr steel deformation

2) Steel 45

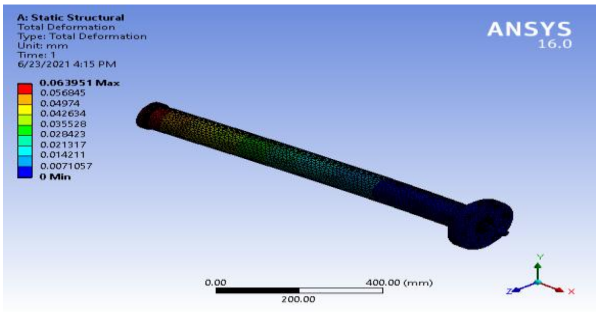


Figure 9: Steel 45 deformation

3) Alloy 4140

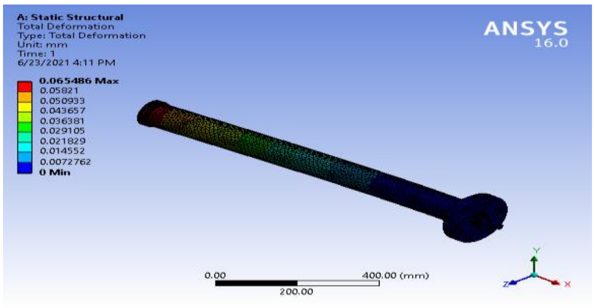


Figure 10: Alloy 4140 deformation

Table 2: Comparison of structure design, material and deformation:

Structure	Material	Total Deformation (µm)
3 Ribs with thin back structure	Alloy 4140	70.393
	Steel 45	68.746
	40Cr steel	68.707
3 Ribs with thick back structure	Alloy 4140	65.880
	Steel 45	64.337
	40Cr steel	64.301
6 Ribs with thin back structure	Alloy 4140	70.009
	Steel 45	68.371
	40Cr steel	68.332
6 Ribs with thick back structure	Alloy 4140	65.486
	Steel 45	63.951
	40Cr steel	63.915

The comparison of different designs and different materials is given in Table 2. Grinding shaft tool design of 6 ribs with thick back structure has the minimum deformation with 40Cr steel material. Deformation in gravity and cutting force direction against 40Cr steel with six ribs and a thick back structure are 10.423µm and 63.16µm respectively as shown below: -

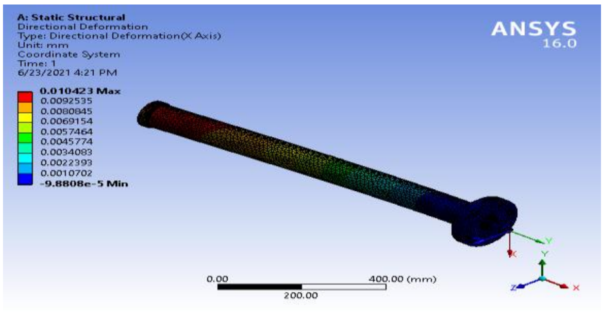


Figure 11: Deflection in gravity direction

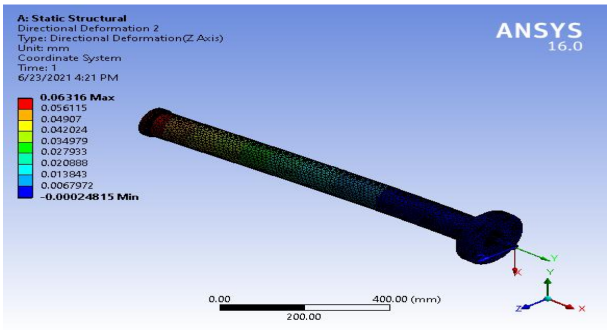


Figure 12: Deflection in cutting force direction

DYNAMIC ANALYSIS:

The dynamic analysis is performed to analyze the dynamic characteristics of the mechanical structure under the influence of vibration excitation.

Modal Analysis:

The Modal analysis of the grinding shaft tool is performed in ANSYS Workbench. The initial six different shape modes are presented below, and the frequencies against each mode given in the table 3.

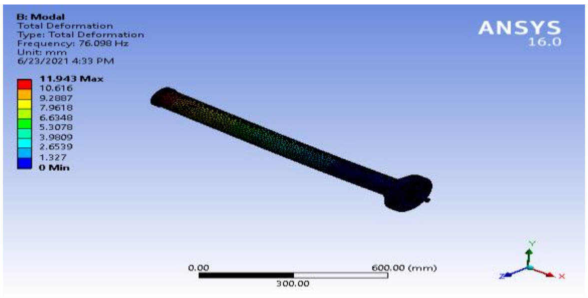


Figure 13: Mode shape 1

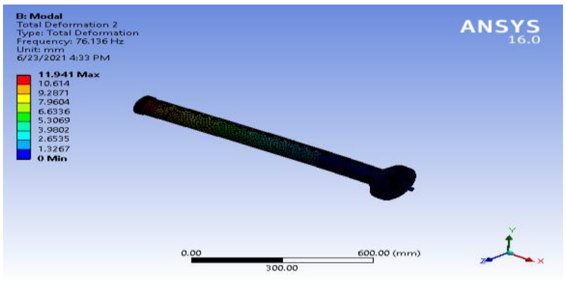


Figure 14: Mode shape 2

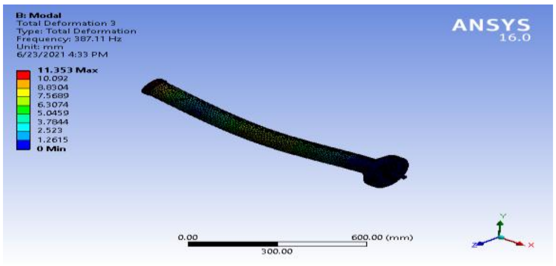


Figure 15: Mode shape 3

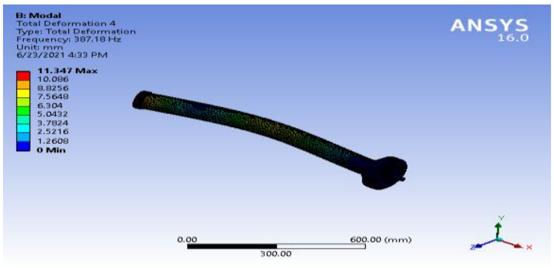


Figure 16: Mode shape 4

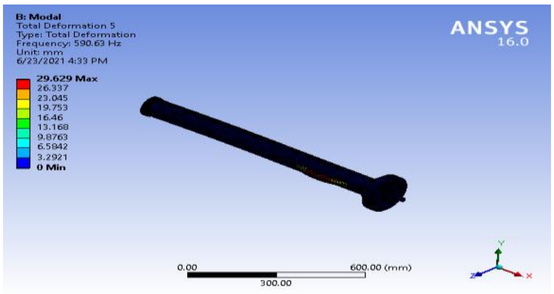


Figure 17: Mode shape 5

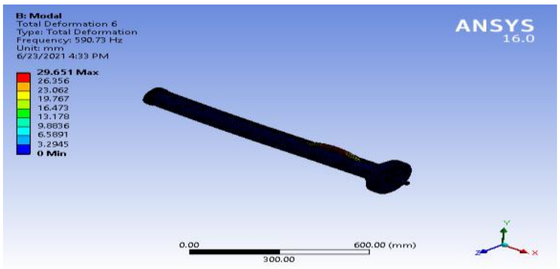


Figure 18: Mode shape 6

Table 3: Modal frequencies

Mode	Frequency [Hz]
1	76.098
2	76.136
3	387.11
4	387.18
5	590.63
6	590.73

The frequency in the first two modes is close. The maximum speed of the grinding shaft is 8000 rpm, so there is a need to avoid the range of the first two modes, but the required range of working speed is between 6000 rpm to 8000 rpm against the frequency range of 100 Hz to 135 Hz, which is in the 3rd mode. C. Guo et al. [6] states that the maximum rotational speed of the tool cannot surpass 75 % of the critical speed. Moreover, from the modal analysis, it is substantiated that the critical speed for that mode is 23226.6 rpm, which is well beyond the operating speed range.

Harmonic Analysis:

When the forced frequency reaches the natural frequency of the machine, it can immensely affect the precision of the machining. To authenticate and avoid resonance of the structure design at the critical frequencies is significate to carry structure through the harmonic analysis. The analysis is performed between the range of 100 to 700 Hz with an incremental of 10 Hz. The figure illustrates the amplitude resonance with different frequencies in both gravity and cutting force directions. The maximum deformation is near the 100 Hz frequency, about 1.8797e-2 mm and 2.0443e-2 mm in the Y and Z axes, respectively. It is clear from the results that the structure does not reach high deformation at the critical frequencies. The analysis is performed in ANSYS Workbench.

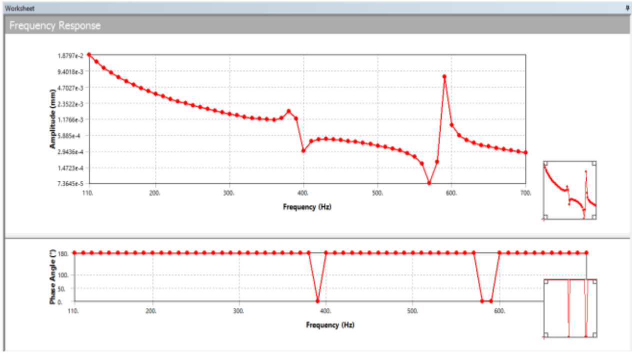


Figure 19: Frequency response in y- axis

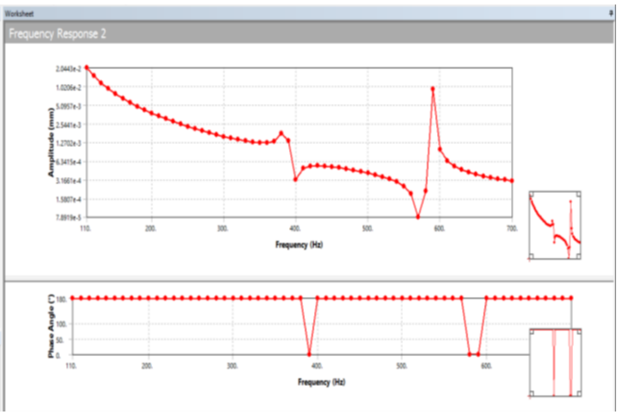


Figure 20: Frequency response in z- axis

CONCLUSION

In this study, an optimized structure of the deep hole internal grinding machine shaft tool is introduced. The static structural, modal, and harmonic analyses are performed using ANSYS workbench to verify and analyze the structure's statically and dynamically. The optimized material is 40Cr steel with six ribs and a thick back structure design. The deformation in gravity direction and cutting force direction is 10.423μm and 63.16μm respectively. Frequencies against six modes are 76.098Hz, 76.136Hz, 387.11Hz, 387.18Hz, 590.63Hz, and 590.73Hz. The operating speed range is in 3rd mode and critical speed at this mode is 23226.6 rpm which is much higher than the required speed. In harmonic analysis, the maximum deformation near the 100 Hz frequency, about 1.8797e-2mm and 2.0443e-2mm in the Y and Z axes, respectively are much less than the maximum deformation.

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