Global Journal of Researches in Engineering: A
Mechanical and Mechanics Engineering
Volume 17 Issue 2 Version 1.0 Year 2017
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN:2249-4596 Print ISSN:0975-5861

Dynamic Structural Analysis of Great Five-Axis Turning-Milling Complex CNC Machine

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GJRE-A Classification: FOR Code: 091399

Strictly as per the compliance and regulations of:

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Abstract- The computer aided engineering (CAE) with commercial software is used to analyze the free vibration frequencies, linear dynamic stress and deformation for secondary shaft system, primary shaft system and machinery bed in great five-axis turning-milling complex computer numerical control (CNC) machine. It is reasonable to use CAE software in the CNC intelligent manufacturing processes for time saving, component quantity upgrading and engineer training. It is desirable to select the maximum displacement and natural frequencies values as the basic data to design the CNC machine in safety condition for avoiding resonance. It is also valuable to design and choose the good region of rotational speed for the motors in the CNC system to provide a smoothly operation by using not in the same values of natural frequencies. The natural frequencies, linear dynamic stresses and displacements of total CNC machinery are obtained by using the commercial computer software SOLIDWORKS® 2014 simulation module.

Keywords: CAE, frequencies, dynamic, stress, deformation, CNC.

I. Introduction

It is desirable to reduce the development time for the machinery parts by using structural analysis program in computer aided engineering (CAE) and by preparing three dimensional (3D) diagram in computer aided design (CAD). In 2016, Wang et al. [1] used a CAD/CAE integrated reanalysis design system to shorten the design cycle for vehicular development. In 2015, Chen et al. [2] presented the intelligent manufacturing processes in a computer numerical control (CNC) system by using a cyber-physical system (CPS) models. In 2014, Mourtzis et al. [3] presented the CAE simulation in the computer aided technologies (CAx) is essential for digital manufacturing. In 2009, Lee and Han [4] predicted automotive fatigue by using the finite element (FE) model of CAE structural analysis. In 2006, Zhang and Han [5] reduced the development time for dynamic and acoustic of CAE analyses in engine designs. In 2003, Zhang et al. [6] used the CAE programs written with FORTRAN and C languages to investigate the dynamic behaviors of a CNC machining tool. In 1990, Doyle and Case [7] presented the CAE commercial software in the manufacturing engineering for the students education. There are some commercial CAE simulation software: e.g. CATIA®, ANSYS®, SOLIDWORKS®, Creo®, Inventor®, FreeCAD, NX™ Nastran®, Abaqus®, HyperSizer®, midas® etc.. In 2014, Vivekananda et al. [8] used ANSYS® to compute the natural frequency of vibration for ultrasonic assisted turning (UAT) in machining process. In 2013, Euan et al. [9] used the Matlab® to simulate dynamic cutting forces for ceramic milling tools.

For the great five-axis turning-milling complex CNC machine stiffness design, analysis and construction, in 2016, Hong et al. [10] used the SOLIDWORKS® CAE software to obtain the linearly static stresses and displacements for the secondary shaft system, primary shaft system and machinery bed. It is interesting to analyze the dynamic structural stiffness design of great five-axis turning-milling complex CNC machine by using commercial CAE software. In this paper, the natural frequencies, linearly dynamic stresses and displacements of secondary shaft system, primary shaft system and machinery bed of CNC machines are obtained by using the SOLIDWORKS® simulation module. The maximum values of linear dynamic stress and displacement are also provided to give a reference and prediction in the future construction of complex CNC machine.

II. Method of Simulations

In the linear dynamic structural analysis with considering inertial force, damping force and impact force, without considering the nonlinear state of the contact surface. A general matrix equation of mathematical model is used in the SOLIDWORKS® simulation module computer program to solve for vibration frequency, stress and displacement results as follows,

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\}=\{f(t)\}, \quad (1)$$

where $[M]$ is material mass matrix, $[C]$ is damping matrix, $[K]$ is material stiffness matrix, $\{\ddot{u}(t)\}$ is acceleration vector varied with time t, $\{\dot{u}(t)\}$ is velocity vector varied with t, $\{u(t)\}$ is displacement vector varied with t, $\{f(t)\}$ is external load vector also varied with t.

To use the commercial CAE software and run the linear dynamic results for complex CNC machine, firstly it is necessary to prepare the assembling 3D parts

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of great five-axis turning-milling complex CNC machine as shown in Fig. 1 and presented by Hong et al. [10]. The dimensions of main parts are provided respectively, for machinery bed is 8470mm x 1463mm x 783mm, for primary shaft system is 1190.5mm x 940mm x 860mm, for secondary shaft system is 1397m x 845mm x 1426mm, for work piece is cylindrical column with diameter mm and length 5000mm. There are three positions (0mm, 4000mm and 6900mm) of secondary shaft system can be moved from 0mm to 6900mm, used to computed and analyzed for the CNC machine. Secondly, it is necessary to define the individual material of assembling 3D parts for great five-axis turning-milling complex CNC machine. The materials of main parts are given, for machinery bed, shaft systems and work piece are cast iron. The yield stress of cast iron material is 275MPa. To prevent failure in the CNC machine, the linear dynamic value of working stress in each material of components should smaller than its yield stress value. There are five types of clamp supported (4, 8, 14, 20 and 36 positions) boundary conditions of machinery bed are used to computed and analyzed for the CNC machine linear dynamic studies. The supported positions at one side are matched to another side, e.g. the total 36 positions with 18 positions at each side of machinery bed. To find the more suitable number meshes used in the computation and analyses for the CNC machine dynamic results, it is necessary to make convergence study of meshes. There are 200.00mm, 160.00mm, 155.00mm, 150.00mm and 145.00mm of maximum size lengths of five type meshes used to find the natural frequency converged values of total machinery bed.

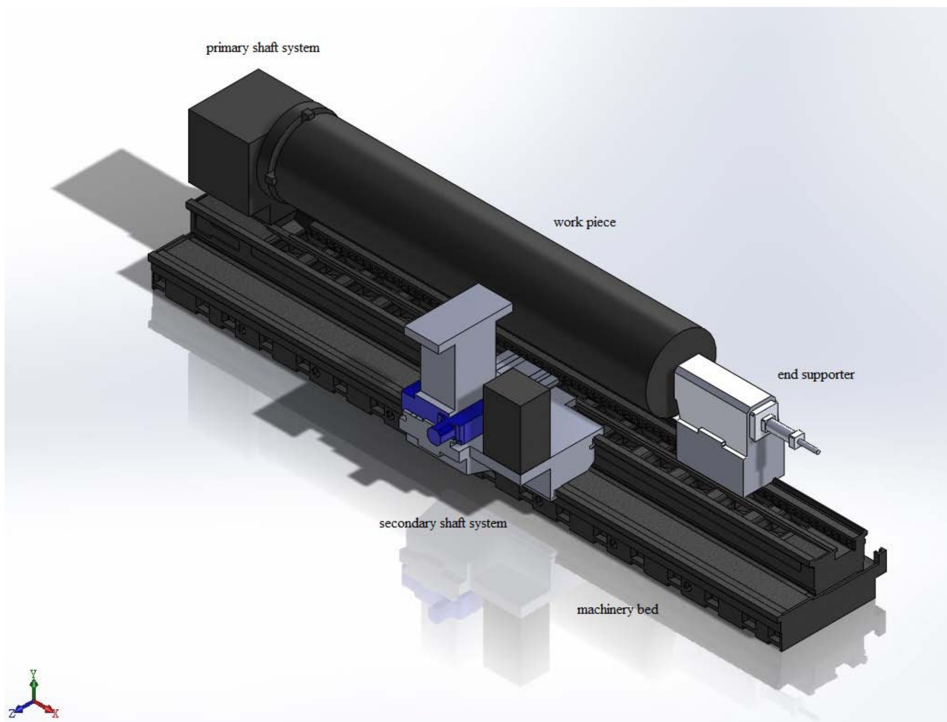

Figure 1: Assembling 3D parts of great five-axis turning-milling complex CNC machine

III. Results and Discussions

a) Convergence results

Convergence results of free vibration frequencies values of 1st mode in total 36 positions clamp supported machinery bed with secondary shaft system at 0mm location in CNC machine are listed in the Table 1. There are 200.00mm, 160.00mm, 155.00mm, 150.00mm and 145.00mm for maximum size length to calculate and study the vibration frequencies for first 1 mode of total machinery. The error of vibration frequencies is 7.783e-05 for 150.00mm and 145.00mm maximum size lengths. The mesh grids of maximum size length 150.00mm can be considered in good dynamical convergence condition, natural frequency converges to 25.694Hz and used this grids to calculate the stresses and displacements for further dynamic computation with the SOLIDWORKS® 2014 simulation module.

b) Dynamic results due to free vibration

Dynamic 1st mode displacement results of total 4, 8, 14, 20 and 36 positions clamp supported machinery bed (weight 13 tons) with secondary shaft system located at x axis: 0mm in CNC machine due to free vibration effect are shown in Figs. 2-6, the compared value of maximum displacement are shown in Table 2, the maximum value of dynamic 1st mode displacement is 8.641mm for total 4 clamp position, free vibration frequencies values of first 5 modes are shown

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in Table 3, the frequencies values of all first 5 modes are increasing with total numbers of clamps (e.g. from 16.238Hz to 25.694Hz for mode 1). When the secondary shaft system moved and located at x axis: 4000mm in CNC machine due to free vibration effect, dynamic first 5 modes displacement results of total 36 clamp positions are shown in *Figs. 7-11*, the maximum value of dynamic 5th mode displacement is 12.17mm. When the secondary shaft system moved and located at x axis: 6900mm in CNC machine due to free vibration effect, dynamic first 5 modes displacement results of total 36 clamp positions are shown in *Figs.12-16*, the maximum value of dynamic 5th mode displacement is 12.31mm. The compared values of first 5 modes maximum displacement and frequencies values due to free vibration effect for secondary shaft system located at x axis: 0mm, 4000mm and 6900mm of total 36 clamp positions are shown in *Tables 4-5*, respectively. The maximum displacement and frequencies values are selected as the basic data to design the CNC machine in safety condition for avoiding resonance, e.g. the rotational speed of motor used might not be in the low speed regions nearly 245.3596rpm for mode 1 of 36 positions clamp (25.694Hz).

c) Dynamic results under torque load

It needs a lot of computer memory 118GB to run the results of linear dynamic simulation, it is necessary for hard disk to occupy 500GB memory and execute its program. For secondary shaft system locates at x axis: 0mm of total 36 clamp positions of CNC machine under torque load 10000Nm applied at rotational head of primary shaft system, the linear dynamic results of stress and displacement are shown in *Figs.17-18*. The dynamic maximum stress (4.7MPa) occurred at the bottom corner of primary shaft system and maximum displacement (0.01889mm) occurred at jaw corner of primary shaft system are found. For secondary shaft system locates at x axis: 0mm, 4000mm and 6900mm of total 36 clamp positions of CNC machine under torque load 10000Nm applied at work piece, the linear dynamic results of stress and displacement are shown in *Figs.19-24*, respectively. The dynamic maximum stress (6.6MPa) and displacement (0.02168mm) occurred at jaw corner of primary shaft system are found when secondary shaft locates at x axis: 0mm, the dynamic maximum stress (6.7MPa) and displacement (0.02586mm) occurred at jaw corner of primary shaft system are found when secondary shaft locates at x axis: 4000mm, the dynamic maximum stress (6.8MPa) and displacement (0.02572mm) occurred at jaw corner of primary shaft system are found when secondary shaft locates at x axis: 6900mm.

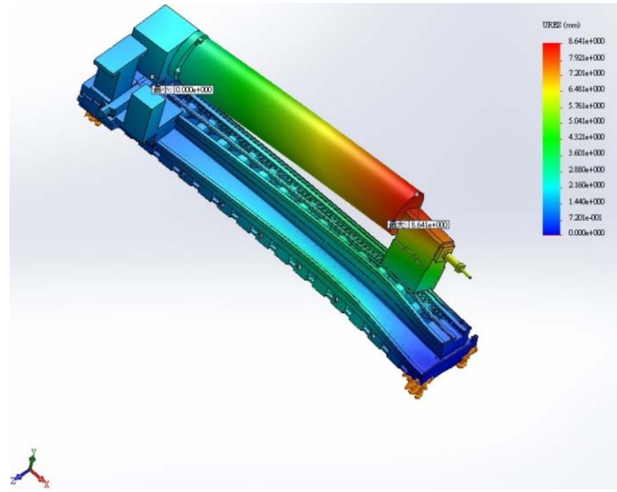


Figure 2: Dynamic 1st mode displacement for total 4 clamp positions for secondary shaft system at x axis: 0mm

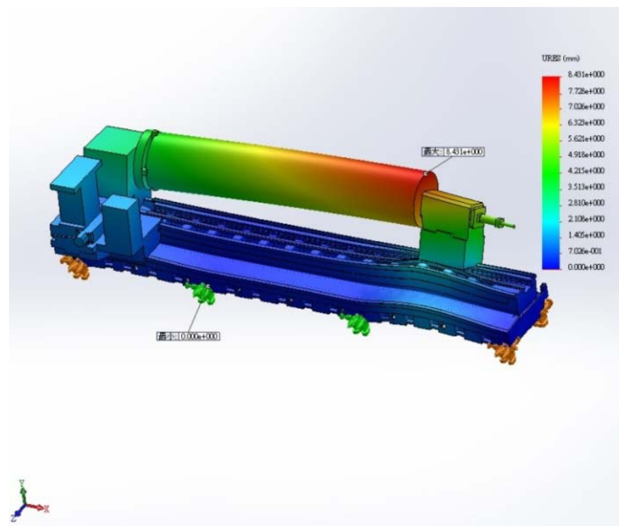


Figure 3: Dynamic 1st mode displacement for total 8 clamp positions for secondary shaft system at x axis: 0mm

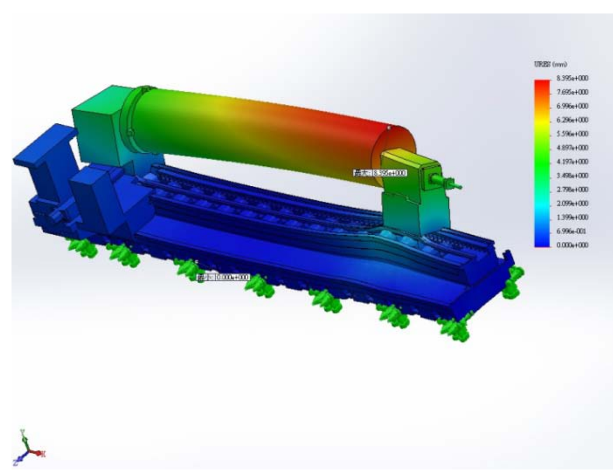
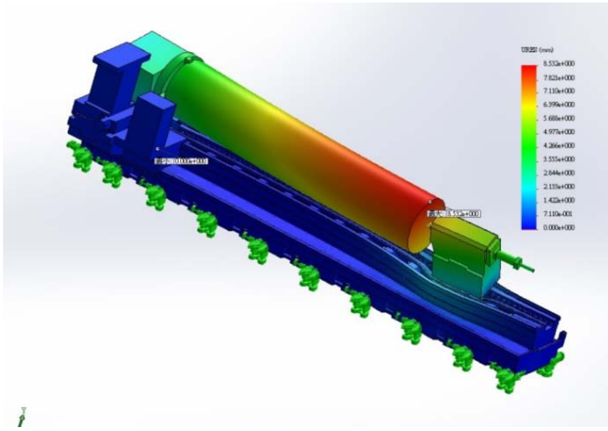


Figure 4: Dynamic 1st mode displacement for total 14 clamp positions for secondary shaft system at x axis: 0mm



Figurer 5: Dynamic 1st mode displacement for total 20 clamp positions for secondary shaft system at x axis: 0mm

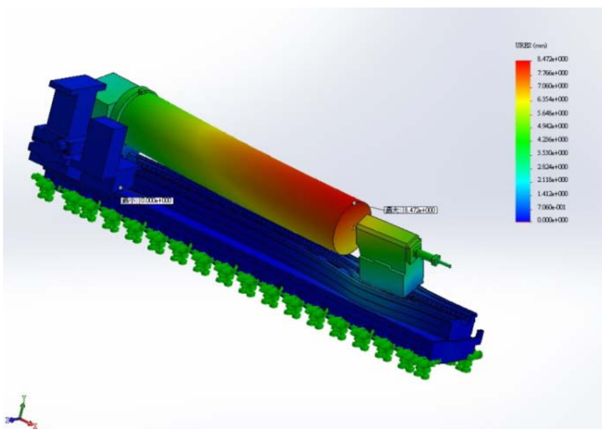


Figure 6: Dynamic 1st mode displacement for total 36 clamp positions for secondary shaft system at x axis: 0mm

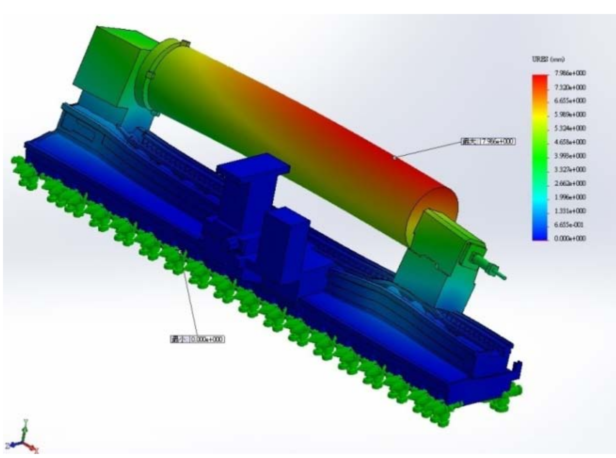


Figure 7: Dynamic 1st mode displacement for total 36 clamp positions for secondary shaft system at x axis: 4000mm

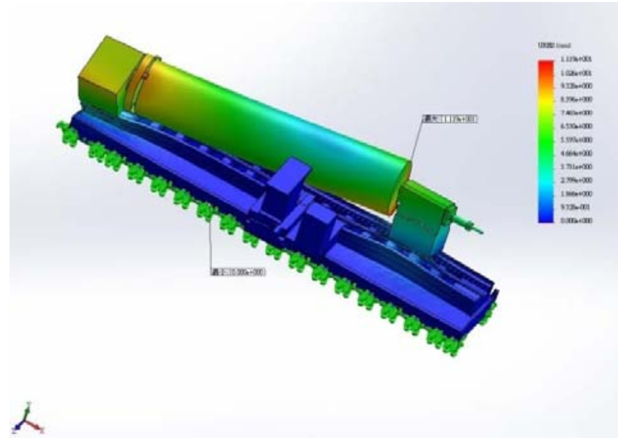


Figure 8: Dynamic 2nd mode displacement for total 36 clamp positions for secondary shaft system at x axis: 4000mm

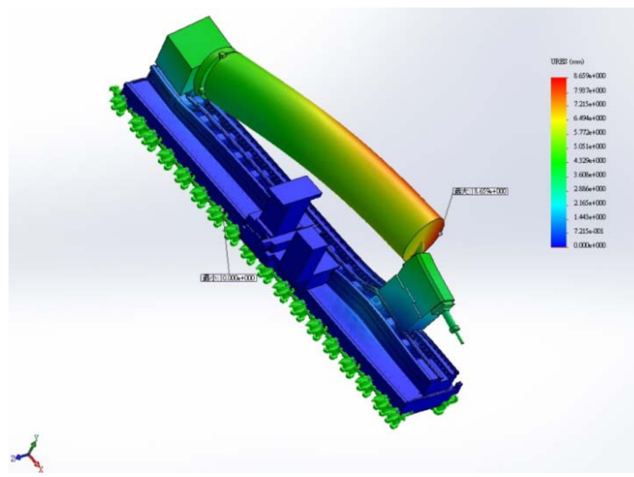


Figure 9: Dynamic 3rd mode displacement for total 36 clamp positions for secondary shaft system at x axis: 4000mm

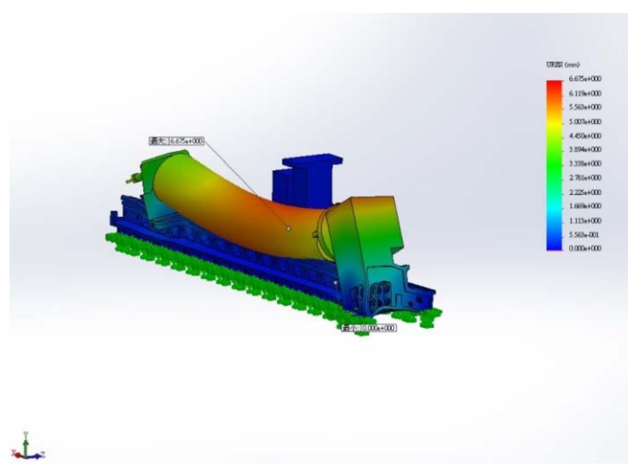


Figure 10: Dynamic 4th mode displacement for total 36 clamp positions for secondary shaft system at x axis: 4000mm

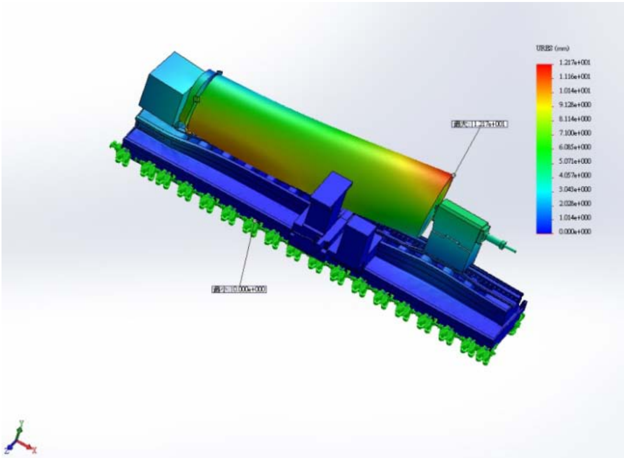


Figure 11: Dynamic 5th mode displacement for total 36 clamp positions for secondary shaft system at x axis: 4000mm

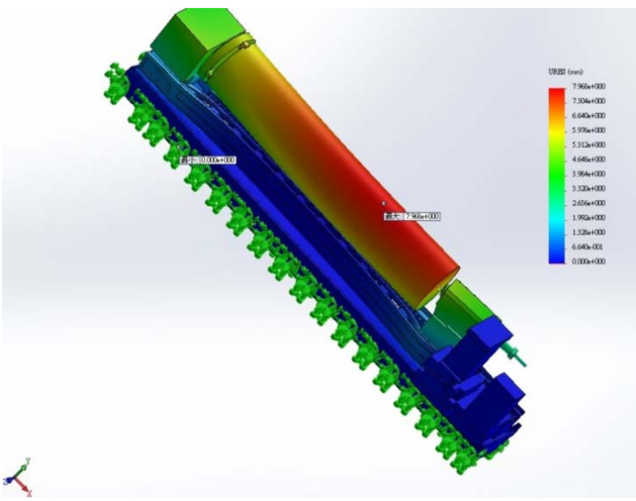


Figure12: Dynamic 1st mode displacement for total 36 clamp positions for secondary shaft system at x axis: 6900mm

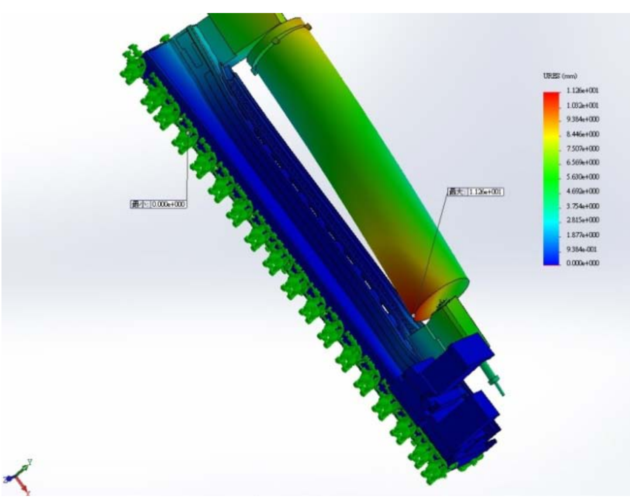


Figure 13: Dynamic 2nd mode displacement for total 36 clamp positions for secondary shaft system at x axis: 6900mm

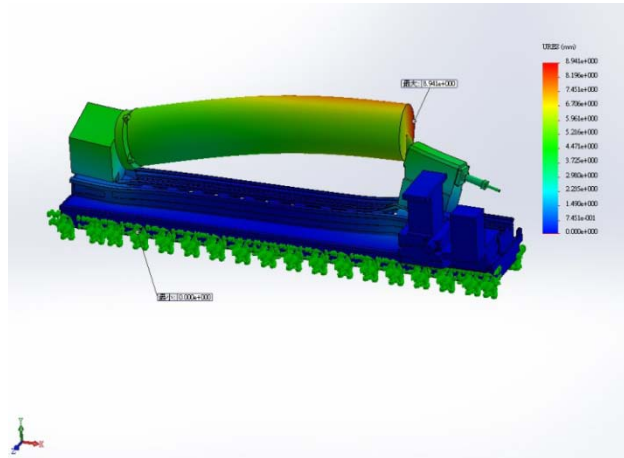


Figure 14: Dynamic 3rd mode displacement for total 36 clamp positions for secondary shaft system at x axis: 6900mm

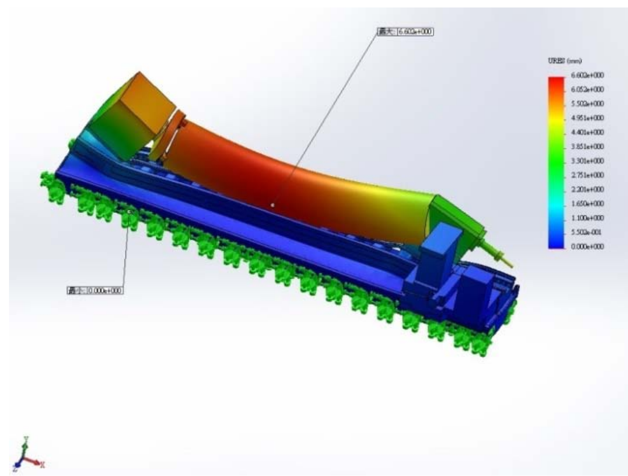


Figure 15: Dynamic 4th mode displacement for total 36 clamp positions for secondary shaft system at x axis: 6900mm

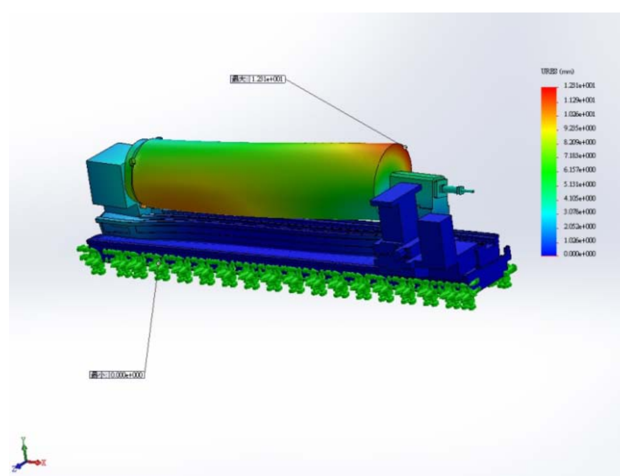


Figure 16: Dynamic 5th mode displacement for total 36 clamp positions for secondary shaft system at x axis: 6900mm

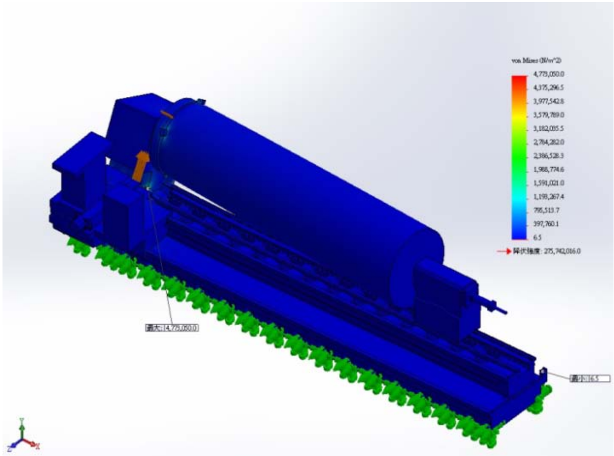


Figure 17: Stress for secondary shaft system at x axis: 0mm under torque 10000Nm at head of primary shaft

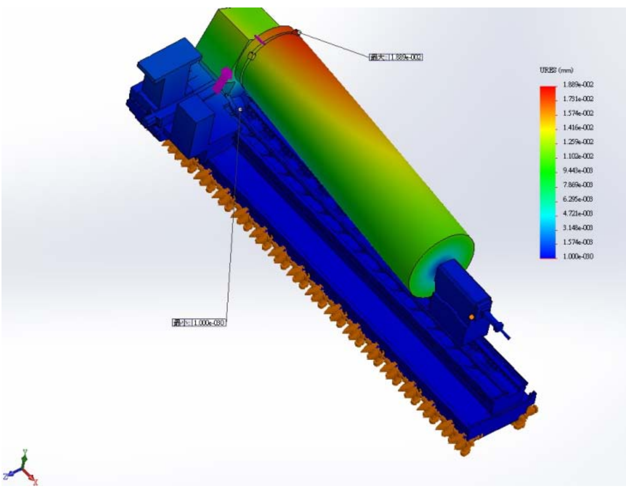


Figure18. Displacement for secondary shaft system at x axis: 0mm under torque 10000Nm at head of primary shaft

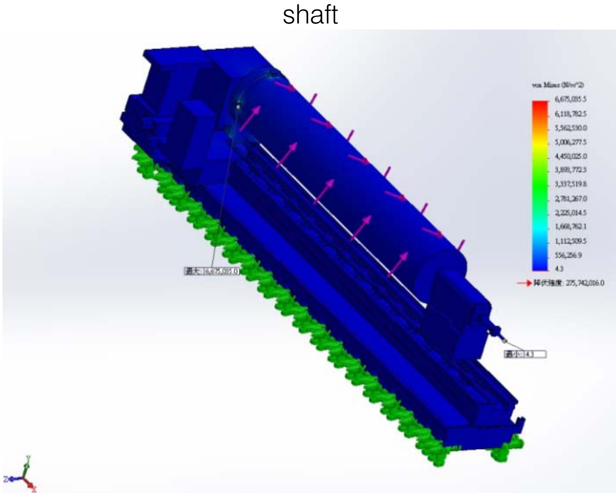


Figure 19: Stress for secondary shaft system at x axis: 0mm under torque 10000Nm at work piece

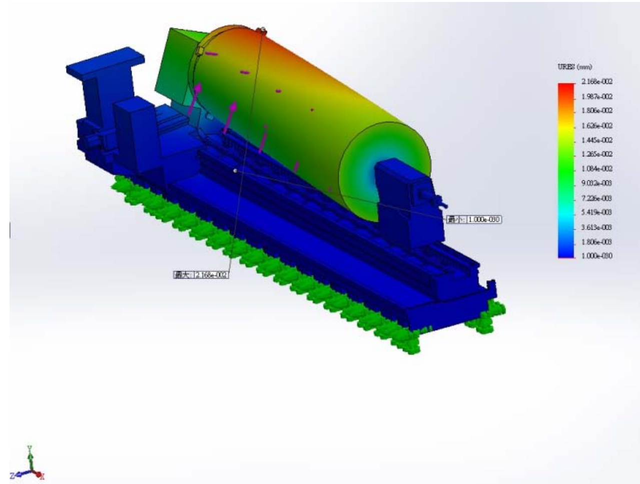


Figure 20: Displacement for secondary shaft system at x axis: 0mm under torque 10000Nm at work piece

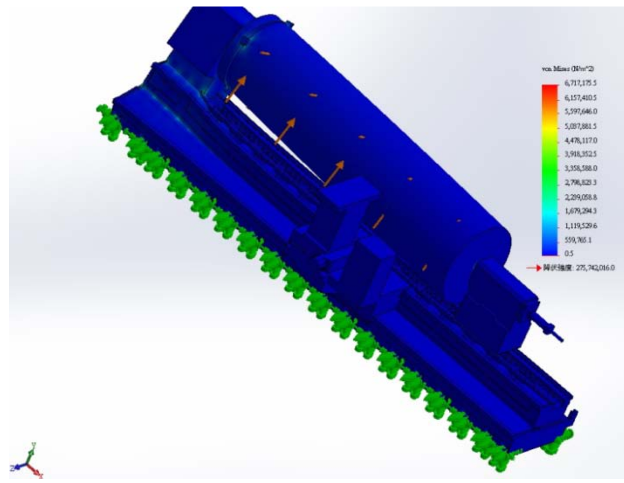


Figure 21: Stress for secondary shaft system at x axis: 4000mm under torque 10000Nm at work piece

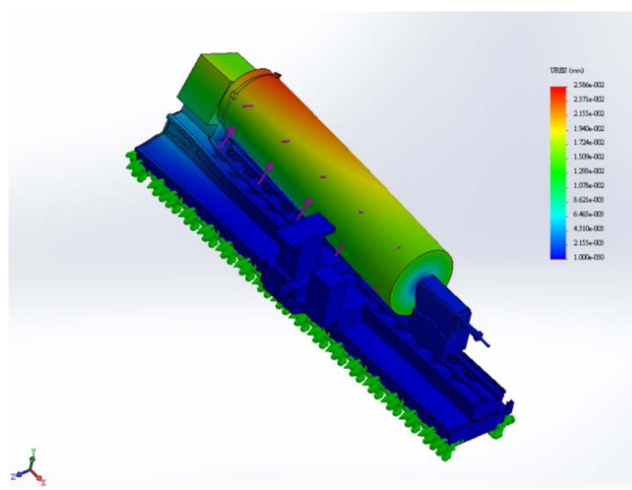


Figure 22: Displacement for secondary shaft system at x axis: 4000mm under torque 10000Nm at work piece

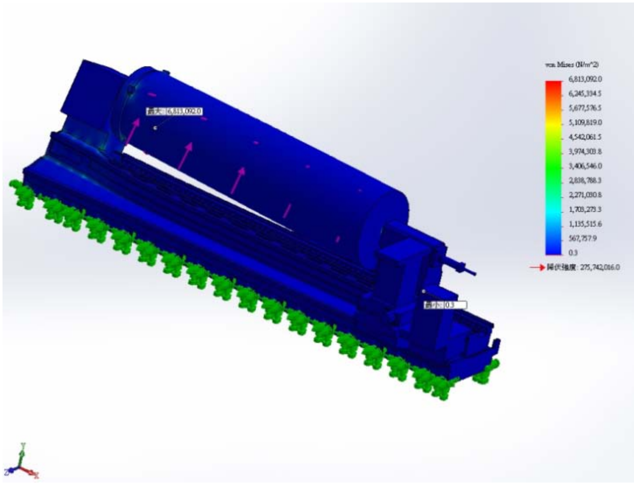


Figure 23: Stress for secondary shaft system at x axis: 6900mm under torque 10000Nm at work piece

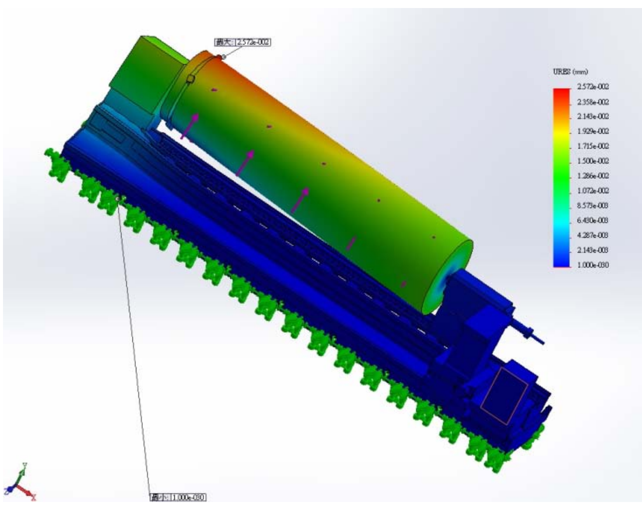


Figure 24: Displacement for secondary shaft system at x axis: 6900mm under torque 10000Nm at work piece

IV. Conclusion

In this paper, the free vibration frequencies values, linear dynamic stresses and displacements of secondary shaft system, primary shaft system and machinery bed of CNC machines are obtained by using the SOLIDWORKS® 2014 simulation module. The frequencies values, dynamic stress and displacement for five types of clamp supported boundary conditions and three positions of secondary shaft located in machinery bed under free vibration and torque loads are studied. It is desirable to select the maximum displacement and natural frequencies values as the basic data to design the CNC machine in safety condition for avoiding resonance. The maximum values of linear dynamic stress and displacement are also given and considered as the referred values for the judgments of yielding status and safety condition in the future construction of CNC machine.

V. Acknowledgements

The completion of this paper was made possible by a grant MOST 103-302-2-004 from Ministry of Science and Technology, Taiwan, ROC.

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Table 1: Convergence results

Maximum mesh grid sizes	Frequencies of 1st mode
200.00mm	25.822Hz
160.00mm	25.743Hz
155.00mm	25.721Hz
150.00mm	25.694Hz
145.00mm	25.696Hz

Table 2: Maximum displacements (mm) when secondary shaft at x axis: 0mm

Modes	Boundary conditions				
	4 clamps	8 clamps	14 clamps	20 clamps	36 clamps
Mode 1	8.641mm	8.431mm	8.395mm	8.532mm	8.472mm
Mode 2	7.999mm	9.841mm	10.44mm	9.962mm	10.06mm
Mode 3	7.338mm	7.785mm	8.844mm	9.899mm	9.965mm
Mode 4	9.326mm	6.893mm	7.012mm	6.701mm	6.739mm
Mode 5	13.34mm	14.66mm	13.02mm	10.60mm	11.23mm

Table 3: Free vibration frequencies (Hz) when secondary shaft at x axis: 0mm

Modes	Boundary conditions				
	4 clamps	8 clamps	14 clamps	20 clamps	36 clamps
Mode 1	16.238Hz	21.135Hz	24.043Hz	25.106Hz	25.694Hz
Mode 2	25.579Hz	34.006Hz	38.533Hz	40.825Hz	41.344Hz
Mode 3	30.677Hz	37.979Hz	40.954Hz	43.559Hz	44.088Hz
Mode 4	31.408Hz	40.342Hz	45.080Hz	45.279Hz	46.734Hz
Mode 5	40.885Hz	53.836Hz	63.058Hz	66.638Hz	68.290Hz

Table 4: Maximum displacements (mm) for total 36 clamp positions

Modes	Secondary shaft system		
	at x axis: 0mm	at x axis: 4000mm	at x axis: 6900mm
Mode 1	8.472mm	7.986mm	7.968mm
Mode 2	10.06mm	11.19mm	11.26mm
Mode 3	9.965mm	8.659mm	8.941mm
Mode 4	6.739mm	6.675mm	6.602mm
Mode 5	11.23mm	12.17mm	12.31mm

Table 5: Free vibration frequencies (Hz) for total 36 clamp positions

Modes	Secondary shaft system		
	at x axis: 0mm	at x axis: 4000mm	at x axis: 6900mm
Mode 1	25.694Hz	24.616Hz	25.249Hz
Mode 2	41.344Hz	37.936Hz	38.738Hz
Mode 3	44.088Hz	43.413Hz	43.653Hz
Mode 4	46.734Hz	46.054Hz	46.268Hz
Mode 5	68.290Hz	68.723Hz	69.046Hz