International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 24 (2017) pp. 14664-14668

CNC Machine Capability Study based on Structural and Thermal Analysis of Ball Screw Using Finite Element Method

Izatul Hamimi Abdul Razak[1]*, Wan Mansor Wan Muhamad[2], Meseret Nasir Reshid[2] and Nur Shazila Baharudin[2]

[1,2]Mechanical and Manufacturing Section, Universiti Kuala Lumpur Malaysia France Institute, 43650 Bandar Baru Bangi, Malaysia.
**Corresponding author's e-mail*

Abstract

Modern manufacturing industry highly demands high precision in machining to seek greater quality finishing. Therefore, a Computer Numerical Control (CNC) machine tool is equipped with a ball screw driving system, mainly, due to its high efficiency. However, most of the time, errors occur in the feed drive system are primarily caused by the friction heat generated at the moving parts such as screw shaft, nut, end-bearing, and slide ways which affects machining accuracy especially on the positions along each axis. In this study, simulation works were conducted using finite element analysis (FEA) software, HyperWorks to study and analyse the von Mises stresses and deformation. For the linear static or structural analysis, total load of 4342 N was applied and the maximum stress of 0.4183 MPa and deflection of 0.1023 µm of screw shaft deflection were obtained. For thermal analysis, thermal load of 49.929 ºC and structural load of 4342 N were applied and the maximum stress due to thermal stress obtained was 323.6 MPa, while maximum deformation was 7.183 µm. It was also found that the machine is capable of operating at worst condition with safety factor of 1.3 with respect to its material yield strength.

Keywords: Ball screw feed drive; FEA; Thermal stress; Structural stress; Deformation.

INTRODUCTION

Ball screw feed drive system is important component in modern CNC machine tools that converts the rotational motion of the electrical motor to linear motion of the slide. This system has been applied in machine tool table for the accurate positioning due to its relatively high stiffness and low sensitivity to variations in workpiece inertia during the cutting processes. A ball screw is a mechanical device which converts the rotational motion of the electrical motor to linear motion of the slide. The most common way of using a ball screw consists in the rotary screw arrangement. The screw is supported on roller packs in the fixed part of the machine and it is operated by a rotary servomotor.

A common ball screw system is an assembly of a ball screw, with an external helical groove or raceway, a ball nut with an internal helical groove and raceway, and a rolling system for re-circulating balls that fitted between the ball screw and the ball nut as shown in Figure 1.

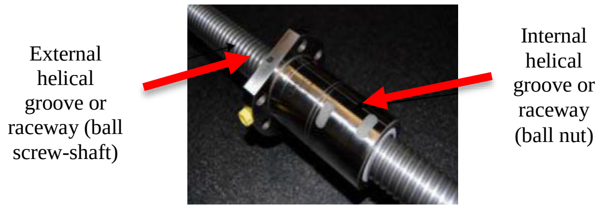


Figure 1: The ball screw system assembly

In high speed machining, e.g.; for 3 axis CNC machine tools is equipped with a ball screw driving system. Most of the time, thermal errors on feed drive system are primarily caused by the friction heat generated at moving parts such as screw shaft, nut, end-bearing, and slide ways (Figure 2). This friction heat generated is major effects on machining accuracy especially on the positioning accuracy along each axis [1, 2]. According to Yun et al., [3], within the various sources of machine tools errors, thermal error comprise 40 – 70% of total dimensional and shape errors in precision machining followed by geometric errors. As these deformation occurs rapidly it would slowly increase the changes to the dimensional accuracy of the machine until it reaches to the some value that can be considered as no longer an accurate machine.

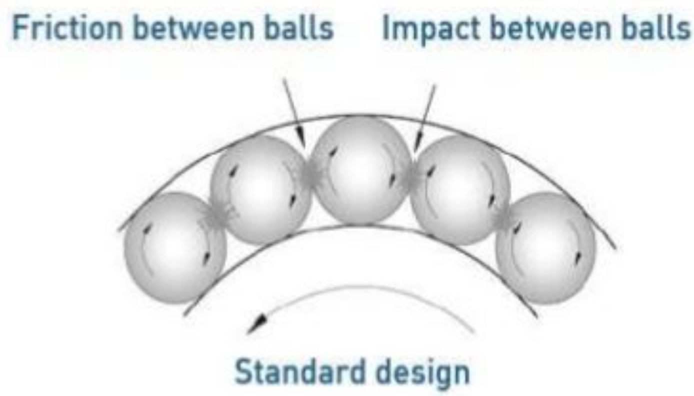


Figure 2: Friction heat generated

Running a machine with a condition lower than the machine's limitation might keep the machine long lasting. Major concerns arise with the machine condition when it needs to be run simultaneously under the most extreme conditions. Since there was no available knowledge about the machine can sustain and perform well in these conditions, there are a need to study the linear static analysis and thermal stress analysis on the ball screw feed drive system.

According to Muhammed [3], ball screw system was forced to work harder due to the high speed of machining, which then induced heat flux by friction between the two moving components. This led to thermal expansion and affects the machining accuracy as well [4]. Also, it was found that the maximum speed that a ball screw can reach was generally limited by the critical speed of the screw shaft [5].

In this paper, displacement and von Mises stress that influenced by the factors of force and heat friction on the ball screw system of the existing CNC machine were determined by performing the structural analysis and thermal stress analysis through Altair Hyperworks software. Maximum values of rotational speed and workpiece load were applied, and validated through analytical method. This research focused on CNC milling machine LAGUNMATIC 250 model.

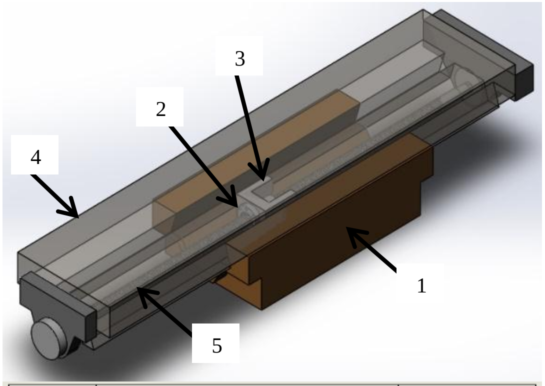
STRUCTURAL AND THERMAL STRESS ANALYSIS

Structural and thermal stress analyses of the ball screw were carried out using finite element analysis (FEA). In general, FEA is a numerical computerized analysis that allows creating model geometry, applying certain loads and boundary conditions, and meshing process with aims to numerically calculate the predicted stresses and deflections on geometry. A high end FEA package, Altair Hyperworks software was employed to investigate the linear static and the thermal deformation on a ball screw system.

The FEA process in Hyperworks software was carried out in three main stages; pre-processing stage which describes the type of analysis, meshing or splitting the model into finite number of elements, material properties, loads (boundary conditions) and restraints; processing stage computes and solves numerically the case of the model considering the inputs used in the pre-processor; and finally post-processing stages is where the results are collected and interpreted.

3D modelling

The ball screw system was modelled in Solidworks modelling software. Assembly of the CNC milling table is modelled as in Figure 3 which consists of the table, slider, screw shaft, ball nut, ball nut housing and the simple/fixed bearing supports. The table is 1118 x 254 mm length while the screw is 1095 mm length with 26 mm diameter (as referred from the CNC LAGUNMATIC 250 model's specification. The ball screw and flange nut model, where the present study focused at is illustrated in Figure 4,



ITEM NO.	PART NAME	QTY.
1	Slider	1
2	Flange Nut	1
3	Housing flange	1
4	Table	1
5	Screw Shaft - Ball Screw	1

Figure 3: Ball screw system assembly model

Figure 4: Ball screw and flange nut model

Assigning materials

The screw model material properties, real constants and material unit type properties were then defined. All components were assigned as steel, except for screw shaft which was AISI 4140. The material properties are depicted in Table 1.

Table 1: The material properties of AISI 4140 and steel

Property	Unit	Steel	AISI 4140
Young Modulus ,E	MPa	210 000	205 000
Poisson Ratio	-	0.3	0.29
Density	Ton/mm3	7.85e-9	7.85e-9
Thermal Expansion, A	$℃^{-1}$	1e-5	1..22e-5
Thermal Conductivity, K	W/(m·K)	73.0	46.6

Loads and boundary conditions

Two types of load were identified to be applied on the ball screw, which are thermal and structural load. Thermal load was determined based on frictions which occurred between balls and the shaft during operation, while structural loads are based on total loads exerted by material weight as well as downward cutting force during operation. Since the purpose of study was to determine maximum deformation of ball screw system, the extreme conditions of loading allowed by the machine were applied. Thermal load was defined as in Eq. 1 to Eq. 3.

$$Thermal\ load = \Delta T + T_{initial} \tag{1}$$

$$\Delta T = \frac{Q}{\mu c} \tag{2}$$

$$Q = \mu L \Delta s \tag{3}$$

Where; μ is coefficient of friction, which is 0.16; L is reaction force (simulation), which is 0.001; Δs is friction path, which is 5830mm; c is specific heat, which is 3.933 J/g ºC and Q is heat energy. Q is obtained at 0.9328 J; hence the thermal load applied was 49.929 ºC.

The structural load, or the downward load applied on the milling table was defined from the total loads of maximum workpiece capacity determined for the machine and maximum cutting force during operation. The cutting force was computed based on Eq. 4, and the list of parameters used are depicted in Table 2.

$$F_c = \frac{P(60{,}000{,}000)}{\pi d n_{spindle}} \tag{4}$$

Where, Fc is cutting force, P is power supplied, d is the diameter of spindle, and n is the spindle speed. Thus, the total load applied on the table is 4342 N.

Table 2: The parameters applied

No.	Parameters	Values
1	Spindle speed	4250 rpm
2	Power	5.6 kW
3	Maximum table load + table	529 kg
4	Cutting force	1006.6 N
5	Workpiece capacity	340 kg
6	Total force	4342 N
7	Thermal load	49.929 ºC

There were two analyses carried out in the investigation: (1) Structural analysis with 4342 N load without considering thermal load, and (2) Thermal analysis with 49.929 ºC thermal load plus 4342 N structural load. Practically, load was applied on the component as shown in Figure 5, representing the cutting force with workpiece during operation. In order to achieve higher stiffness to the screw and displacement accuracy, both ends of the screw section were constrained at all degree of freedom, at point as shown in Figure 6.

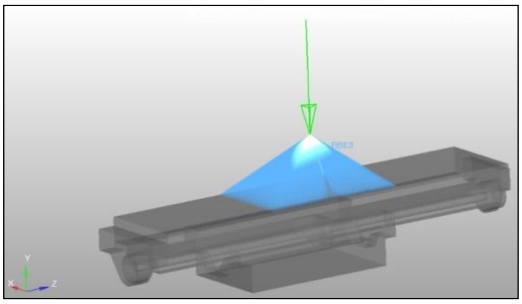


Figure 5: The green arrow (force) acting on the rbe3 component

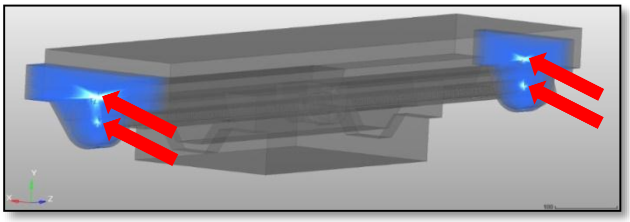


Figure 6: The red arrows show constraints at all degree of freedom at that point

Once complete with the load and constraints setting, the simulation was continued under OptiStruct option and meshed by tetras for 3D type option with minimum element size for result accurateness.

Safety factor of the ball screw feed drive system also were determined to analyze either the maximum stress was acceptable by following equation 5.

$$\text{Safety factor,} \quad n = \frac{S_y}{\sigma} \tag{5}$$

Where, S_y is the material yield strength of the screw shaft material and σ is the maximum vonMises stress. As guideline, referring to guidelines for safety factor conditions, the allowable safety factor for general industrial use is 1 to 2 [8].

RESULTS AND DISCUSSION

Structural analysis

The total allowable load of 4342 N (Table 3.2) was applied at the middle of ball screw shaft and the effects in terms of stress as well as deformation were analysed under static linear analysis. Figure 8 represents the von Mises stress distribution along the ball screw shaft. Maximum stress of 0.4183 MPa was identified about at the middle of the screw shaft. For more detail, the specific point of higher stress is shown in Figure 9. However, the stress value is far from the shaft's material yield strength; 415 MPa. This shows rigidity characteristic of the screw shaft as it was crucial for the CNC machine accuracy.

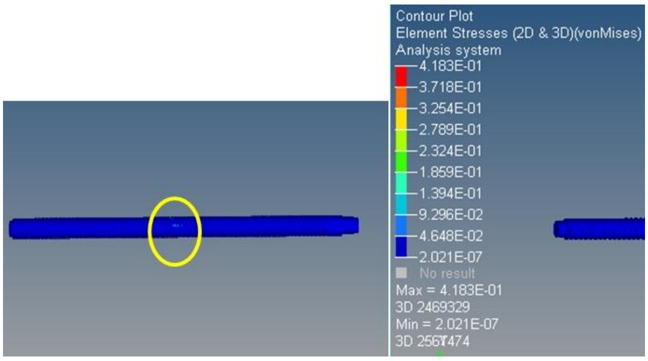


Figure 8: The Von Mises Stress result for linear static analysis

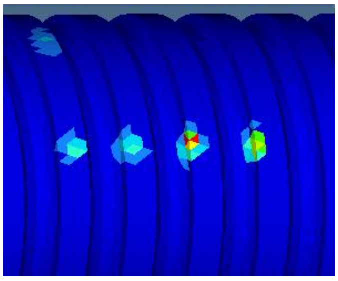


Figure 9: The higher stress point on the screw shaft

The shaft deformation result is presenting in Figure 10. The maximum shaft deformation is shown at the middle of the shaft, with displacement value of 0.1023 µm. This however can be considered as a small deflection compared to the displacement value taken from Hong et al.,'s [9] research which was 20.009 µm. The very minimum deformation confirms the reliability of the screw shaft in accuracy machining of the CNC machine.

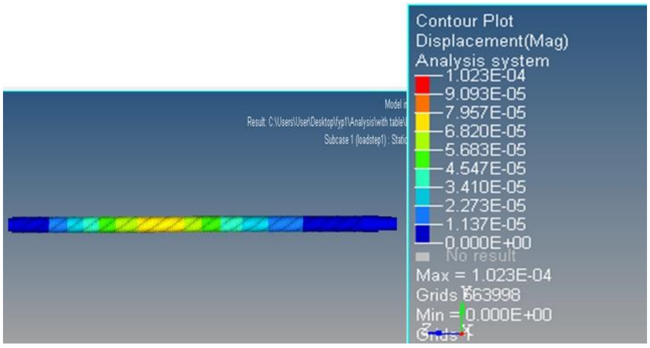


Figure 10: The displacement result for linear static analysis

Therefore, as a conclusion from this structural analysis, the shaft is far from yielding and has more than sufficient rigidity when there is no temperature effect or thermal load introduced to it.

Thermal stress analysis

Thermal load of 49.929 ºC and structural load of 4342 N were applied, and the stress distribution on the ball screw shaft is presented in Figure 11 and the detail view is as in Figure 12. The maximum stress due to thermal stress was 323.6 MPa is located at the edges of the screw shaft thread. Whereas, maximum deformation due to thermal load recorded was 7.183 µm, as shown in Figure13.

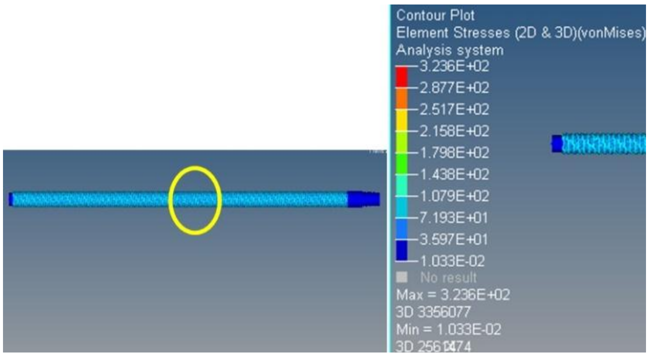


Figure 11: The Von Misses Stress result for thermal stress analysis

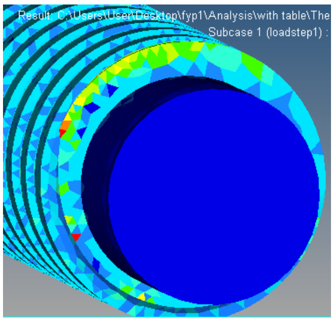


Figure 12: The higher thermal stress zone

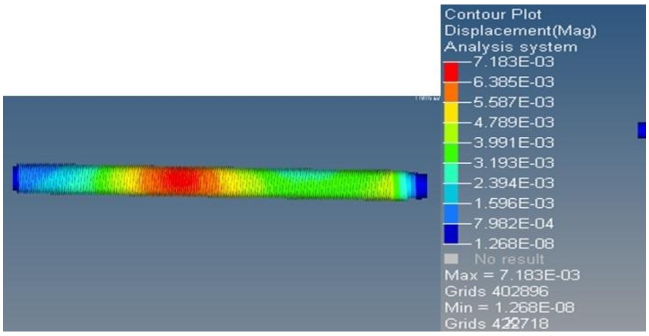


Figure 13: The displacement result for thermal stress analysis

From the thermal analysis, the safety factor obtained is 1.3 and this is within an acceptable range. The resulting deformation is also below minimum requirement, denoting that the shaft has the required rigidity for safe operations.

CONCLUSION

In this study, the capability of feed drive system of CNC milling machine model Lagunmatic 250 was assessed in terms of the structural and thermal capabilities under the extreme load conditions. Owing to the accuracy properties of CNC machine, even very small deflection in the feed drive system might contribute to inaccuracy in machining of finished products. Research work was conducted through simulation to determine the stresses and deformation of ball screw shaft using Finite Element Analysis, when extreme loading conditions were applied on it. The obtained results prove the great stiffness of the ball screw structure, with safety factor of 1.3.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Kuala Lumpur through the Short Term Grant STR14048 for the financial support given in the completion of this research.

REFERENCES

[1] Y. Lu, and M.N. Islam, An experimental investigation of thermal effects on the dimensional accuracy of machined parts. Research Paper, Curtin University of Technology (2010).

[2] J. Xia, Y. Hu, Y. Lu, and B. Wu. Testing research on the thermal error characteristic of ballscrew feed system. In Advanced Design and Manufacture to Gain a Competitive Edge, Springer London (2008) 303-313.

[3] M. A. Muhammed, The effect of heat generated by friction in the ball-screw-nut system on the precision of high speed machine, Amara Technical Institute (2011). 2-12.

[4] C.H. Wu, and Y.T. Kung, Thermal analysis for feed drive system of CNC machine centre, International Journal of Machine Tools & Manufacture 43 (2003), 1521 – 1528.

[5] J. M. Azkoita, J. J. Zulaika and R. Gonzalez, High speed machining: a challenge for ball screw drives (2010). Retrieved from file:///E:/calibration/Azkoitia_josemiguel_revised. pdf.

[6] J. Xia, Y. Hu, B. Wu, and T. Shi, Research on thermal dynamics characteristics and modeling approach of ball screw. The International Journal of Advanced Manufacturing Technology, 43:5-6 (2009) 421-430.

[7] W.D. Pilkey, and D.F. Pilkey, Peterson's Stress-Concentration Factors, 3rd ed. John Wiley & Sons (2008).

[8] Precision Machine Component – NSK Linear Guides, Ball Screws, Monocarriers (2009), Motion and Control NSK, NSK Ltd. Retrieved May, 30, 2017 from: https://www.pkservis.com/data/web/upload /nsk/precisio-machines-components.pdf

[9] P. Hong, Y. Pan, and T. Zhang, Dynamic characteristics analysis of ball screw based on workbench. American International Journal of Contemporary Research, Vol 5, No.3 (2015) 115-120.