JMPM: Jurnal Material dan Proses Manufaktur
Vol. 7, No. 1, p19-26, Juni 2023
DOI: https//doi.org/10.18196/jmpm.v7i1.17906

Modal Analysis of CNC Milling Machine Bed Made of Different Alloys using Finite Element Modeling

Mohd Hazri Omar[a]*, Mohamad Nazri Abdul Halim[b], Mohd Fadzli Othman[b]
[a] Dept. of Mechanical Engineering, Politeknik Tuanku Syed Sirajuddin, Pauh Putra, 02600 Arau, Perlis, Malaysia.
[b] Dept. of Mechanical Engineering, Politeknik Sultan Abdul Halim Mu'adzam Shah, 06000 Jitra, Kedah, Malaysia.
*e-mail: hazriomar@hotmail.com

Kata kunci:

Mesin Perkakas; Parameter Modal; Machine Bed; Mesin Frais CNC; Autodesk Inventor

ABSTRAK

Selama bertahun-tahun, ada penekanan yang kuat untuk memprediksi perilaku dinamis struktur alat mesin dengan mengidentifikasi parameter modal. *Bed* mesin adalah salah satu komponen yang paling penting dalam mesin *milling* CNC karena fungsinya secara signifikan mempengaruhi kualitas produk akhir. *Bed* berfungsi sebagai fondasi mesin, menopang semua komponen penting mesin. *Bed* juga digunakan untuk menghindari deformasi yang disebabkan oleh beban statis dan dinamis. Penelitian ini bertujuan untuk membandingkan parameter modal dari beberapa paduan yang digunakan sebagai material *bed*, seperti baja karbon, baja paduan, dan baja tahan karat, dengan parameter modal dari material yang umum. Model tiga dimensi dan analisis modal unggun dilakukan dalam perangkat lunak Autodesk Inventor. Baja paduan menunjukkan nilai frekuensi natural tertinggi dibandingkan dengan material lain karena *modulus young* yang tinggi dan densitas yang rendah. Bentuk modus yang serupa diamati dengan besaran yang bervariasi pada semua material. Berdasarkan temuan ini, baja paduan dapat menjadi alternatif yang layak untuk besi tuang dalam struktur alas mesin perkakas.

***Keyword*:**

Machine Tool; Modal Parameters; Machine Bed; CNC Milling Machine; Autodesk Inventor

ABSTRACT

Over the years, there has been a strong emphasis on predicting the dynamic behavior of machine tool structures by identifying modal parameters. The machine bed is one of the most significant components in a CNC milling machine because its functionality significantly affects the final product's quality. The bed acts as the machine's foundation, supporting all the machine's critical components. It is also utilized to avoid deformation caused by static and dynamic loads. This study aims to compare the modal parameters of several alloys used as bed materials, such as carbon steel, alloy steel, and stainless steel, to those of a common material. A three-dimensional model and modal analysis of the bed were conducted in Autodesk Inventor software. Alloy steel shows the highest values of natural frequencies compared to other materials due to its high young modulus and low density. A similar mode shape is observed with varied magnitude in all the materials. According to the findings, alloy steel could be a viable alternative to cast iron in machine tools' bed structures.

1. INTRODUCTION

A substantial emphasis has been placed on gaining a better knowledge of the dynamic behavior of machine tool structures. Understanding these dynamic parameters in machine tool structures is crucial for achieving good surface quality and chatter-free machining [1]. Modal analysis is a technique for determining the underlying dynamic properties of a system. Modal analysis displays natural frequencies and mode shapes, which can be used to improve and optimize the design of a structure or component. The techniques used in the modal analysis are experimental modal analysis (EMA), operational modal analysis (OMA), finite element modeling (FEM), and impact synchronous modal analysis (iSMA) [2, 3]. With the advancement of computational systems, modal analysis utilizing FEM is commonly utilized to predict a structure's modal parameters. It is regarded as a good tool for numerical modeling in structural engineering because it can handle complex structural geometry and perform various analyses. Researchers have used a range of software to do modal analysis, including ANSYS [4], ABACUS [5], Autodesk Inventor (AI) [6], and SolidWorks [7].

One of the essential parts of a machine tool is the bed structure since the functionality of this part directly affects the quality of the finished product [8]. The bed is the machine's base, supporting its vital components. It is also utilized to avoid static and dynamic load deformation. The machine tool bed must meet two essential functional requirements, which are high structural rigidity and high damping. The rigidity of the bed is frequently insufficient because of inadequate structural design, which causes vibration and affects machine tool efficiency [9]. Structural stiffness and damping can be enhanced through material and design advancements. Most of the current machine beds are built of cast iron, which causes various problems with machine tools [10]. Cast iron cannot bear unexpected loads while in operation due to a variety of casting defects [11]. Regarding the design advancements, Duan et al. [12] improved the torsional and bending stiffness of the lathe bed structure by incorporating several strengthened plate combinations. Structural mode shapes were used to locate weak areas for the stiffened plate. According to the simulation results, the dynamic performances of modified lathe-bed structures outperformed the original structure significantly.

The correlation between Young's modulus and the density of a material is essential in designing a structure. Hassan et al. [13] showed that the dynamic stiffness would increase as the density of the material decreased. Barboni et al. [14] showed that the dynamic stiffness is proportional to Young's modulus. From the theory of beam, the natural frequency is proportional to the dynamic stiffness and is in inverse proportion to mass [15]. As a result, a material with a higher Young's modulus and a lower density will have a higher natural frequency. Many studies have proposed different materials for bed structures as an alternative to existing cast iron. Mohring et al. [16] reviewed the mechanical properties of various machine tool materials and addressed material selection as well as an application for high-performance machine tools. Kumar et al. [11] performed a modal and harmonic analysis on a CNC milling machine to compare machine beds made of existing grey cast iron with proposed aluminum silicon carbide (Al-SiC). A three-dimensional model of the CNC machine bed was created in CATIA and was analyzed in the Ansys workbench. It was revealed that Al-SiC had greater natural frequencies than grey cast iron does. Mahendrakumar et al. [17] used a polyester (NP) composite produced from Himalayan nettle to improve the dynamic properties of a micro lathe bed. Several cross-sections and rib configurations were examined to increase the nettle-polyester composite lathe bed's bending and torsional stiffness. Chinnuraj et al. [18] focused on evaluating various steel reinforcements in an epoxy granite composite for a lathe bed to attain better static and dynamic properties than the present cast iron bed. Five distinct epoxy granite beds with steel reinforcing designs were built as finite element models. In terms of rigidity and mass, one of the proposed epoxy granite bed designs surpassed the cast iron bed. Ahmad and Jagadeesha [19] assessed the dynamic parameters of the proposed basalt fiber polymer concrete lathe bed using modal analysis and harmonic response analysis. When the results were compared, it was discovered that they were nearly equal to traditional materials such as cast iron.

This paper aims to extract the modal parameters, mainly natural frequencies of bed structure made from four different materials using FEM software, AI. Under the same boundary conditions, the natural frequencies of carbon steel, alloy steel, and stainless steel are compared with those of a typical material, cast iron. It is essential to observe modal parameter changes to identify potential material improvements for the bed structure that could isolate natural frequency from the operational range.

2. MATERIALS AND METHODS

In this study, the geometry of the CNC milling machine bed was adopted by Kumar et al. [11], as shown in Figure 1. The three-dimensional model of the bed was developed in AI software, consisting of front and rear sections, as shown in Figure 2. The four different materials that were considered for the modal analysis were cast iron, carbon steel, alloy steel, and stainless steel; and their mechanical properties are listed in Table 1. The modal analysis tool in Autodesk Inventor 2019 was used to investigate the effect of various materials on the natural frequencies of the bed. Modal analysis on the bed was performed under free-free conditions, and the corresponding modal parameters were determined by neglecting the rigid body modes.

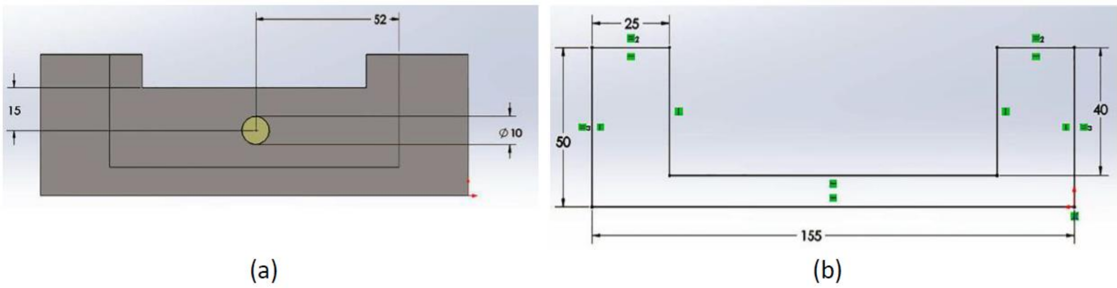

Figure 1. The geometry of the CNC milling machine bed: (a) rear section, (b) front section (Kumar et al., 2022)

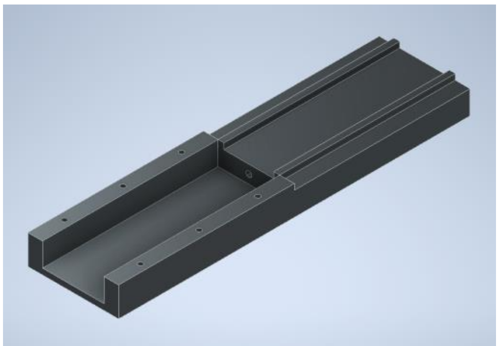

Figure 2. 3D model in Autodesk Inventor

Table 1. Mechanical properties of materials

Material	Young's modulus (Gpa)	Shear modulus (GPa)	Poisson's ratio	Mass density (kg/ m³)
Cast Iron	110	58	0.28	7200
Carbon Steel	200	80	0.29	7860
Stainless Steel	193	86	0.30	8000
Alloy Steel	205	80	0.30	7720

One of the most fundamental challenges in FEM is selecting the correct mesh size [20, 21]. Large elements may yield less accurate results, while small elements may yield better results. A smaller mesh size may also result in a longer processing time. Therefore, this study begins by choosing the appropriate mesh size by analyzing the natural frequencies of the current cast iron bed.

In AI modal analysis tool, mesh settings can be controlled by adjusting the value of the average element size. The value represents the average distance between mesh element nodes. AI recommended using this value between 0.05 and 0.1, whose default value is 0.1. Three values, 0.1, 0.075, and 0.05, representing the maximum, intermediate, and minimum recommended average element sizes, are investigated to determine the best mesh size.

The natural frequencies of the first six modes are collected for each average element size. Variations of these frequencies within the first six vibration modes are tabled as a function of the average element sizes. The value of natural frequencies of the smallest average element sizes is treated as a baseline value. It is assumed that lower average element sizes predict natural frequencies better. Then, the percentage of total errors is calculated by summing the errors of the first six natural frequencies.

3. RESULTS AND DISCUSSION

3.1 Analyzing the effect of mesh size

Modal analysis on the cast iron bed was carried out under free–free conditions using AI. The first six natural frequencies and corresponding modes were extracted by ignoring the rigid body mode shapes. Table 2 compares the number of nodes and elements for each mesh size. It can be observed that the greater the average element sizes, the lower the number of nodes and elements. Thus, the lower the number of degrees of freedom. For the average element size equal to 0.1, the number of elements is reduced to almost 50% from the average element size equal to 0.05. There is a significant reduction in the number of nodes and elements.

Table 2. The number of nodes and elements for each mesh size

Average element size	No. of nodes	Nodes reduction (%)	No. of elements	Elements reduction (%)
0.05	4513	0.0	2458	0.0
0.075	2707	40.0	1401	43.0
0.1	2374	47.4	1237	49.7

Then, a comparison of the natural frequencies for the three average element sizes is shown in Table 3. It is observed that the total error increases to greater than 30% as average element sizes are increased. The highest difference in natural frequency is observed in the third mode. Since the error is significant, the value of average element sizes equal to 0.05 is selected for comparing the natural frequencies of different materials in this study.

Table 3. Natural frequencies for the different mesh sizes

Mode	Natural Frequency (Hz)			Error (%)	
	Average element size				
	(A) 0.05	(B) 0.075	(C) 0.1	Between A & B	Between A & C
1	504	507	508	0.58	0.85
2	515	551	557	6.90	8.17
3	1151	1345	1351	16.87	17.39
4	1322	1350	1352	2.12	2.23
5	1397	1409	1409	0.84	0.79
6	1610	1658	1670	2.98	3.76
Total error (%)				30.29	33.19

The first three mode shapes for the CI bed are shown in Figure 3 to Figure 5. In the first mode, the bed experiences bending motion on the x-axis. Torsional motion in the x-axis is observed in the second mode, while torsional motion in the y-axis is observed in the third mode. Higher motion is observed in the front section since this part has a lower thickness, reducing its stiffness.

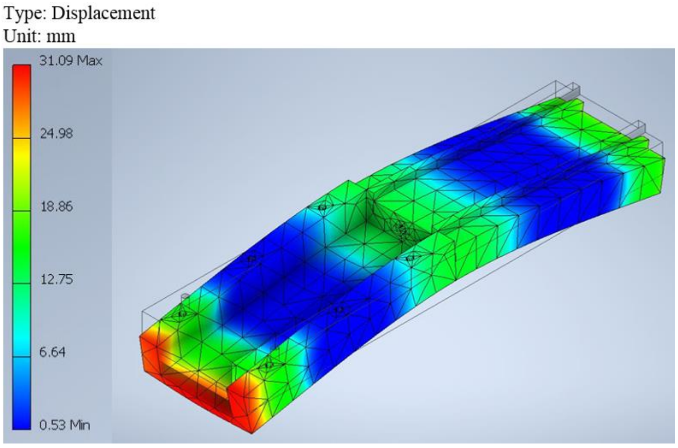

Figure 3. First mode shape

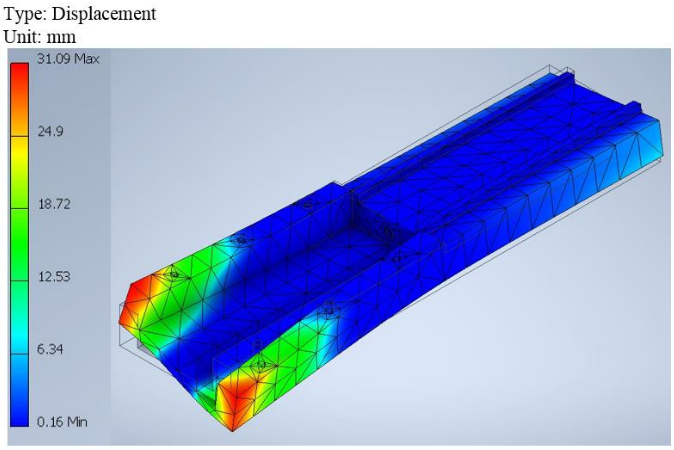

Figure 4. Second mode shape

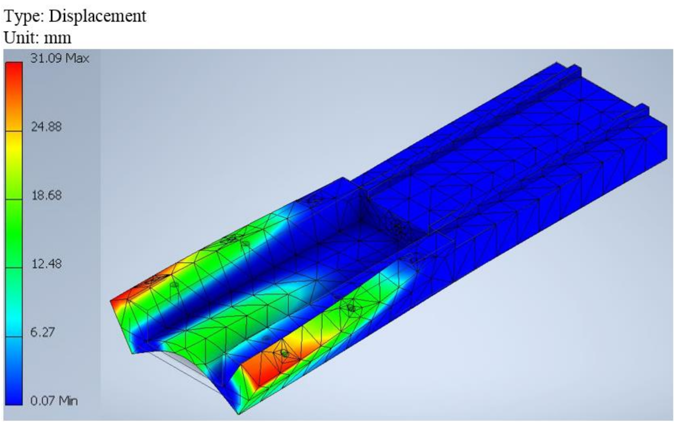

Figure 5. Third mode shape

3.2 Effect of material on modal parameters

The analysis for different types of material under free-free boundary conditions was studied in this section. The comparison of the natural frequencies for each material is shown in Table 4. Higher natural frequencies are observed for alloy steel, and lower natural frequencies are observed for stainless steel. Due to its high Young's modulus and low density, alloy steel has a higher natural frequency than carbon steel and stainless steel.

Table 4. Natural frequencies for the different materials

Mode	Natural Frequency (Hz)			
	Cast Iron	Alloy steel	Carbon Steel	Stainless Steel
1	504	632	619	603
2	515	646	635	616
3	1151	1444	1416	1377
4	1322	1659	1629	1582
5	1397	1753	1718	1672
6	1610	2019	1981	1926

In comparison with the cast iron bed, Figure 6 shows a percentage of improvement in natural frequencies for the first six modes. The percentage of increment in natural frequencies is almost constant for each mode. Alloy steel has an average of about 25% increment, followed by carbon steel with 23% and 19% for stainless steel as compared to a cast iron bed.

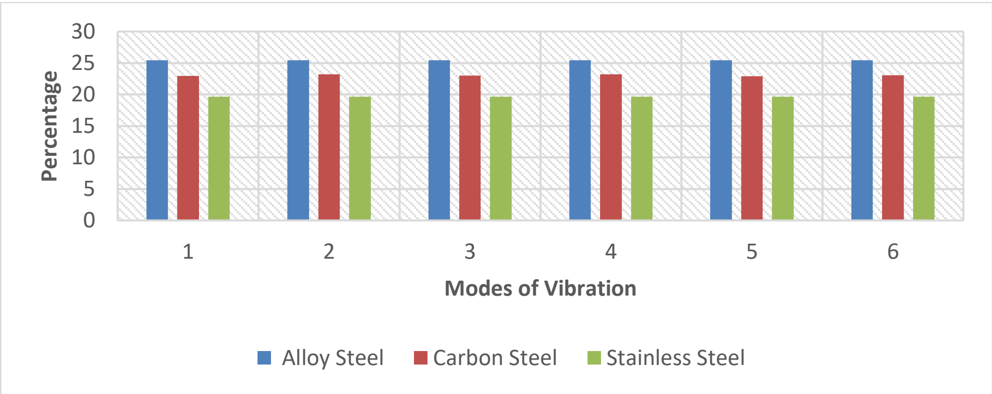

Figure 6. Percentage of improvement in the natural frequency for the first six modes

4. CONCLUSION

In the present work, the three-dimensional model and modal analysis of the CNC milling machine bed under free-free boundary conditions are studied in AI software. The bed is modeled with four different materials such as carbon steel, alloy steel, stainless steel, and cast iron. This study started with determining the mesh size by varying the value of the average element size in the AI modal analysis tool. The result on existing material, the cast iron bed has shown an average element size equal to 0.05, giving better natural frequencies prediction. Then, the first six natural frequencies for another three materials were simulated. A higher increment in natural frequencies as compared to cast iron bed is observed in alloy steel with an increment of about 25%. Carbon steel and stainless steel increased by 23% and 19%, respectively. Material with higher Young's modulus and lower density increased the natural frequencies. Results thus give a better understanding of the materials suitable for the machine bed, which is one of the essential components of the machine tool. Finally, utilizing alloy steel is advantageous to the industry since it provides better isolation from machine operating frequencies.

REFERENCES

[1] Lamraoui M, El Badaoui M, Guilleti F. "Chatter stability prediction for CNC machine tool in operating condition through operational modal analysis". *Mechanics and Industry*; 17. Epub ahead of print 2016. DOI: 10.1051/meca/2015038.

[2] Sharma JK. "Theoretical and experimental modal analysis of beam". In: *Lecture Notes in Electrical Engineering*. 2019. Epub ahead of print 2019. DOI: 10.1007/978-981-13-1642-5_16.

[3] Zahid F Bin, Ong ZC, Khoo SY. "A review of operational modal analysis techniques for in-service modal identification". *Journal of the Brazilian Society of Mechanical Sciences and Engineering*; 42. Epub ahead of print 2020. DOI: 10.1007/s40430-020-02470-8.

[4] Xiaoguang T, Xiaozhong R, Sai G, et al. "Lightweight optimization design of horizontal double-sided combined machine tool bed based on ANSys workbench". *Academic Journal of Manufacturing Engineering*; 17.

[5] Thasneem MM, Thankachan P, Madhavan Pillai TM. "Computational and Experimental Modal Analysis of a Three-Storied Building Model". In: *IOP Conference Series: Materials Science and Engineering*. 2020. Epub ahead of print 2020. DOI: 10.1088/1757-899X/936/1/012018.

[6] Wilk A, Judek S, Karwowski K, et al. "Modal analysis of railway current collectors using Autodesk Inventor". In: *MATEC Web of Conferences*. 2018. Epub ahead of print 2018. DOI: 10.1051/matecconf/201818004004.

[7] RUSAN C-I, CIUPAN C. "STATIC AND MODAL ANALYSIS OF HIGH-SPEED CNC MILLING SPINDLE". *ACTA TECHNICA NAPOCENSIS-Series: APPLIED MATHEMATICS, MECHANICS, and ENGINEERING*; 63.

[8] Yang H, Zhao R, Li W, et al. "Static and Dynamic Characteristics Modeling for CK61125 CNC Lathe Bed Basing on FEM". In: *Procedia Engineering*. 2017. Epub ahead of print 2017. DOI: 10.1016/j.proeng.2017.01.171.

[9] Guang-chen X, Xing-wei S. "Analysis and structural optimization of bed structure for CNC lathe based on modal strain energy sensitivity". *The Journal of Engineering* 2020; 2020: 111–114.

[10] Murugan S, Thyla PR. "Mechanical and dynamic properties of alternate materials for machine tool structures: A review". *Journal of Reinforced Plastics and Composites*; 37. Epub ahead of print 2018. DOI: 10.1177/0731684418799946.

[11] Kumar R, Jain A, Mishra SK, et al. "Comparative structural analysis of CNC milling machine bed using Al-SIC/graphite, al alloy and Al-SIC composite material". *Mater Today Proc* 2022; 51: 735–741.

[12] Duan YD, Zhang GP, Guo C, et al. "Improvement design research of a CNC lathe-bed structure". In: *Applied Mechanics and Materials*. Trans Tech Publ, 2011, pp. 1028–1032.

[13] Hassan AM, Rezali KAM, Jalil NAA, et al. "The Effect of Preload, Density and Thickness on Seat Dynamic Stiffness". *Pertanika J Sci Technol* 2023; 31: 1267–1278.

[14] Barboni L, Gillich GR, Chioncel CP, et al. "A Method to Precise Determine the Young's Modulus from Dynamic Measurements". In: *IOP Conference Series: Materials Science and Engineering*. Institute of Physics Publishing, 2018. Epub ahead of print 26 October 2018. DOI: 10.1088/1757-899X/416/1/012063.

[15] Manral ARS, Gariya N, Bansal G, et al. "Structural and modal analysis of chicken feather fibre (CFF) with epoxy-resin matrix composite material". In: *Materials Today: Proceedings*. Elsevier Ltd, 2019, pp. 2558–2563.

[16] Möhring H-C, Brecher C, Abele E, et al. "Materials in machine tool structures". *CIRP Annals* 2015; 64: 725–748.

[17] Mahendrakumar N, Thyla PR, Mohanram P V., et al. "Study on static and dynamic characteristics of nettle–polyester composite micro lathe bed". *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*; 233. Epub ahead of print 2019. DOI: 10.1177/1464420716663568.

[18] Chinnuraj S, Thyla PR, Elango S, et al. "Static and dynamic behavior of steel-reinforced epoxy granite CNC lathe bed using finite element analysis". *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 2020; 234: 595–609.

[19] Ahmad SF, Jagadeesha T. "Modelling and dynamic simulation of polymer concrete material for machine tool structure of a lathe". *Mater Today Proc* 2021; 45: 5732–5738.

[20] Omar R, Rani MNA, Yunus MA, et al. "Investigation of Mesh Size effect on dynamic behaviour of an assembled structure with bolted joints using finite element method". *International Journal of Automotive and Mechanical Engineering*; 15. Epub ahead of print 2018. DOI: 10.15282/ijame.15.3.2018.22.0437.

[21] Sazzad MdM, Azad MdS, Islam MdT, et al. "Effect of mesh size of floor slab against lateral loads while using Etabs program". *International Journal of Advanced Structures and Geotechnical Engineering*; 6.