Effect of Mesh Size on the Natural Frequencies of Lathe Spindle

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Abstract
Improved computer numerical control (CNC) machine tool performance is critical in machining accuracy as modern manufacturing advances, particularly high-speed and high-precision machining. As a fundamental component of CNC machine tools, the dynamic properties of a spindle have a significant impact on machining performance. Modal analysis is one method for assessing the dynamic characteristics of mechanical components. Modal analysis is a process of extracting modal parameters (natural frequency and mode shape). This study aims to investigate how the mesh size of the finite element model affects the natural frequencies of the spindle. A three-dimensional model of the spindle was developed and analyzed in Autodesk Inventor software. Observation on changes of the natural frequencies was carried out by using a range of mesh sizes. The mesh size was controlled by varying the value of the average element size in AI modal analysis tool. The number of nodes and elements of the finite element models were compared, as well as the percentage of total error. Results revealed that mesh sizes have a significant effect on the accuracy in predicting natural frequencies. Differ in natural frequencies depend on the size of the mesh. Finally, significant research prospects are extensively explained based on present studies and will be critical in conducting modal analysis for machine tools spindle.

Keywords: spindle, modal analysis, mesh size

1.0 Introduction

Computer numerical control (CNC) is widely utilized in lathe and milling machines. High-speed machine tool operation can cause plenty of problems in the production process due to the vibration phenomenon. Machine tool vibrations have adverse effects such as noise and disruption and the possibility of severe structural damage (Chinnuraj et al., 2020). Dynamic characteristics stand out as a critical factor in the structures of high-speed machine tools. Modal analysis is one method for assessing the dynamic characteristics of mechanical components. Natural frequencies and mode shapes are displayed in modal analysis, which can be utilized to improve and optimize the design of a structure or component. Experimental modal analysis (EMA) and finite element method (FEM) are the two techniques that can be used to determine natural frequencies.

The spindle is an essential component since it determines the machine's precision and efficiency. A comprehensive understanding of the machine tool spindle system's dynamic characteristics significantly impacts the machine tool's capabilities and attaining high-performance cutting (Miao et al., 2021). According to Guo et al. (2013), spindle parts account for 60 to 80 percent of total machine processing displacement faults. Therefore, determining the dynamic characteristics of the machine tool spindle system is critical.

In FEM, one of the most critical issues is the overall optimization of meshing or the appropriate mesh size selection (Sazzad et al., 2017). The size of very large elements may result in less accurate results, whereas small elements may result in more accurate results. Small mesh size also could lead to higher processing time. This paper aims to study the effects of the mesh size on the lathe spindle under fixed-fixed conditions. Changes in the simulated natural frequencies are compared in terms of total error.

2.0 Literature Review

Several researchers have investigated the effects of mesh sizes on the modal analysis of various components. Martin and Arokkiaswamy (2016) compared different mesh sizes on the natural frequencies of a fan hub frame, where the results were compared with EMA. Crastiu et al. (2018) investigated the influence of element size on the natural frequencies under different boundary conditions. The results have shown that the natural frequencies are different for each element size. The number of nodes and elements of the FE models and percentage of the total error has been used to evaluate the effect of mesh size in an assembled structure with bolted joints by Omar et al. (2018).

There have been a significant number of studies utilizing FEM for the modal analysis of spindle systems. Kong and Cheng (2017) have used ANSYS workbench to determine the spindle first five natural frequencies. Subbarao and Dey (2020) used modal analysis in optimizing material for lathe spindle. Modal analysis on a high-speed milling spindle under three different bearing's span lengths using SolidWorks Simulation been conducted by Rusan and Ciupan (2020). Wang et al. (2021) carried out a modal analysis on the self-balancing motorized spindle using a hexahedral mesh with element sizes limited to 6mm.

Autodesk Inventor (AI) is one of the commercial software that offers modal analysis tools. Wilk et al. (2018) used AI for modal analysis of pantograph components where critical parts were modelled with a higher density of meshes. The success of AI in conducting modal analysis also can be found in Ooi et al. (2012). Thus, previous works have shown the capability of FEM in predicting the natural frequencies of the machine tool spindle. None of the previous works discusses the effects of mesh size on the natural frequencies of the lathe spindle to the best of the authors' knowledge. So, this study is significant as it considers different mesh sizes for predicting the natural frequencies of the spindle.

3.0 Methodology

In this study, the three-dimensional model of the lathe spindle was developed in AI software as shown in Figure 1. The dimensions of the spindle were adopted from Subbarao and Dey (2020). A straight steel shaft with an inner diameter of 35 mm, an outside diameter of 65 mm and a total length of 508 mm served as the test model. The bearing supports at two locations were expected to be cylindrical supports, which enable rotational motion along the shaft axis but restrict axial and radial motion.

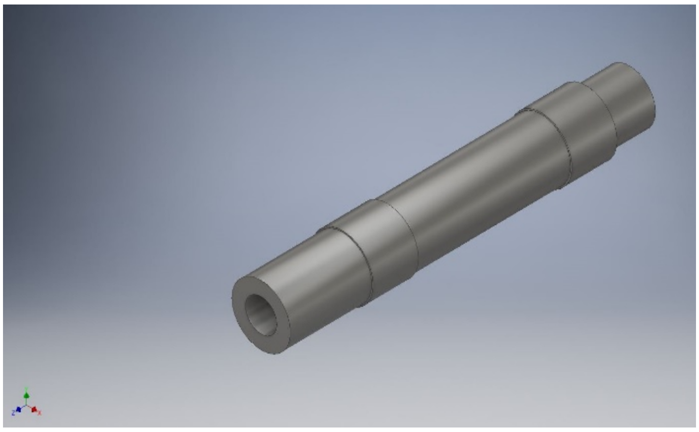

Figure 1: Three-dimensional spindle model

The mechanical properties of the spindle shaft are as in Table 1.

Table 1: Mechanical properties of the spindle

Property	Value	Unit
Young's modulus	110	Gpa
Poisson's ratio	0.28	unitless
Mass density	7.20	g/cm3

In AI modal analysis tool, mesh settings can be controlled by adjusting the value of average element size. The average element size represents the average distance between mesh element nodes. The value represents a fraction of the longest model dimension in the x, y, or z directions. The precision of such outcomes is also determined by the level of detail entered into the software. AI recommended using this value between 0.05 and 0.1, where its defaults value is 0.1. Throughout this study, the average element size was varied from 0.01 to 0.1.

For each mesh size, the natural frequencies of the first six modes are collected. Variations of these frequencies within six vibration modes are plotted as a function of the mesh size. The value of natural frequencies of the smallest mesh size is treated as a baseline value. It is based on the assumption that the small mesh size gives better prediction on natural frequencies value. Then, percentage of total errors were calculated by summing the errors for the first six natural frequencies.

4.0 Finding and Analysis

In this work, the modal analysis tool provided by Autodesk Inventor '19 was utilized to study the effect of mesh size on the natural frequencies of the spindle. For this task, a typical set of parameter values from Table 1 was chosen. The mesh size was controlled by varying the value of the average element size ranging from 0.01 to 0.1. For comparison purposes, the values obtained from the average element size of 0.01 was treated as the baseline value.

Table 2 shows a comparison of the number of nodes and elements for each mesh size. It can be observed that the greater the mesh size, the lower the number of nodes and elements. Thus, the lower the number of degrees of freedom. From Figure 2, for the average element size equal to 0.05, the number of elements is just 2% from the average element size equal to 0.01. Therefore, there is a significant reduction in the number of nodes and elements for coarse mesh.

Table 2: Number of nodes and elements for each mesh size

Average Element Size	No. of Nodes	No. of Elements
0.01	140866	93136
0.03	7181	4057
0.05	3450	1774
0.07	2151	1081
0.08	2018	1030
0.1	2001	1061

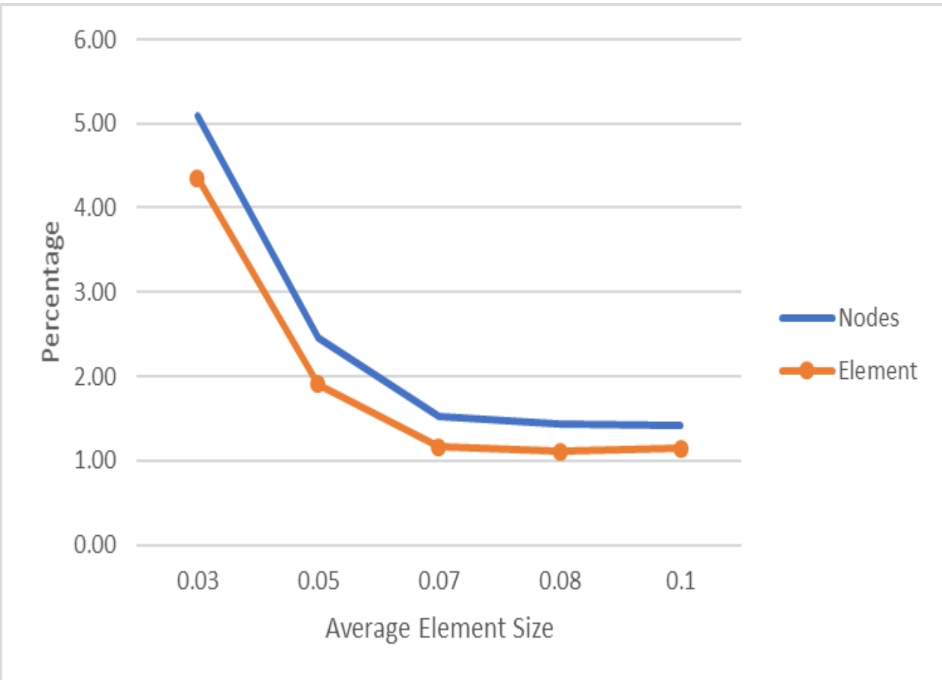

Figure 2: The percentage of the number of elements and nodes

The comparison on the natural frequencies for three mesh sizes is shown in Table 3. It is observed that the first and second modes have very close or identical natural frequencies. However, they are excited about different kinds of mode shapes which are bending on a different axis. There also exists a significant increase in the natural frequencies from the fourth to fifth modes.

Table 3: Natural frequencies for the different mesh sizes

Mode	Frequency (Hz)		
	0.01	0.05	0.1
1	3452.13	3453.23	3379.38
2	3452.55	3456.87	3419.36
3	4736.51	4785.42	4738.83
4	4739.93	4785.79	4760.43
5	6674.60	6637.40	6550.12
6	7043.58	7011.46	6956.13

Table 4 shows the calculated error percentage for three mesh sizes. The total error percentage was calculated by summing the error for the first six modes. Figure 3 shows the percentage of total error for all considered mesh sizes. The highest total error is on average element size equal to 0.07. The average element size equal to 0.05 gives satisfactory results since only 3% differ from the smallest mesh size.

Table 4: Percentage of error for the different mesh sizes

Mode	Error (%)		
	0.05	0.07	0.1
1	0.03	2.46	2.11
2	0.13	1.63	0.96
3	1.03	0.91	0.05
4	0.97	0.74	0.43
5	0.56	1.58	1.86
6	0.46	1.61	1.24
Total error (%)	3.17	6.86	6.66

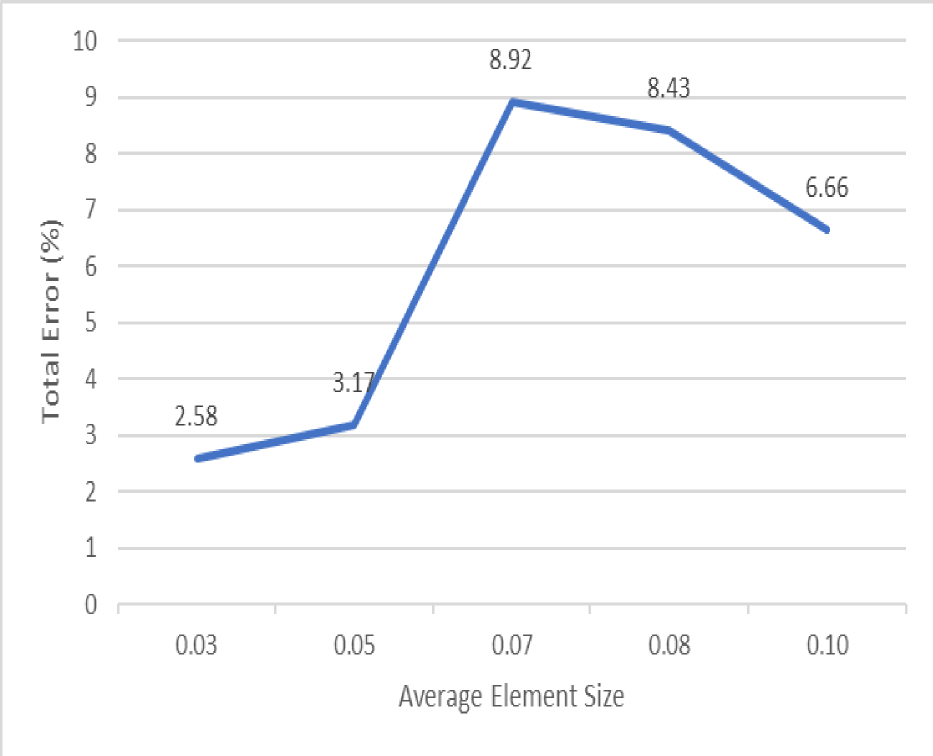

Figure 3: Effect of the mesh size on the percentage of total error

Finally, the first six mode shapes for the average mesh size equal to 0.01 are shown in Figure 4 to Figure 9. It can be seen that the spindle experienced different modes of vibration, such as bending in the middle part, as shown in Figure 7. The corresponding frequencies are depicted in Table 3.

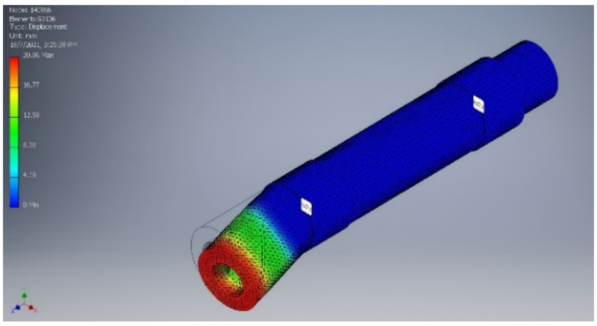

Figure 4: Mode shape 1

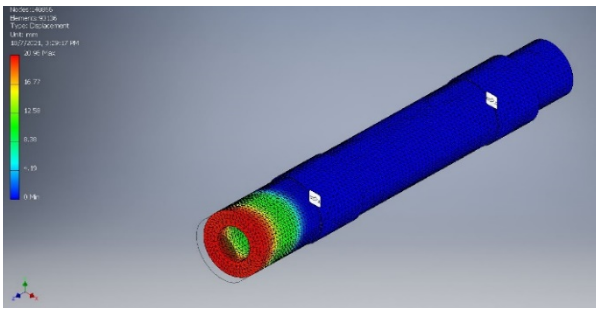

Figure 5: Mode shape 2

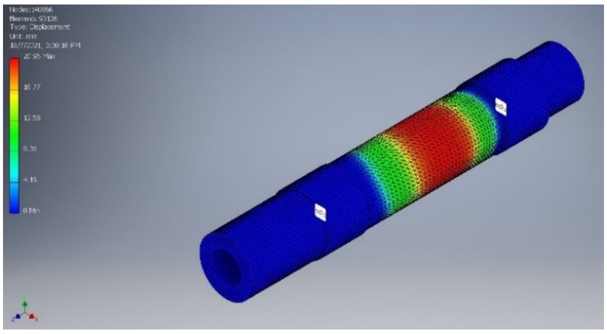

Figure 6: Mode shape 3

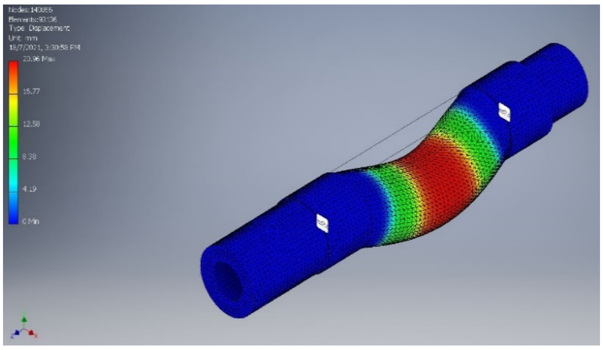

Figure 7: Mode shape 4

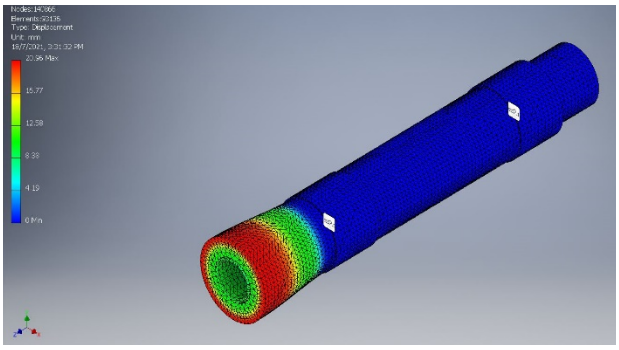

Figure 8: Mode shape 5

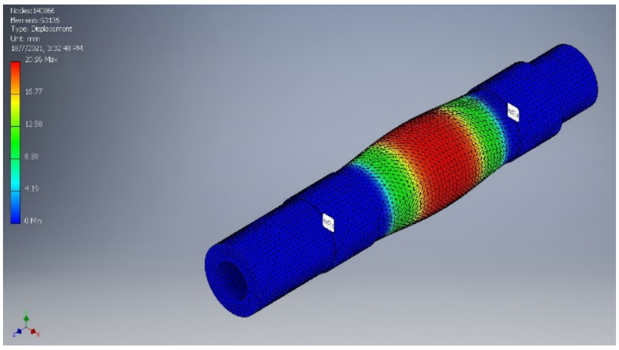

Figure 9: Mode shape 6

5.0 Conclusion

The effect of mesh size on the accuracy of natural frequencies of lathe spindle was thoroughly investigated in this research using the finite element method. Results showed that the differ in natural frequencies depend on the size of the mesh. AI recommended using this value between 0.05 and 0.1. For the considered spindle model, it was found that the model with the average element size of 0.05 obtains a satisfactory accuracy with an appropriate number of elements and nodes. In the future, the real-world three-dimensional model, which consists of round corners, chamfers, and other features, need to be accounted for in the models. The current study only considers spindle under fixed-fixed conditions, and the results were obtained through numerical simulations. So, future research may be extended to various boundary conditions and validated by experimental works. Then, the Modal Assurance Criterion (MAC), which indicate the correlation level of mode shapes, can be considered.

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