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The effect of material and location of the spindle on the vibration behavior of Gate milling machine

Hojjatollah Mohseni Takallu[1], Mostafa Omidi bidgoli[2*], Sayyedmohammad Hosseini[3]

[1] Department of Mechanical Engineering, Sirjan Branch, Islamic Azad University, Sirjan, Iran

[2] Department of Mechanical Engineering, Badroud Branch, Islamic Azad University, Badroud, Iran

[3] Department of Mechanical Engineering, University of Hormozgan, Bandarabbas, Iran

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Extended Abstract

Introduction

Surface roughness is a key indicator of machining quality and is strongly influenced by vibration behavior during cutting operations. In CNC machining, especially at micrometer-level precision, unwanted vibrations such as chatter significantly deteriorate surface integrity, dimensional accuracy, tool life, and machine durability. While industrial-scale CNC machines are typically designed with sufficient structural rigidity and vibration considerations, desktop CNC machines often suffer from insufficient structural optimization due to cost-driven design constraints.

Among various vibration sources, structural vibrations caused by changes in machine geometry and configuration remain less explored, particularly in mini and desktop CNC lathes. One critical yet under-investigated factor is the influence of spindle position—both vertical and lateral—on the dynamic behavior of the machine structure. Changes in spindle height and transverse position modify the effective stiffness and mass distribution of the system, potentially altering its natural frequencies and mode shapes. Understanding these effects is essential for improving machining stability and surface quality, especially in high-precision applications such as gemstone and jewelry machining.

Methodology

In this study, a commercially available desktop CNC lathe was selected as the reference system. A detailed three-dimensional geometric model of the entire machine assembly—including the bed, table, guide rails, spindle holder, columns, and spindle—was developed using SolidWorks and imported into ANSYS Workbench for finite element analysis. Modal analysis was performed to evaluate the free vibration characteristics of the system. Both aluminum alloy and structural steel were considered as candidate materials for the machine structure to assess their influence on vibration behavior. Mesh convergence and quality were carefully examined using a combination of Hex20 and Tet10 elements to ensure numerical reliability.

The model was validated through free–free boundary condition analysis, where the first three natural frequencies were expected to approach zero, confirming correct assembly and constraint definitions. Subsequently, the first six natural frequencies and corresponding mode shapes were extracted under fixed-base conditions.

To investigate operational variability, parametric modal analyses were conducted by systematically altering the spindle position in two directions: (i) vertical displacement along the spindle guide to simulate machining of workpieces with different thicknesses, and (ii) lateral displacement across the table width to represent machining of elongated workpieces. The resulting changes in natural frequencies and mode shapes were analyzed to assess the risk of resonance and vibration amplification.

Results and Discussion

The validated finite element model demonstrated that the first six natural frequencies of the desktop CNC lathe lie within the range of approximately 28–48 Hz for both aluminum and steel structures, well below the excitation frequencies associated with spindle rotation. This indicates a negligible risk of resonance during normal operation.

Material comparison revealed that while changing the structural material from aluminum to steel does not significantly alter mode shapes, it substantially reduces vibration amplitudes due to higher stiffness and damping capacity. Steel structures exhibited noticeably lower deformation levels, particularly in spindle-support-related modes.
Parametric analysis showed that variations in spindle height have minimal influence on the natural frequencies and overall dynamic behavior of the structure. Only minor changes were observed in higher-order modes, primarily associated with the gravitational load of the spindle assembly. In contrast, lateral displacement of the spindle resulted in increased natural frequencies in higher modes, with up to a 25% increase in the sixth mode when the spindle was positioned near the machine edges. The symmetry of frequency responses for left and right positions confirmed the accuracy and consistency of the numerical model.
Overall, the results indicate that structural material selection has a more pronounced impact on vibration mitigation than spindle positioning, and that the desktop CNC lathe remains dynamically stable across its operational workspace.

Conclusion

The findings of this study highlight the importance of structural vibration analysis in the design and optimization of desktop CNC machines. While aluminum structures offer advantages in terms of weight reduction and cost, steel structures provide superior vibration damping and improved machining stability, making them more suitable for high-precision applications such as gemstone and jewelry manufacturing.
Future research should focus on localized structural reinforcement, hybrid material configurations, and passive or active damping strategies to further suppress critical vibration modes. Experimental modal testing is also recommended to complement numerical simulations and validate real-world performance. By integrating structural optimization with advanced control strategies, the reliability and surface quality of compact CNC machining systems can be significantly enhanced.

Keywords: CNC, machine, vibrations, natural frequency, frequency mode

*mostafaomidibidgoli@gmail.com

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