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OPTIMIZATION OF SPINDLE SYSTEM FIRST NATURAL FREQUENCY VALUES USING RESPONSE SURFACE METHODOLOGY AND ANALYSIS OF VARIANCE

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The object of this research is the dynamical performance of horizontal lathe spindle systems, which encounter challenges related to vibration and structural integrity during high-precision machining. In particular, the study aims to improve the system's dynamic performance by raising its first natural frequency to minimize chatter and bolster its capacity to endure operational stresses. The process of optimization was done by utilizing Response Surface Methodology in conjunction with Analysis of Variance, two methodologies that are acknowledged for their efficiency in statistical analysis and experimental design. Modifications were made to the spindle design in two stages: first, the rear bearing location (located at the end of the spindle opposite the chuck) was optimized, and then the shaft geometry was adjusted to improve natural frequency and stress resistance while keeping the overall mass of the system the same. The optimized design achieved an increase in the first natural frequency (from 529.47 Hz to 852.52 Hz) and an enhancement in stress capacity (from 250 MPa to 48.98 MPa), as confirmed by ANSYS V19 simulations. By shifting up the value of the first natural frequency, chatter is less likely to occur. This leads to more stable performance and better machining accuracy under higher operational loads.

These findings are important in precision machining applications, where vibration control and structural integrity are critical to performance. The paper concludes with a detailed comparison between the optimized and non-optimized models, along with an evaluation of the influence of bearing stiffness on system dynamics. The numerical improvements highlight the effectiveness of both Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) in optimizing mechanical system performance

Keywords: spindle optimization, chatter reduction, machining stability, vibration control, lathe spindle

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1. Introduction

Chatter is a fundamental problem in machining processes, resulting in poor surface quality, elevated noise levels, tool deterioration, and increased energy consumption. For those consequences, chatter must be avoided. That attracts the attention of researchers to this phenomenon, to study it then trying to control it and control the conditions that lead to its occurrence.

The publications related to areas related to chatter in machining over a period of time ranging from year 1995 to year 2019 is demonstrated in Fig. 1. The x-axis denotes the years, whereas the y-axis indicates the quantity of published articles. It can be clearly seen that there is an upward trend in the number of publications related to chatter in machining [1].

In general, chatter in machining can be dealt with through controlling the cutting parameters and the selection of the cutting tool. An important parameter that can be controlled to avoid chatter is the spindle speed, for that reason, the concept of the so-called Spindle Speed Variation is introduced. In this method, the spindle speed is not constant, it varies all the time in a way that doesn't affect the workpiece, which guarantees that one important parameter of chatter occurrence (the speed of the spindle) is not met since it is variant all the machining time [2].

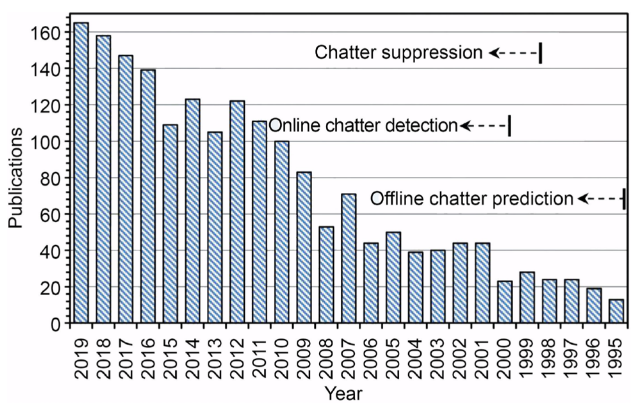


Fig. 1. Trend of chatter publications over time [1]

Stability Lobes Diagrams (SLD) is a well-established technique employed to determine cutting parameters for preventing chatter. Creating these diagrams can be achieved either experimentally, or by the help of chatter theory. The experimental approach is achieved by carrying out machining operations under different cutting conditions to gather data, from which the stable and non-stable areas are identified. Fig. 2 illustrates an experimentally constructed Stability Lobe Diagram (SLD).

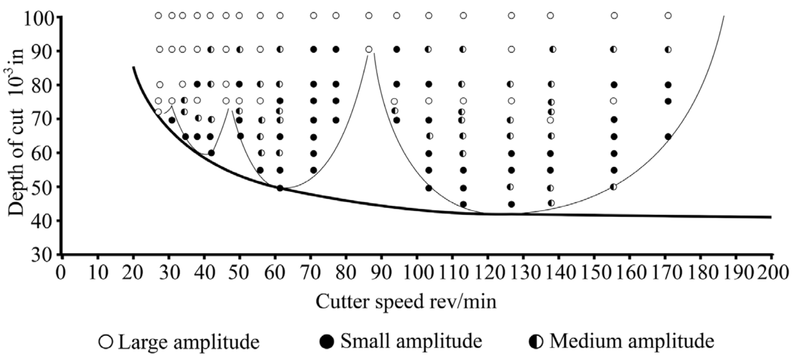


Fig. 2. Experimental stability Lobe diagram for milling [2]

Another approach utilizes devices known as Tuned Mass Dampers (TMD). The concept of a TMD cutting tool is based on the integration of a secondary mass, referred to as the tuned mass, which is specifically calibrated to counteract the vibrations produced during the cutting process. Instead of completely removing the system's inherent resonance frequency, this technique lessens the resonance impact by redistributing energy between the system and the TMD, thereby effectively lowering the peak response of the system at its resonance frequency. The tuned mass damper is carefully placed and engineered to significantly minimize chatter while enhancing the stability of the machining process [3, 4].

However, the technology has some limitations in perfect chatter control especially when it comes to more complex and sophisticated precision machining. In sectors like aerospace, automotive and medical manufacturing, these require more machining stability, accuracy, and seeking for better vibration control in order to meet those very tight quality requirements. To prevent chatter-related problems, and to deal with even faster machining speeds as well as more demanding production requirements servo-based spindle technology is key.

Chatter, as a self-excited vibration, severely affects the machining industry due to the feedback loop that amplifies the vibrations and leads to destabilization of the cutting process. This dynamic instability affects not only the quality of the machined surface but also involves great acceleration of tool wear, consumption of energy, and creation of noise in operation. These consequences have raised chatter to a critical level, necessitating advanced research and engineering solutions in order to enable stable and precise machining under various operating conditions.

The importance of reducing chatter is crucial in high-precision manufacturing sectors such as aerospace, medical, and automotive industries, where tight tolerances and excellent surface finishes are essential. Controlling and minimizing chatter is key to ensuring the reliability and efficiency needed to meet these demanding standards, especially as contemporary machining systems work at increased speeds and under heavier loads.

Considering the limitations of traditional methods like spindle speed variation and tuned mass dampers, ongoing research emphasizes the critical role of structural optimization in lathe spindle systems. Chatter, a persistent issue in high-precision machining, has long prompted researchers to seek effective solutions due to its detrimental effects on surface quality, energy consumption, tool life, and overall productivity. The rise of advanced manufacturing techniques and increasing demands for precision in industries such as aerospace, automotive, and medical have intensified the need for more dependable solutions to reduce chatter.

Research into spindle system dynamics and structural integrity is essential for tackling these challenges. By enhancing spindle natural frequencies, dynamic stiffness, and overall stability, researchers aim to improve machining performance under higher operational loads and speeds. These advancements are a direct response to modern machining needs, where lightweight designs are crucial but can lead to structural weaknesses, necessitating innovative optimization strategies.

The importance of this research area continues to expand as industries demand faster, more precise, and more efficient machining systems to meet contemporary production standards. By addressing these challenges through structural optimization, significant progress can be made in developing chatter-resistant, high-performing lathe spindle systems, ensuring that manufacturing processes remain stable and cost-effective in today's operational landscape.

2. Literature review and problem statement

Research focusing on the optimization of spindle systems via structural modifications has uncovered various effective strategies. In [5], a detailed model was created aimed at decreasing radial vibrations in high-precision spindles resulting from unbalanced forces. The study employed a flexible rotor supported by angular contact ball bearings, with motion equations derived using FEM. A hybrid genetic algorithm (HGA) optimized parameters including shaft diameter, bearing damping, and stiffness. The optimization process considered multiple objectives simultaneously, balancing performance metrics against practical constraints. The findings indicated a reduction of around 45.1 % in radial vibration amplitude at 8000 rpm, highlighting the considerable promise of structural optimization. However, the study noted limitations in accounting for time-varying bearing dynamics and natural frequency changes, suggesting areas for future research.

The issue of chatter is closely linked to the vibration dynamics of the machine tool. Chatter occurs when the cutting forces interact with the spindle system's natural vibration modes, creating a feedback loop that intensifies vibrations. This resonance happens when the operational frequency approaches the system's natural frequency, leading to instability in the machining process. To tackle this problem, it's essential to adjust the spindle's natural frequency to a range that falls outside of normal operational conditions, as shown in this study through structural optimizations.

Another significant contribution [6] focused on both energy consumption and performance optimization of lathe spindle systems. The research developed a comprehensive approach considering energy consumption alongside traditional performance indicators. This dual focus represented an important step toward sustainable manufacturing while maintaining high performance standards. Key structural parameters included bearing location, shaft segment lengths, and segment diameters. The optimization effectively decreased energy usage while preserving acceptable static and dynamic performance, though it didn't consider chuck mass optimization, which significantly affects system response. The study demonstrated the feasibility of simultaneously addressing environmental and performance considerations in spindle design.

Research in [7] utilized genetic algorithms to optimize bearing locations on motorized spindle shafts, specifically targeting first-mode natural frequency maximization. This approach demonstrated the potential of evolutionary algorithms in spindle design optimization, offering a systematic method for improving dynamic performance. The study provided valuable insights into the relationship between bearing placement and system dynamics.

However, one limitation of this approach is that it heavily relies on the accuracy of the initial model and assumptions. Although the optimization showed good results, real-world conditions or variations in manufacturing tolerances may affect the outcomes, and the model may need further refinement to handle more complex systems or additional constraints.

A notable and extensive research study [8] presented a multi-objective optimization approach employing particle swarm optimization (PSO) specifically for the design of spindle-bearing systems. This technique aimed to enhance natural frequencies, increase static stiffness, and minimize friction torque concurrently, reflecting a comprehensive strategy for optimizing the system.

The research methodology carefully balanced competing objectives while maintaining practical constraints. The enhanced designs resulted in notable advancements, with first and second natural frequencies rising by 10 % and 6 %, respectively, alongside a roughly 26 % enhancement in static stiffness. These results demonstrated the potential for substantial performance enhancement through structural optimization. However, the approach faced challenges in computational complexity and required further validation across different operational scenarios, highlighting the need for continued research in this area.

In [9], the researchers developed a method to improve the dynamic performance of grinding machine spindles, focusing on reducing vibrations during operation. They used a frequency domain approach to examine the forces affecting the spindle and how its frequency response behaves. The optimization process aimed at two key factors: modal frequency (the natural vibration frequency of the spindle) and dynamic stiffness (the spindle's ability to resist deformation). Their findings showed that improving dynamic stiffness had the most significant impact on reducing vibration, making it the key factor for better performance.

However, there was a limitation with the modal frequency optimization. While adjusting the spindle's modal frequency helped reduce vibrations at certain speeds, it didn't fully lower vibrations across the entire range of spindle speeds. In contrast, improving dynamic stiffness led to a more consistent reduction in vibration, offering a more reliable solution for enhancing spindle performance overall. So, while adjusting the modal frequency had some benefits, focusing on dynamic stiffness proved to be a more effective approach for optimizing grinding spindle performance.

In [10], the authors focused on optimizing spindle vibrations in a surface grinding machine to reduce chatter, which can negatively impact surface quality, wear down grinding wheels, and cause machine instability. They used the Taguchi method to identify the main factors affecting vibration, such as rotational speed, feed rates, and the placement of the accelerometer. The results showed that the best settings for minimizing vibration were a rotational speed of 1500 rpm, a Z-direction feed of 7.5 mm, and an X-direction feed rate of 42 times/min, with the accelerometer placed on the right. Among these, the X-direction feed rate had the most significant effect on reducing vibration. However, one limitation of the study is the use of the Taguchi method, which assumes factors are independent, potentially overlooking more complex interactions between them. Additionally, the research didn't fully consider the impact of other machine factors, such as the rigidity of the machine or spindle stability, which could affect the practical application of the findings in real-world settings.

The authors of [11] focuses on improving the stability and dynamic performance of spindle systems in machining centers, particularly by examining how the stiffness of the spindle and the configuration of tools impact vibration and machining precision. The research involved creating detailed 3D models of spindle-tool assemblies using software like SOLIDWORKS and ANSYS, simulating real-world conditions to study how forces like centrifugal effects and gyroscopic moments influence stability. By using advanced finite element analysis and a mathematical approach called the D-partitions method, the authors identified stable operating zones and the best settings for tool configurations to reduce vibration and improve machining accuracy.

The findings show that optimizing key parameters, such as tool overhang and spindle support positioning, can significantly enhance vibration resistance in machining centers, leading to more accurate and stable machining processes. The study offers a practical approach for design engineers to predict system performance and fine-tune machine settings, contributing to consistent machining quality in production.

The main drawback of this study is that the D-partitions method used in the stability analysis has inherent complexities that may restrict its scalability to larger or more intricate spindle systems.

These structural modification approaches represent a promising direction in spindle system optimization, though challenges remain in computational efficiency, comprehensive validation, and accounting for all relevant system parameters. Future research opportunities exist in developing more integrated approaches that consider both structural and operational parameters while maintaining practical implement ability. The field continues to evolve, with new optimization techniques and computational tools offering increasingly sophisticated solutions to these complex design challenges.

3. The aim and objective of the study

The aim of this study is enhancing the spindle system design of a lathe machine to reduce the incidence of chatter while ensuring the system's structural integrity is not affected negatively while maintaining the overall mass of the spindle system.

To achieve this aim, the following objectives are accomplished:

– to optimize the rear bearing location of horizontal lathe spindle system using RSM with conjunction with ANOVA in order to shift up its first natural frequency value;

– to optimize the geometry of the shaft of the spindle system by increasing its diameter next to the chuck while reducing its thickness in a way that guarantees maintaining the overall mass of the spindle system using RSM integrated with ANOVA;

– to investigate the effect of optimizing the geometry of the shaft of the spindle system on the structural integrity of the spindle system using the FEA;

– to investigate the relation between the stiffness of the bearing and the optimum location of rear bearing.

4. Materials and methods

The object of research is the dynamical performance of a lathe spindle system. As shown in Fig. 3, the system is composed of a workpiece, a chuck, three bearings, and a shaft of uniform thickness.

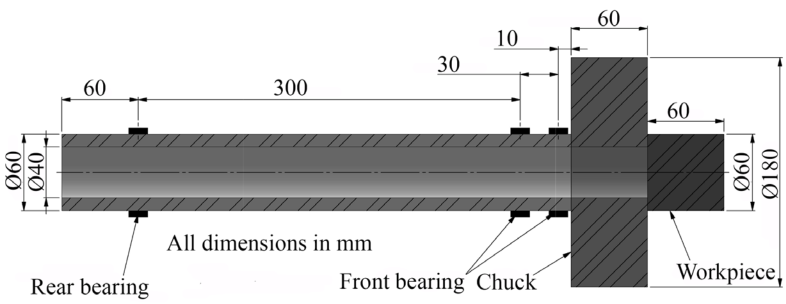


Fig. 3. Section view of lathe spindle proposed model

The main hypothesis of the study proposes that optimizing key dimensional parameters of the spindle system (shaft geometry and bearing location) through Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) can significantly reduce chatter occurrence while maintaining the structural integrity of the system.

The research implementation required specialized software tools for different aspects of the study:

– DS SolidWorks was employed for the detailed modelling of the spindle system;

– ANSYS V19 was utilized to conduct comprehensive finite element analysis;

– Design Expert software was used for implementing RSM and ANOVA in the optimization process.

The optimization process operated within specific operational constraints to ensure practical applicability:

– a minimum inner shaft diameter of 40 mm was maintained to accommodate the bar feeding mechanism;

– the shaft was designed with a thickness exceeding 7 mm to accommodate a maximum permissible twist angle of 0.25 degrees per meter [12];

– the system is capable of managing a torque of 576 N·m, as specified for the HAAS ST-35L CNC lathe [13];

– throughout the analysis, a bearing stiffness of 7.5×10^8 N/m was utilized [14, 15].

The system dynamics were modelled using the fundamental vibration differential equation:

$$[M]\{\ddot{X}\}+[R]\{\dot{X}\}+[K]\{X\}=\{F\}. \quad (1)$$

For rotor dynamics, this was extended to:

$$[M]\{\ddot{X}\}+([R]+[R_{gyro}])\{\dot{X}\}+ \\ +([K]+[H])\{X\}=\{F\}, \quad (2)$$

where M – mass matrix, kg; $\ddot{X}$ – acceleration vector, m/s^2; R – damping matrix, N·s/m; $\dot{X}$ – velocity vector, m/s; K – stiffness matrix, N/m; X – displacement vector, m; F – external load vector, N; R_{gyro} – gyroscopic matrix, kg·m^2/s; H – circulatory matrix, kg·m^2/s.

These equations incorporate the gyroscopic effect, which plays a crucial role in system stability and natural frequencies.

The system is designed to reduce chatter by carefully repositioning the rear bearing and altering the spindle shaft geometry. These changes aim to raise the first natural frequency, moving it out of the operational ranges that are susceptible to chatter, while also enhancing stress resistance to ensure structural integrity under load.

The study employed an integrated approach combining RSM with ANOVA through a systematic process:

1. Design of experiments (DOE). The initial phase involved systematic variation of input variables, specifically the shaft geometry and bearing location. This structured approach enabled comprehensive data collection regarding the natural frequency response of the system under various parameter combinations.

2. Response surface analysis. Following the experimental phase, empirical models were developed to characterize the relationships between parameters. This involved detailed regression analysis of the experimental data to establish response surfaces that accurately represented the behavior of the system.

3. Statistical analysis. ANOVA was implemented to determine the statistical significance of individual parameters and their interactions. This phase included careful evaluation of F-statistics to identify the most influential factors affecting system performance.

4. Optimization process. The final phase integrated the findings from RSM and ANOVA to determine optimal parameter values within the established operational constraints. This process was followed by validation of the optimization results to ensure practical applicability.

This comprehensive methodology enabled systematic optimization of the spindle system while ensuring that all critical operational requirements and structural integrity constraints were maintained throughout the process.

The approach provides a robust framework for achieving improved chatter resistance in lathe spindle systems through careful parameter optimization.

5. Results of the structural optimizing a lathe spindle in terms of shifting up the value of its first natural frequency

5. 1. The optimization of the location of the rear bearing

In this part, a response surface is constructed. To do so, it is essential to create a mathematical model that relates the inputs (factors) and the outputs (variables), a quadratic model is employed for nonlinear relationships and then, ANOVA is employed for the verification of accuracy.

Table 1 experiments employ ANSYS V19 software to collect data for ANOVA analysis and to create response surfaces.

The proposed spindle model was modified in terms of its radius next to the chuck and its rear bearing location according to the data provided in Table 1, specifically the data in columns two and three.

Fig. 4 illustrates the response surface aimed at optimizing the position of the rear bearing, where Axis A denotes the radius of the shaft and Axis B indicates the location of the rear bearing. The third, vertical axis represents frequency.

Table 1

Runs used to construct the response surface 1

Run	Factor 1 A: radius, mm	Factor 2 B: rear bearing location, mm	Response 1 frequency, Hz
1	32.2	32.3	642.7
2	20	7.5	506.2
3	32.2	103.7	706.1
4	44.4	7.5	712.1
5	20	200	612.0
6	14.9	103.7	488.9
7	32.2	239.8	654.4
8	44.4	200	826.9
9	49.5	103.7	860.9

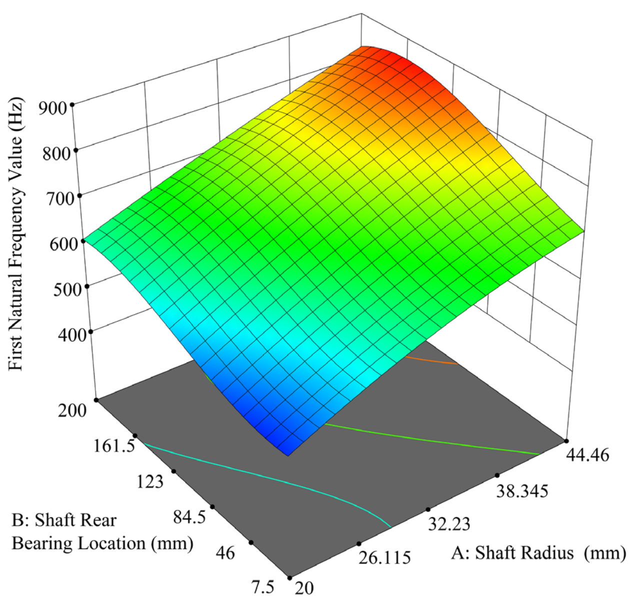


Fig. 4. The response surface of optimizing the rear bearing location

As can be seen in Fig. 4, the highest point of the surface is at a shaft radius of 44.46 mm and at a rear bearing position between 155 and 165 mm from the end of the shaft.

5. 2. The optimization of the geometry of the shaft

The same steps are repeated in this section as seen in Table 2.

Fig. 5 illustrates the response surface utilized for the optimization of shaft geometry, where Axis A denotes the thickness of the shaft and Axis B indicates the radius of the shaft adjacent to the chuck. The third, vertical axis represents frequency.

Table 2

Runes used to construct the response surface 2

Run	Factor 1 A: thickness of the shaft, mm	Factor 2 B: radius, mm	Response 1 frequency, Hz
1	8.5	32.23	676.821
2	10	20	535.424
3	7	20	448.772
4	8.5	49.5258	692.912
5	7	44.46	760
6	8.5	14.9342	406.017
7	6.37868	32.23	760
8	10.6213	32.23	747.674
9	10	44.46	586.935

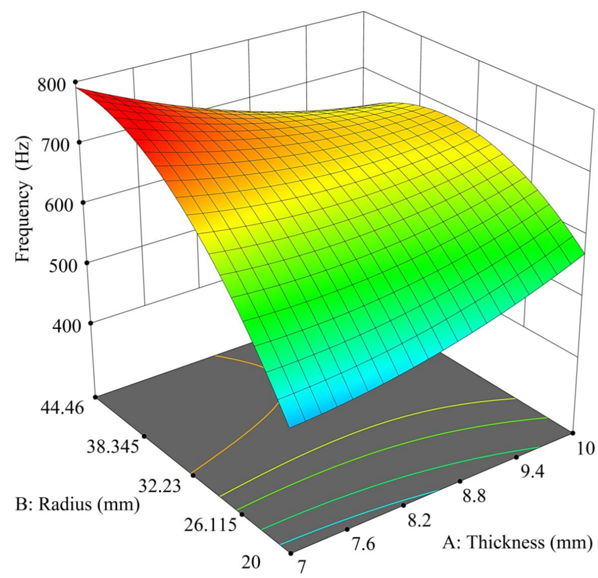
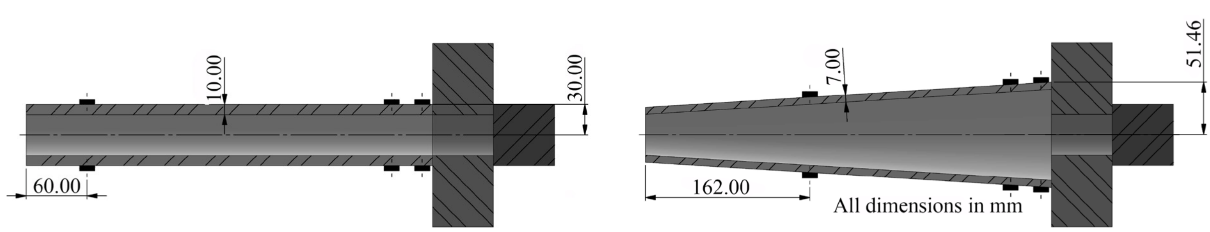


Fig. 5. The response surface of optimizing the geometry of the shaft

According to Fig. 5, the highest point of the response surface is located at a shaft thickness of 7 mm and a shaft radius of 44.46 mm, indicating improved performance in stress capacity and chatter frequency compared to the non-optimized model. This comparison is depicted in Fig. 6.

Fig. 7 compares the frequency response of the proposed spindle model and the optimized spindle model.



a *b*

Fig. 6. The proposed and optimized spindle models: *a* – the proposed model; *b* – the optimized model

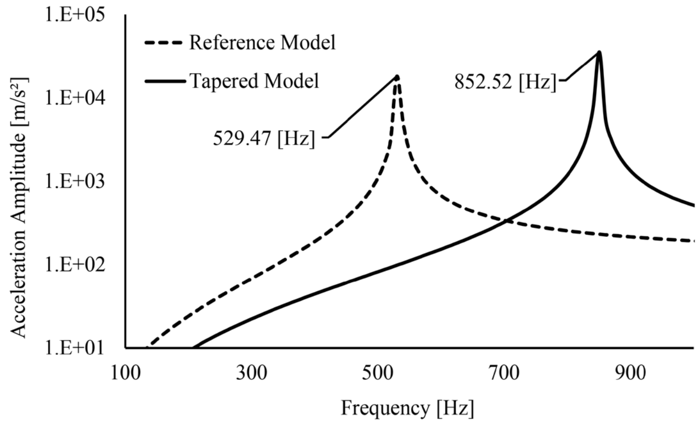


Fig. 7. Frequency response of the optimized and the non-optimized models

As shown in Fig. 7, the improved model's initial natural frequency was measured at 323.05, signifying a 60.5 % increase.

5. 3. Investigating the optimized spindle system's structural integrity

In order to determine its optimal improved stress capacity, the study compares a load that results in permanent spindle system deformation with a 15.375 kN load applied to a non-optimized model workpiece. The optimized model is also tested under this same load, with the assumption of rigid supports in both scenarios. A comprehensive visual analysis in Fig. 8 reveals how both spindle configurations – before and after enhancement – respond to applied loads, while also showing their respective constraint parameters.

As observed in Fig. 8, a relatively large enhancement in stress capacity is achieved after optimization.

5. 4. Investigating the relation between the value of the stiffness of the bearing and the optimum rear bearing location

The rigidity of the rear bearing is affected by the bearing preload [16]. The study quantifies positioning adjustments and resonance modifications that occur when enhancing the posterior bearing's rigidity by one-tenth of its original value.

The analysis is conducted again to assess the variations in the optimal bearing location. The values of the used stiffness of the bearing alongside with the optimum rear bearing location with the associated natural frequency values of the spindle system are listed in Table 3.

Table 3 shows that as the bearing stiffness increases, the ideal position for the rear bearing moves slightly, and the system's frequency rises.

Table 3

System response variables as functions of rear support stiffness

Bearing stiffness, N/m	Optimum rear bearing location, mm	Frequency, Hz
7.50+008	162	850.75
8.25+008	167	855.43
9.00+008	169	858.12
9.75+008	171	860.41

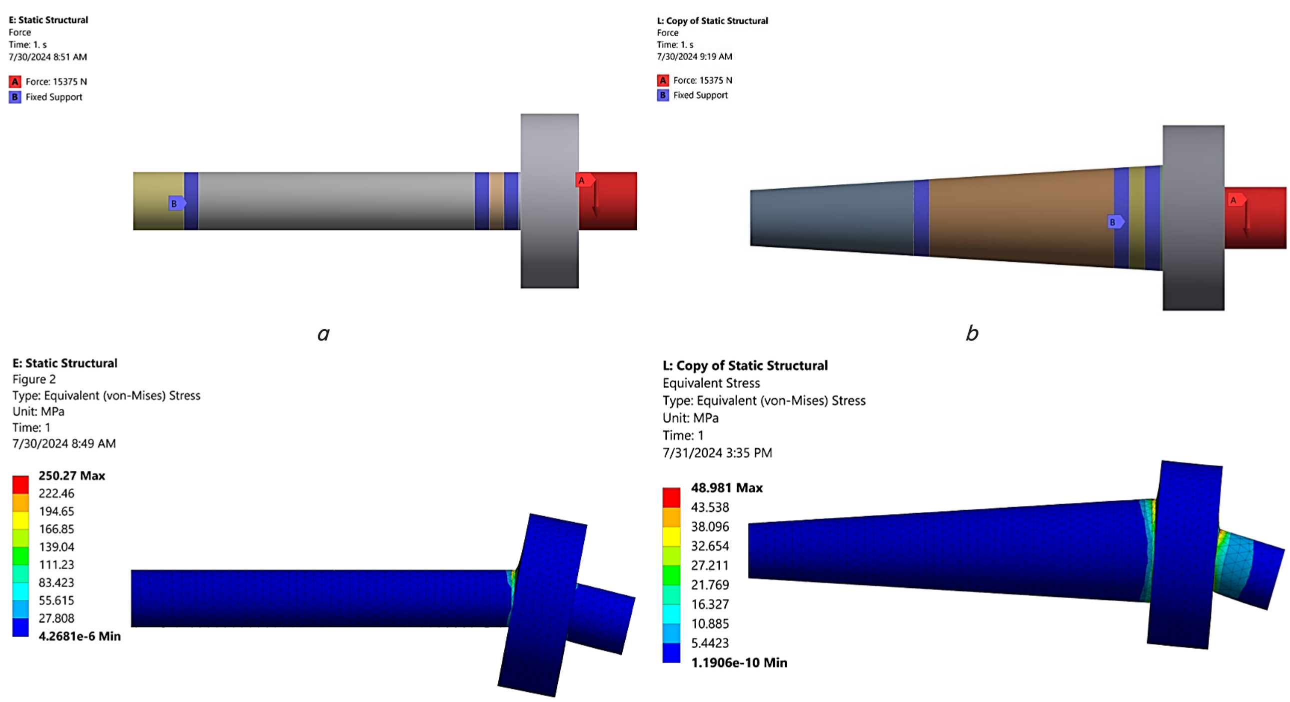


Fig. 8. Comparative structural analysis:
a – control model boundary parameters; *b* – optimized design boundary parameters; *c* – mechanical stress response in control configuration; *d* – mechanical stress response in optimized configuration

6. Discussion of spindle optimization effects on natural frequency and structural integrity

Optimizing the rear bearing location significantly impacts the spindle system's natural frequency. As shown in Table 1, varying shaft radius and bearing location yields different frequencies, with the highest response of 860.9 Hz at a 49.5 mm radius and 103.7 mm bearing position. Fig. 4 further illustrates that a radius of 44.4 mm and a bearing location between 155–165 mm provides the best stability. The quadratic model and ANOVA confirm this as the optimal configuration, supporting the study's goal of reducing chatter by maximizing natural frequency.

Modifying shaft geometry, specifically thickness and radius, boosted the natural frequency, as shown in Table 2. The optimal configuration – a 7 mm thickness and 44.46 mm radius – yielded a maximum frequency of 760 Hz. Fig. 5 illustrates that thinner sections near the chuck enhance both stress capacity and frequency response, supporting the idea that geometry changes improve dynamic performance and chatter resistance.

Fig. 7 compares the optimized and non-optimized models, with the optimized version achieving a first natural frequency of 323.05 Hz – a 60.5 % increase. This significant rise confirms that structural modifications, especially in geometry, positively impact natural frequency and reduce chatter.

The study's load analysis reveals that the optimized spindle design has improved stress capacity, as shown in Fig. 8. The optimized model withstands loads more effectively, maintaining integrity at stress levels that previously caused deformation in the non-optimized model. This confirms that geometry adjustments near the chuck enhance both stability and durability.

Table 3 shows that increasing rear bearing stiffness leads to higher frequencies and optimal bearing positions, highlighting the role of bearing properties in fine-tuning resonance. Greater stiffness enhances the spindle's vibration resistance, supporting the study's structural optimization goals.

In [9], researchers aimed to reduce spindle vibrations by improving dynamic stiffness, finding that while adjustments to modal frequency helped, they didn't consistently reduce vibration across all speeds. Unlike this single-focus approach, the present study combines rear bearing location and shaft geometry adjustments to simultaneously boost natural frequency and spindle stability. This dual optimization achieves consistent vibration reduction over a broader speed range, addressing the limitations in [9] where modal frequency tuning alone couldn't fully control vibration across varying speeds.

In [11], the authors improved spindle stability by optimizing tool overhang and spindle support through detailed FEA models, focusing on tool-related configurations. In contrast, this study enhances spindle stability by optimizing the spindle's internal structure – specifically shaft geometry and rear bearing stiffness – which directly increases the first natural frequency. This approach offers stability benefits beyond tool configuration, enabling more intrinsic improvements that apply across various tool settings and extending stability advantages to a wider range of machining applications.

In [11], the D-partitions method was used for stability analysis, but its complexity limited scalability. This study addresses that limitation by using RSM and ANOVA, which simplify computation by modeling interactions with empirical response surfaces rather than complex stability partitions. This approach offers a more practical and accessible method for spindle optimization in real-world machining environments, avoiding the scalability challenges noted in [11].

In Section 2, the problem of chatter in machining operations is highlighted for its negative impact on surface quality, tool wear, machine stability, and energy use. Traditional solutions generally focus on adjusting cutting parameters or tool configurations, offering only partial control over spindle vibrations and failing to address structural instability within the spindle system itself.

This study tackles the issue by focusing on internal structural optimizations, specifically the design and placement of the rear bearing and the spindle shaft geometry. By optimizing these components, the solution directly increases natural frequency and stiffness – key factors in reducing internal spindle vibrations. This foundational approach offers a more effective solution for minimizing chatter.

Rear bearing location and shaft geometry. Optimizing the rear bearing placement and shaft geometry substantially increases the spindle system's first natural frequency (Fig. 7), with a 60.5 % boost over the non-optimized model. This higher frequency shifts the system's resonance away from typical operational ranges, significantly reducing the chances of self-excited vibrations, or chatter, across a wide speed range.

Fig. 8, *c*, *d* show the optimized model's improved stress resistance, with the spindle demonstrating higher load tolerance without deformation. This increased stress capacity allows the spindle to withstand the forces of high-speed machining, maintaining stability and performance and fulfilling the need for a more robust structure under operational stresses.

This study uses Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) to address the limitations of traditional methods, which often ignore complex interactions between spindle components. Unlike simpler approaches, RSM and ANOVA consider the interactions between variables like shaft radius, thickness, and rear bearing position (Tables 1, 2). This detailed modeling enables precise adjustments of multiple factors, optimizing spindle stability and frequency performance without sacrificing structural integrity.

The response surfaces from RSM highlight optimal regions for rear bearing location and shaft geometry that maximize frequency response. This provides empirical evidence that these parameters are crucial for achieving a stable, low-vibration design.

The study assumes constant bearing stiffness, as shown in Table 3, even though bearing stiffness can vary with different operational loads and speeds. This static assumption may not fully account for dynamic changes in bearing response during high-speed machining, potentially impacting vibration characteristics.

The optimization process relies on Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) using advanced software like ANSYS and Design Expert, which require specialized expertise and access to simulation tools. This may limit the solution's accessibility for small or medium-sized machine shops that lack the resources or technical skills to perform such analysis.

The model assumes a simplified, uniform spindle structure, overlooking complexities like non-uniform material properties, time-varying bearing dynamics, and thermal effects. In reality, spindle systems may exhibit non-linear interactions among components, particularly under varying speeds, temperatures, and loads.

The study on spindle system optimization ignoring important factors like wear, long-term performance, and varying operational conditions. The research doesn't consider how the optimizations might apply to other types of machines.

Future research could incorporate variable stiffness modeling by measuring bearing stiffness at different loads and speeds or using predictive models to simulate these variations. These findings could then be integrated into the Response Surface Methodology (RSM) framework to optimize bearing placement and spindle geometry while accounting for stiffness changes. This would enable the model to more accurately reflect the impact of stiffness on frequency response and stability, resulting in a more robust and adaptable spindle design.

Future research could focus on developing a streamlined version of RSM and ANOVA that uses only the most influential parameters identified in this study, simplifying the optimization process. Additionally, alternative methods like Taguchi or heuristic approaches (e.g., genetic algorithms) could be explored for cases with limited computational resources. Testing these simplified models on various spindle systems would help validate their accuracy and practical utility, making spindle optimization more accessible without compromising performance gains.

7. Conclusions

1. Optimizing the rear bearing location. The position of the rear bearing was adjusted to increase the spindle's first natural frequency, which helped reduce the risk of chatter. By using Response Surface Methodology (RSM) combined with ANOVA, the new bearing location led to a more stable spindle, improving its performance during high-speed operations. This was achieved at arear bearing location ranged between 155 mm and 165 mm from the free end of the spindle system compared to 60 mm as the initial position of the rear bearing.

2. Improving shaft geometry. The shaft design was optimized by increasing its diameter near the chuck and reducing its thickness, ensuring that the spindle's overall mass remained the same. This change, made using RSM and ANOVA, boosted the spindle's stiffness and vibration resistance, leading to better dynamic performance while staying within the mass constraints. This was achieved at a radius of 44.46 next to the chuck and a thickness of the shaft of 7 mm while the initial uniform radius is 30 mm and the initial thickness is 10 mm.

3. Maintaining structural integrity with shaft optimization. The impact of the shaft's new design on the spindle's structural integrity was tested using Finite Element Analysis (FEA). The analysis showed that the optimization improved the spindle's ability to resist deformation and vibrations, without compromising its strength. The optimized design proved to be reliable for long-term use. The applied load that leads to the yield point (250 MPa) at the workpiece is 15.375 kN, the same load leads to a stress of 48.89 MPa in the case of the optimized spindle system.

4. Optimizing bearing stiffness and location. The relationship between bearing stiffness and rear bearing location was studied, and the results showed that adjusting both factors together further reduced vibrations and chatter. This optimization resulted in a more stable spindle, ensuring high precision during operations. Increasing the bearing stiffness by 10 %, from 7.5+008 (N/m) to 9.75+008 (N/m), resulted in a shift in the optimum rear bearing location from 162 mm to 171 mm. This adjustment also led to an increase in the first natural frequency from 850.75 Hz to 860.41 Hz.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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