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IMPROVING CHATTER PERFORMANCE OF A LATHE SPINDLE THROUGH GRAPHO-OPTIMIZATION

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Abstract: Structural modifications to spindle systems have been demonstrated in previous studies to improve their dynamical performance. The aim of this study is to improve the performance of a lathe spindle system in terms of chatter occurrence, while maintaining the same overall mass of the system. The design of the spindle system is optimized using the grapho-optimization method, employing the Kuhn-Tucker optimality criterion to evaluate the design parameters. Specifically, the thickness of the spindle shaft and the diameter of the shaft next to the chuck are varied. The optimized spindle system shows a significant improvement in the first natural frequency value compared to the original design; the first natural frequency is increased by 59.7 %.

Keywords: *Spindle system, Chatter, Spindle model, FEM analysis*

1. INTRODUCTION

Machine tools depend on spindle systems to hold and rotate cutting tools or workpieces. Spindle shaft stiffness affects its static and dynamic behaviour, affecting lathe machine performance (Rayapati & Rathijit, 2020). Previous studies have examined spindle models, from simplified Euler-Bernoulli beam theory models (Alzghoul, Cabezas, & Szilágyi, 2022) to more complex models using Timoshenko beam theory in the systems receptance coupling approach (Alzghoul, Sarka, & Szabó, 2022) (Kato, Kono, & Kakinuma, 2022), and models solved and analysed using the finite element method with computer programs like ANSYS (Mahdavinejad, 2005) (Baker & Rouch, 2002). Despite these efforts, optimizing spindle design for lathe machine applications is difficult. Production quality and efficiency depend on spindle system performance (Yan & Zhu, 2019) (Alzghoul, Sarka, & Szabó, 2022). Studies have shown that spindle system structural modifications improve dynamical performance (Tong, Hwang, Shim, Oh, & Hong, 2020) (Lv, Li, Jin, He, & Li, 2021) (Lin, 2014). The current study uses grapho-optimization to optimize a spindle system in a lathe machine to reduce chatter while maintaining mass. The Kuhn-Tucker optimality criterion is used to evaluate design parameters like spindle shaft thickness and shaft diameter next to the chuck (Szabó, 2018) and the location of the rear bearing. Finite element analysis calculates natural frequency.

2. ANALYSIS

The proposed model of the lathe spindle consists of a shaft with uniform thickness, three bearings, a chuck, and a workpiece. Figure 1 is the section view of the model. Major considerations need to be taken into account. Firstly, the minimum diameter of the shaft should not be less than 55 mm, as it is necessary for the bar feeding mechanism. Additionally, the thickness of the shaft must not be less than 7 mm, considering the maximum allowable angle of twist to be 0.25 °/m (Zsáry, 1999), the applied torque applied to the spindle is 576 Nm (based on the data sheet of Haas ST-35L CNC lathe (Haas, 2023)). Finally, the stiffness of the bearings is assumed to be 7.5+008 N/m (Stone, 2014).

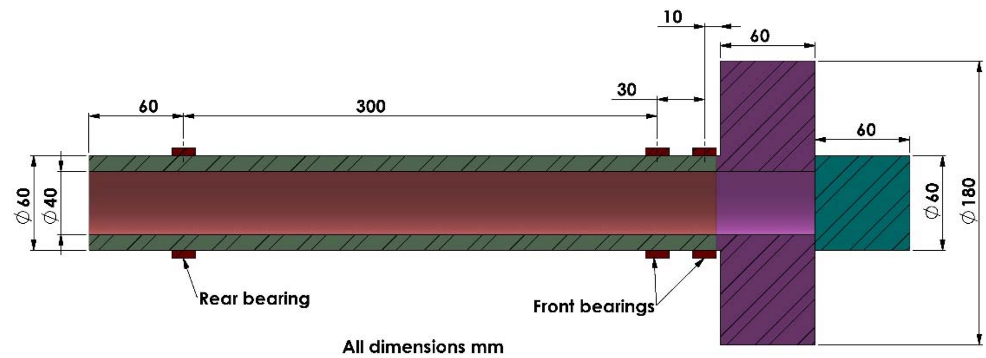

Figure 1. *Section view of lathe spindle proposed model.*

A single diagram with the objective function iso-lines and feasible region borders can represent constrained optimization problems. The optimization system is created by setting the constraints of the optimization problem and defining the objective function and its contours. To maintain shaft mass, the proposed model increases the inner diameter of the shaft adjacent to the chuck while reducing its thickness. Two variables are introduced and related by the formula for the volume of a truncated hollow cone, as the pre-optimized shaft system volume is 628318.53 mm^3. The two variables are the cone's second radius (R) and thickness (t). Figure 2 illustrates the truncated hollow cone.

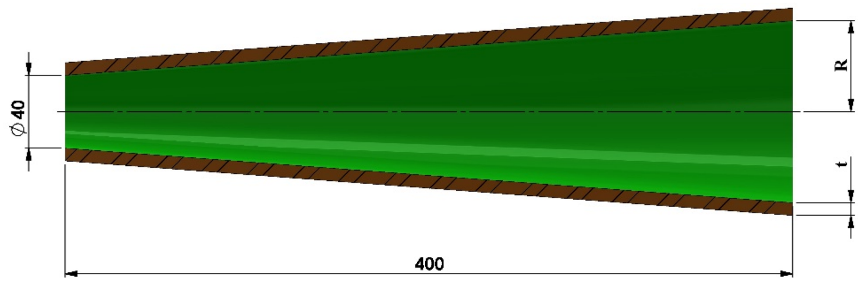

Figure 2. *Section view of the truncated hollow cone representation for optimizing spindle shaft design*

The relationship between the variables is derived from the volume equation and is presented as equation (1).

$$R = \frac{650.33 - 27.5t - t^2}{t} \quad (1)$$

Additional constraints are introduced as follows:

$$R \geq 27.5\, mm \quad (2)$$

$$7 \leq t \leq 10\, mm \quad (3)$$

Where R is the internal radius next to the chuck (mm) and t is the thickness of the shaft (mm).
The first natural frequency of the spindle system was determined using the Finite Element Method with ANSYS 19 for a range of R and t values to establish the objective function. A second-degree polynomial representing the objective function in equation (4) was fitted to the data set.

$$R(t) = 4.41t^2 - 125.54t + 1141.8 \quad (4)$$

The optimization process is visualized in Figure 3, which shows a plot of the objective function and its contours alongside the implicit and explicit constraints.

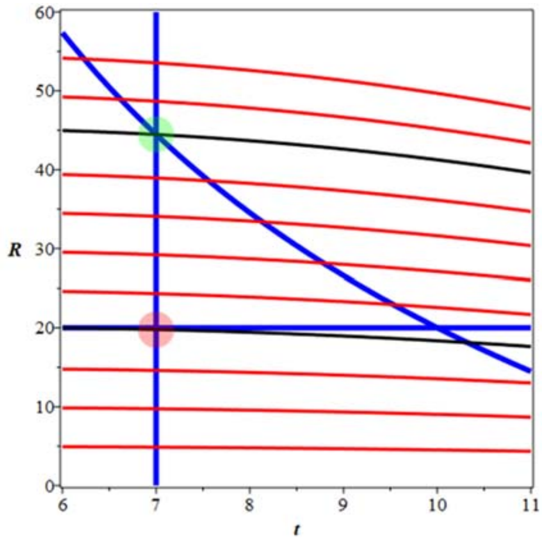

Figure 3. *The plot of the constraints and the objective function contours of the first natural frequency*

In Figure 3, the feasible solution region is the area between the constraint borders (blue lines and curve). Red contours indicate objective function. Black curves are optimal objective function contours. The green circle is the optimal point where two constraints and one objective function contour intersect. Green circle has 7 mm t, 44.46 mm R. The highest first natural frequency is expected with a 7 mm shaft thickness and 44.46 mm radius adjacent to the chuck.
The second parameter is to investigate the location of the rear bearings (as illustrated in Figure 1), the main steps of the previous part are repeated in order to construct the objective function. For the constraints, the first constraint is the axial location of the bearing taking the left end of the shaft as a reference, then the constraint of the axial location (as illustrated in Figure 1) of the bearing is expressed as:

$$7.5\ mm \leq t \leq 200\ mm \tag{5}$$

Setting L as the axial location of the rear bearing which ranges from 7.5 mm, the bearing centre, to 200 mm, the shaft midpoint. And D as the shaft diameter, L and D relationship is another constraint. (The shaft section is conical now.) This relationship is:

$$D = 0.0612L + 26.54 \quad (6)$$

To determine the objective function, the spindle system is analysed using the finite element method for various D and L values to determine the first natural frequency, which was determined using the Finite Element Method with ANSYS 19 for a range of D and L values to establish the objective function. A third-degree polynomial representing the objective function, Equation 7, was fitted to the data set.

$$D(L) = (-0.3.10^{-5})L^3 - 0.0027L^2 - 1.1843L + 703.62 \quad (7)$$

Figure 4 plots the objective function, contours, and implicit and explicit constraints to illustrate optimization. The optimization problem is plotted to help understand the objective function-constraint relationship.

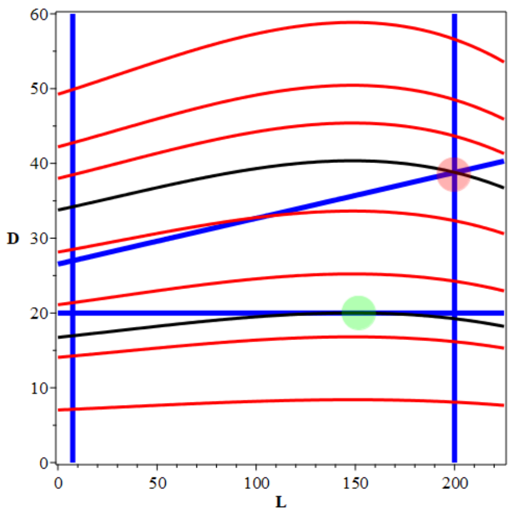

Figure 4. *The rear bearing location constraints and first natural frequency objective function contours plot.*

In Figure 4, the feasible solution region is enclosed between constraint border blue lines. Red curves show objective function contours. Black curves are optimal objective function contours. The green circle is the maximum point because it is tangent to the feasible region. This implies that there is only one intersection solution when the two curves are equal. The green circle has 152 mm L. This implies the highest first natural frequency is 152 mm from the shaft left end at the rear bearing centre. The red point is the minimum optimal point.

3. Results

Figure 5 shows the pre-optimized spindle system in sub-figure 'a' and the optimized version in 'b'. The figure shows optimization changes.

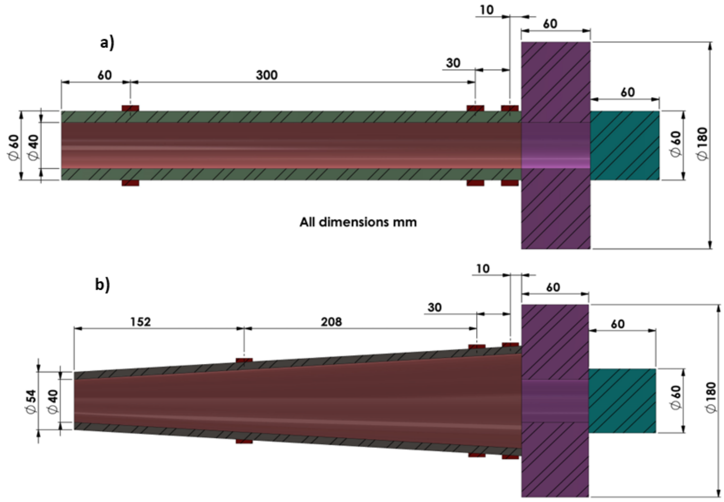

Figure 5. *Comparison of the a) pre-optimized and the b) optimized spindle systems*

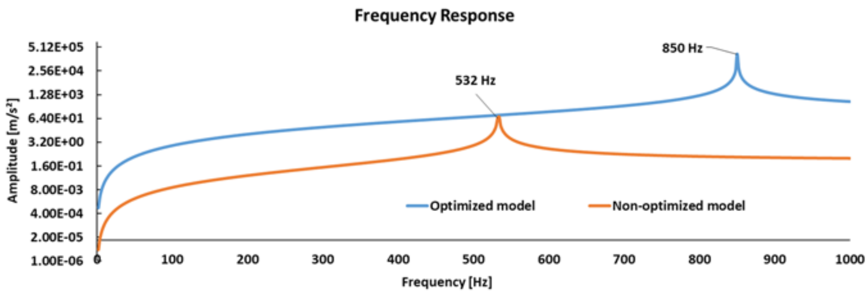

Figure 6. *The frequency response of the pre-optimized spindle system and the optimized spindle system*

Figure 6 compares the frequency response of the optimized and pre-optimized spindle systems. The x-axis shows frequency in Hertz and the y-axis acceleration in m/s^2. Both curves were generated by applying 1 kN (excitation force) to the workpiece and extracting the response with ANSYS 19. The optimized curve shifts right, indicating a higher first natural frequency than the pre-optimized curve.

4. Conclusions

According to this study, structural modifications to spindle systems can significantly improve dynamical performance. The grapho-optimization method improved the first natural frequency of a lathe spindle system while maintaining its mass. The optimization method needs more testing for other spindle systems and applications. This study shows that optimization can improve spindle system performance and industrial process efficiency.

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