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INFLUENCE OF COOLING FLUID TYPE ON THE TEMPERATURE OF HIGH SPEED MOTORIZED SPINDLE

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Abstract: Modern machine tools are expected to deliver significantly higher productivity while minimizing production costs. This requirement has led to the widespread adoption of high-speed machining and the integration of motorized spindles. However, operating at high rotational speeds results in substantial heat generation, which can cause unexpected failures. Therefore, understanding and predicting the thermal behavior of motorized spindles is essential for ensuring operational stability and extending component life. Key sources of heat in motorized spindles include electrical losses within the motor and friction within angular contact ball bearings. To maintain thermal balance, several cooling methods are commonly employed, such as a cooling jacket around the stator, oil mist lubrication, and forced air convection. This paper focuses on the influence of cooling fluid type on the temperature of angular contact ball bearings in a motorized spindle. The cooling system includes a stator cooling jacket, which plays a key role in heat dissipation. A two-dimensional finite element thermal model is developed to simulate heat generation and transfer mechanisms within the spindle assembly. The analysis focuses on temperature distribution in the front and rear bearing regions under two cooling fluid. The simulation results demonstrate noticeable differences in thermal response depending on the coolant type, offering insight into optimal cooling strategies. Water-based cooling shows higher thermal conductivity and efficiency, while oil provides better lubrication and damping characteristics. The study highlights the importance of selecting the appropriate coolant in accordance with spindle design and application requirements. These findings contribute to the ongoing development of more efficient and thermally stable motorized spindle systems for advanced manufacturing.

Keywords: Motorized spindle, angular contact bearings, thermal analysis, cooling fluid, finite element method

1. INTRODUCTION

Machining continues to play a key role in modern manufacturing across a wide range of industries. The majority of metal components undergo some form of machining during their production cycle. As a result, advancements in

machining technologies can significantly influence both production efficiency and overall manufacturing costs. [1] High-speed machining, in particular, has gained considerable attention due to its ability to enhance productivity while simultaneously lowering production expenses. However, increasing spindle speed also leads to negative

effects such as noise, vibration (chatter), and heat generation within the spindle system. [2]

During high-speed machining, the excessive heat causes uneven thermal expansion in different machine components, resulting not only in increased friction and wear of the spindle but also in larger machining tolerances. [3] Although high-speed spindles are relatively new technology, numerous studies have addressed various aspects of spindle systems through different analytical and experimental methods.

The dimensional accuracy and surface quality of the machined workpiece largely depend on the thermal, dynamic, and other characteristics of the machine tool spindle system. High-speed spindles are known to experience reliability issues and sudden failures, which are primarily caused by thermal loads. [4] The authors developed a mathematical model to predict bearing temperatures influenced by heat generated in the motor due to electrical losses. A thermal model of the spindle was created using the finite element method, selected for its capability to effectively integrate heat conduction with complex geometries and physical conditions.

The study also showed that decreasing the fluid flow in the cooling jacket results in higher bearing temperatures, emphasizing the significance of efficient cooling. [5]. Statistics indicate that thermal errors can account for up to 60 - 70% of the total geometric errors in a workpiece. [6] Studies, [7] have demonstrated that thermal deformation in numerical control (NC) lathes can reach values as high as 80 μm at spindle speeds of 2000 rpm, while CNC machining centers may experience thermal errors up to 50 μm at 8000 rpm—levels that are clearly unacceptable for precision machining.

Given these findings, investigating the thermal behavior of spindles is crucial to minimizing their impact on the dimensional accuracy of machine tools.

2. HIGH SPEED MOTORIZED SPINDLE

High speed motorized spindles are key elements in modern machining centers, capable of reaching very high rotational speeds—often tens of thousands of revolutions per minute—which enable faster material removal, improved surface finish, and enhanced machining accuracy.

Compared to conventional spindles, motorized spindles integrate the motor directly into the spindle shaft, eliminating power transmission components such as gears and belts. This design reduces vibrations, improves rotational balance, and allows for precise control of acceleration and deceleration. However, the high-speed operation and significant heat generated by the built-in motor place considerable thermal and mechanical stress on spindle components, pushing them to their operational limits [8]. A schematic of a typical high-speed spindle is shown in Fig. 1.

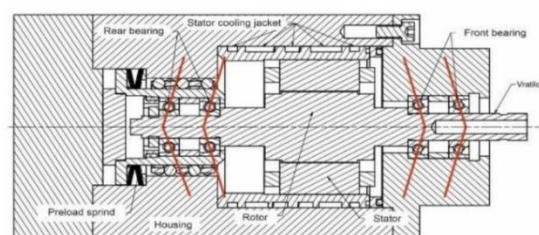


Figure 1. Scheme of high speed spindle

Manufacturers state that high-speed spindles are equipped with efficient liquid cooling systems. Cooling jackets are installed both around the front bearing area and surrounding the spindle, motor, and stator to reduce temperature rises caused by bearing friction and motor losses. By controlling heat generation during operation, the spindle's performance is enhanced, resulting in higher productivity and improved machining quality. The spindle achieves its maximum rated performance within an optimal coolant temperature range of 20 °C to 25 °C. Actual performance, however, varies depending on the coolant temperature and the type of cooling medium used. [9]

3. FINITE ELEMENT MODEL OF MOTORIZED SPINDLE

This paper presents a finite element model analysis of a motorized spindle, emphasizing the role of the cooling jacket and how the flow of different cooling fluids influences the spindle's temperature distribution. The geometry of the spiral cooling jacket surrounding the stator surface of the motorized spindle is illustrated in figure 2.



Figure 2. Schematic geometry of the spiral cooling jacket

Specialized commercial software was employed to develop the 2D surface model of the motorized spindle and perform the detailed thermal analysis. The electric motor inside the spindle acts as a significant heat generator. Most motorized spindles use AC induction motors, with the effective input power of the motor. The heat generated by the motor, which contributes significantly to the spindle's thermal load, can be estimated using the following relation:

$$Q_m = U \cdot I \cdot \cos \varphi - T \cdot \omega \quad (1)$$

In this context, U represents the input voltage, while I denotes the current in each phase. The phase angle φ between voltage and current determines the ratio of real (effective) power to apparent power. The effective electrical input power is partly transformed into mechanical output, while the remainder is lost—primarily in the form of heat.

Where: Q_{motor} is the heat generated by the motor [W], U is the input voltage [V], I is the current [A], φ is the phase angle [rad], T is the torque [Nm], ω is the angular velocity [rad/s],

calculated as $\omega = \frac{2\pi n}{60}$, where n is the rotational speed in revolutions per minute (rpm).

In table 1 has been given motor input parameters.

Table 1. Motor input parameters

Exp no.	Voltage [V]	Frequency [Hz]	Current [A]	Power [kW]	efficiency
1	220	1500	12.3	3	0.88

The main contributors to thermal deformation in the spindle system are the heat generated by the motor and the spindle bearings. Heat removal is primarily managed through forced convection in the cooling channels and by airflow around the spindle housing. This analysis focuses on the impact of different cooling fluids on the temperature distribution within the cooling jacket. The forced convection within the stator cooling channels is characterized by a convective heat transfer coefficient, which is estimated using the following equation:

$$h_v = \frac{Nu \cdot k}{l_t} \quad (2)$$

where Nu is Nusselt number, k is the thermal conductivity of the fluid, l_t channel length.

$$Nu = 0,012(R_e^{0,87} - 280)Pr^{0,4} \left[1 + \left(\frac{D}{L} \right)^{\frac{2}{3}} \right] \left(\frac{Pr}{Pr_w} \right)^{0,11} \quad (3)$$

$$Re = \frac{V \cdot D}{\nu} \quad (4)$$

$$Pr = \frac{Q}{A} = \frac{Q}{h \cdot b} \quad (5)$$

Re is Reynolds number, and Pr is Prandtl number ($0.7 < Pr < 100$) of the coolant, D/L is ratio of diameter to length of the tube or channel (geometrical factor), ν is the kinematic viscosity of the fluid, and $Pr/Pr_w \approx 1$ for water, V is mean flow velocity, ν is kinematic viscosity, Q is volumetric flow rate, A is cross-sectional area through which the

fluid flows, h and b are for a rectangular cross-section.

Heat conduction between the stator, cooling jacket, and spindle housing was calculated and modelled using a thermal resistance network approach. This network defines the conductive and convective resistances among the stator, cooling jacket, and housing components. To simplify the analysis, thermal resistances at each interface were individually calculated, allowing for a more manageable formulation of the heat transfer equations.

$$R = \frac{\ln\left(\frac{R_o}{R_i}\right)}{2 \cdot \pi \cdot l \cdot k} \quad (6)$$

Where R_o is outer radius, R_i is inner radius of considered element, l is element length, and k is the thermal conductivity of material. On the figure 3 conduction network has been presented and R_{khh} is conduction resistance between cooling jacket and housing, where cooling jacket have been considered as cylinder, while R_{skh} is conduction resistance among cooling jacket and stator.

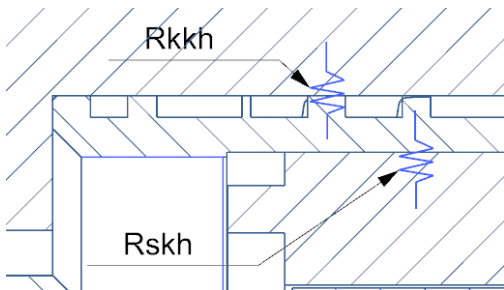


Figure 3. Radial conduction between stator/cooling and jacket/housing

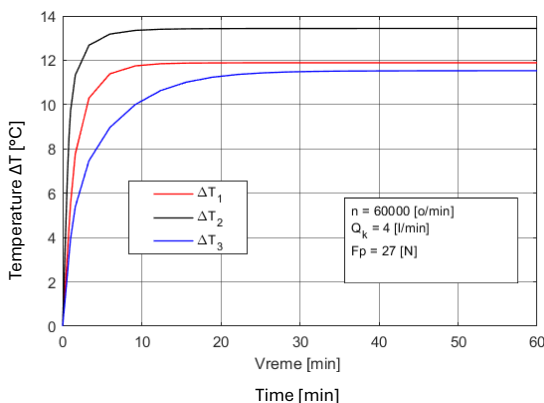


Figure 4. Temperature increase during oil cooling

A free convection coefficient of 12 W/mK is assumed for the ambient air surrounding stationary components such as the spindle housing. The primary objective of this analysis is to develop a mathematical model of the stator cooling jacket and investigate how the type of cooling fluid specifically water and oil, affects the thermal behaviour of the motorized spindle. To isolate this effect, all other heat sources, modes of convection, and radiation are held constant throughout the analysis. Given that spindle bearings are critical to machine performance and reliability, the results focus on their temperature response.

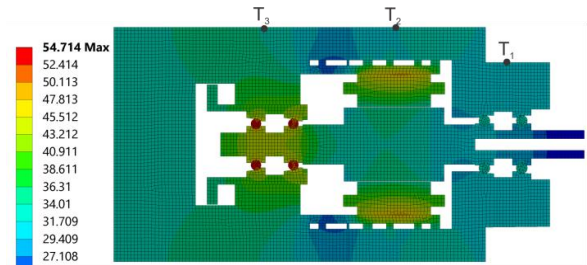


Figure 5. Steady-state temperature distribution at $n=60,000$ rpm with spindle housing cooled by oil.

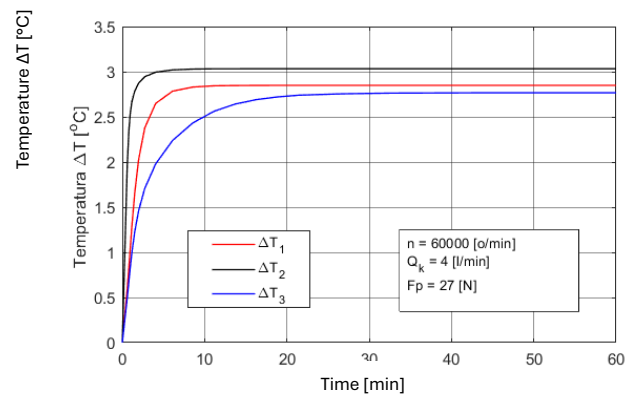


Figure 6. Temperature increase during water cooling

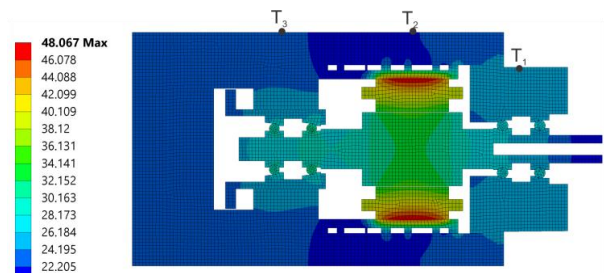


Figure 7. Steady-state temperature distribution at $n=60,000$ rpm with spindle housing cooled by water

4. CONCLUSION

When the housing is cooled with oil, the heat generated in the electric motor and bearings is distributed almost evenly between the housing and the spindle, with a slightly larger portion of the heat directed toward the rear bearing via the spindle. Smaller amount is transferred through the housing toward the front bearing (Figure 4 and 5).

However, with water cooling, the temperature difference between the housing and the spindle is significantly greater (Figure 6 and 7). In this case, a larger portion of the motor-generated heat is carried through the spindle toward the front bearing, while temperatures along the housing remain relatively uniform. This indicates that the heat is distributed almost equally through the housing toward both the front and rear bearings. In conclusion, the developed computational model serves as an effective engineering tool for analysing the thermal behaviour of motorized spindles. Its straightforward structure, based on a thermal resistance network, allows for quick and sufficiently accurate prediction of temperature distribution within key system components.

Moreover, the model facilitates comparison of different cooling fluids, which is essential for optimizing the cooling system during the early stages of design. This approach not only enhances the reliability and operational precision of the spindle but also reduces the risk of thermally induced damage to bearings and other sensitive parts.

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