Active coolant control onto thermal behaviors of precision ball screw unit

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Abstract
Being a critical factor affecting the motion accuracy of precision machine tools, structural thermal elongation of precision ball screw unit is generally caused by the comprehensive influence from heat generations of screw-nut pair/bearings and time-varying ambient temperature. To resist 2 thermal disturbances above to guarantee precisely the original length of screw shaft, an active coolant control strategy is proposed in this paper. This strategy is based on a premise hypothesis: For the slender and long tubular structure of screw shaft, the screw shaft temperature is approximately equal to its recirculating coolant temperature. The reason is that the intensive forced coolant convection is capable of eliminating screw shaft temperature rises caused by friction heat generations and ambient air convections. Based on this premise, screw coolant temperature can be consistently controlled by an active strategy, further to correct the thermal elongation of screw shaft. It can be experimentally verified that the thermal variations of machine positioning accuracy caused by the active coolant control strategy are not more than 10 μm, which are lower than traditional strategy. Besides, based on detected structural temperatures of precision ball screw unit, the theoretical model above is further proved to be reliable by FE simulation method.

Keywords Precision ball screw unit · Thermal behaviors · Active coolant control · Thermal elongation · Heat-fluid-solid coupling

1 Introduction
In recent decades, precision ball screw unit has been widely applied into linear feed systems of various precision machine tools, to convert rotational motion into linear motion [1]. Being the vital factor causing the thermal variations of machine accuracy, the shaft thermal elongation of precision ball screw unit is generally attributed to 2 disturbing factors from a machining activity, which is revealed in Fig. 1: ◦ friction heat generations from screw-nut pair and bearing groups, and ◦ air convective heat transfer with time-varying ambient temperature. For dissipating these disturbing heat transfers, the hollow channel for recirculating coolant is frequently adopted for the shaft design of precision ball screw unit.

Traditionally, the ambient temperature tracking strategy [2] is generally adopted to regulate supply temperature of screw recirculating coolants for precision machining activities. But the disadvantage of this strategy has been gradually exposed: Because coolant supply temperature is dynamically determined based on the ambient temperature detections, disturbing heat transfers onto the screw structure can hardly be dissipated accurately. This restricts the effectiveness of reducing structural thermal elongations of precision ball screw unit [2]. Therefore, it is urgent to develop an active strategy regulating coolant temperature to control thermal behaviors of precision ball screw unit, thus to guarantee precisely its original length for machine accuracy stability.

Many scholars have studied the thermal behaviors modeling of linear feed system of machine tools. On one hand, some scholars investigated the modeling method based on simulation technology. Based on finite element thermal analysis, Mao et al. [3] proposed an iterative finite element thermal analysis algorithm combining experimental data to
calculate the convective heat transfer coefficient (CHTC) of precision ball screw system. Oyanguren et al. [4] presented a numerical modeling strategy to predict the preload variation due to temperature increase using a thermo-mechanical 3D finite element method (FEM)-based model for double nut-ball screw drives. Li et al. [5] applied finite difference method to simulate the temperature distribution and thermal growth of the ball screw feed drive system under various working conditions, and verified that the simulation accuracy could be improved by using the proposed method.

On the other hand, many other scholars established experimentally the thermal model of machine linear feed system. Based on experimental data, Li et al. [6] proposed a new inverse random model by the combination of the stochastic theory, genetic algorithm, and radial basis function neural network (RBFNN). The aim is to predict ball screw system thermal errors, with the randomness of influencing factors being considered. Li et al. [7] put forward a prediction model for thermal errors of the lead screw considering the time-varying heat generation rate of each heat source, with the combination of numerical and experimental methods. Li et al. [8] proposed an adaptive moving thermal network model of the screw system with moving thermal excitation under variable experimental conditions and a real-time prediction method for thermal errors of this system. Shi et al. [9] proposed a Bayesian neural network modeling method based on thermal error detections of machine feed system, which has higher prediction accuracy and multi-condition adaptability than the back propagation (BP) neural network and multiple linear regression model. Gao et al. [10] superimposed the geometric error model based on coordinate rotation transformation and the thermal error model based on BP neural network to obtain a comprehensive model to predict the positioning errors of the linear feed system. Yang et al. [11] used the Elman neural network (ENS) optimized by the differential evolution (DE) algorithm to model the thermal errors of the two-axis differential micro-feed system (TDMS), which is proved to be accurate and robust. The researching activities above mainly focus on the thermal model establishment to accurately predict thermal behaviors of machine feed system, providing preparations for accuracy guarantee of precision machine tools.

Based on the published investigations above onto thermal modeling of machine feed systems, there are still other studies placed emphasis on suppression methods of machine thermal errors. On one hand, some scholars use the compensation method whose main idea is to create an opposite error to eliminate thermal errors of machine feed system, to suppress the thermal error of machine tools [12]. Zaplata and Pajor [13] established the temperature distribution of ball screw-pair by using the partial differential equation (PDE) model, and then measured the temperature distribution of CNC axis online during the operation, to realize the machine thermal error compensation. Shen et al. [14] proposed an offset compensation method by the CNC-PLC technology, which adopted Bayesian Networks to predict thermal errors. Experiments show that this technology can reduce more than 70% of the machining error caused by thermal deformation. Bosetti and Bruschi [15] proposed an active error compensation method for positioning errors, which can be realized by the real-time measurement onto the displacement field of a given structural component without establishing any model of its dynamic/thermal structure behaviors. Based on the thermal deformation balance principle, Ge and Ding [16] used carbon fiber reinforced plastics (CFRPs) with the negative linear expansion coefficient to realize thermal deformation compensation for functional parts of precision machine tools. Wei et al. [17] proposed a method to reduce the influence of thermal deformation onto the electromagnetic (EM) performance of small active phased array antennas (APAs) via the real-time compensation, which has the high prediction accuracy, and the decrease in EM performance caused by antenna panel thermal deformation is effectively reduced.
On the other hand, some other scholars have studied the cooling systems and strategies for precision ball screw units to suppress thermal errors of machine tools. Xu et al. [18–20] developed a high speed/high precision nut/screw air cooling ball screw system to avoid thermal errors which affect the positioning accuracy of precision ball screw feed drive system, and experimentally verified the effectiveness of this method. They also developed a liquid-cooling system using water, coolant oil, light oil, and cutting oil as coolants in a ball screw shaft to avoid thermal errors and achieve temperature equilibrium faster [21]. Shi et al. [22] conducted theoretical modeling and experimental studies onto the temperature control of screw shaft along with heat generation and dissipation interactions, and revealed the cooling effect of forced fluid circulation on the ball screw feed system of precision boring machine. However, the cooling strategies adopted by these studies are open-loop and passive strategies, which cannot realize the real-time monitoring and adaptation onto the time-varying thermal condition of machine feed system.

For this problem, this paper proposes an active coolant control strategy onto thermal behaviors of precision ball screw unit, based on the differentiated multi-loop bath recirculation system [23]. This strategy keeps the recirculating coolant temperature stable, thus to eliminate temperature rise and thermal elongation of screw shaft. The organization of this paper is as follows: Sect. 2 describes the active coolant control principle onto thermal behaviors of precision ball screw unit and its premise hypothesis (theoretical model): Screw shaft temperature is dynamically equal to coolant temperature. To clarify the validity of the proposed active coolant control strategy, Sect. 3 verifies this theoretical model by the numerical simulation method. Section 4 clarifies advantages of the proposed active thermal control strategy for precision ball screw unit based on experimental and simulation results. Eventually, Sect. 5 gives conclusions of the whole research.

2 Active coolant control principle onto thermal behaviors of precision ball screw unit

2.1 Thermal balance — temperature variation — thermal elongation of precision ball screw unit

Because the motor assembly surface of motor-bearing seat is generally equipped with insulation material (revealed in Fig. 1), the thermal influence from motor heat generation onto precision ball screw unit can be ignored. Therefore, as shown in Fig. 2, the structural temperature variation of precision ball screw unit in operation state is mainly affected by the friction heat generations of screw-nut pair/bearings, air convection with the time-varying ambient temperature, and the heat dissipations from recirculation coolant. According to thermoelastic law [24], the structural thermal elongation \( f(\mu m) \) of precision ball screw unit is generated based on its temperature variation, with the time-lag effect:

\[
f = \alpha \Delta T
\]

In Eq. (1), \( \alpha \) is the thermal expansion coefficient of screw shaft material \((K^{-1})\), and \( \Delta T \) is the structural temperature rise of precision ball screw unit \( ^\circ C \).

It can be concluded from Eq. (1) that the thermal elongation of screw shaft can be theoretically eliminated by stabilizing its structural temperature rise \((\Delta T=0)\). According to heat transfer theory, that needs a dynamic power balance between screw structural heat...
generations/ambient air convection and coolant heat dissipations, which must be based on an active coolant control strategy onto thermal behaviors of precision ball screw unit.

### 2.2 Active coolant control strategy for thermal behaviors of precision ball screw unit

#### 2.2.1 Theoretical model for active coolant control strategy

Due to the movement of screw nut along the screw shaft, the resistance temperature detector (RTD) sensor attachment for screw shaft temperature monitoring can cause interference between screw nut and RTD sensor. Therefore, the temperature monitoring onto the screw shaft for this active coolant control strategy is based on the recirculating coolant temperature monitoring.

The strategy realization must be relied on a premise hypothesis (theoretical model for this control strategy): The temperature of a slender tubular structure whose length is much larger than its diameter (screw shaft structure) can be dominantly determined by the temperature of flowing liquid in the tube (recirculation coolant), because of the forced convection heat transfer in the tube:

$$T_{scr} = T_{coo}$$  \hspace{1cm} (2)

In Eq. (2), $T_{coo}$ is the screw coolant temperature ($^\circ$C), and $T_{scr}$ is the screw shaft temperature ($^\circ$C). Based on Eq. (2), screw structural thermal elongation can be suppressed by reducing coolant temperature rises in it. The reliability of this theoretical model is verified in Sect. 4.2.2, and it can be applied to all the precision mechanical components with a slender tubular structure including the precision ball screw unit.

#### 2.2.2 Description of active coolant control strategy

Based on the premise hypothesis above, the active control strategy onto structural thermal behaviors of precision ball screw unit is realized by the closed loop temperature controls onto its recirculating coolant, which is described in Fig. 3: The initial inlet/outlet temperatures $T_{in}(0)$/$T_{out}(0)$ of screw coolant are recorded. Their average value $T_{coo}(0)$ is used as the control target. During the operation of machine feed system, the coolant average temperature at each moment $T_{coo}(\tau)$ is continuously monitored and compared with the control target $T_{coo}(0)$, to obtain the relative temperature:

$$\Delta T_{coo}(\tau) = T_{coo}(\tau) - T_{coo}(0)$$  \hspace{1cm} (3)

The calculated relative temperature value $\Delta T_{coo}(\tau)$ is transmitted to the controlling algorithm to dynamically generate instructions to regulate coolant supply temperature at the next moment $\tau+1$. Consequently, the average temperature of screw coolant is kept stable during the whole operation process.

Because the screw shaft temperature is equal to coolant temperature, this strategy can resist disturbances from internal heat generations and external heat convection of precision ball screw unit onto its structural temperature. Then, the screw thermal elongation can be actively corrected by the stabilization onto screw shaft temperature. Substantially, the realization of this strategy is to dynamically control screw thermal behaviors according to variations of environmental temperature and internal heat generations. Therefore, from the comparison of the controlling effectiveness, this strategy can make screw temperature and thermal elongation remain stable with the time increase, which is more advantageous than traditional open loop and passive strategies.

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**Fig. 3** Description of active coolant control strategy onto structural thermal behaviors of precision ball screw unit
Specially, the closed loop BP-PID algorithm [25] is adopted in this paper for the stabilization control onto the screw coolant temperature. As depicted in Fig. 3, closed loop PID algorithm is utilized to eliminate continuously the relative temperature of screw coolant $\Delta T_{\text{coo}}$. Besides, based on the BP neural network, PID parameters $K_P / K_I / K_D$ are optimally adjusted according to detections onto screw coolant temperature. Furthermore, temperature fluctuations of screw structure (because of the response speed variations of screw structural temperature caused by different coolant types or flow rates) can be stabilized by adjusting appropriately some critical parameters of BP neural network. The aim is to guarantee the thermal elongation correction effectiveness of precision ball screw unit.

2.2.3 Experimental platform for active coolant control strategy

In order to realize the active coolant control strategy onto thermal behaviors of precision ball screw unit above, the experimental platform must be constructed based on necessary RTD sensors and differentiated multi-loop bath recirculation system [23]: As revealed in Fig. 4, RTD sensors are installed at screw coolant channel inlet and outlet to monitor coolant temperature, and the other RTD sensors are mounted nearby the heat generating parts (bearings and screw-nut pair) to detect structural temperature rises of precision ball screw unit.

Meanwhile, as shown in Fig. 5, independent coolant blenders are connected to the coolant channels of 2 precision ball screw units of machine feed system. This makes the differentiated multi-loop bath recirculation system realize dynamic coolant supply temperatures for its left and right screws, according to the received instructions from the controlling module of host computer software.

Based on the preparations above, the experimental platform for active coolant control strategy is constructed according to the principle in Fig. 6: When the machine feed system is in operation, screw coolant temperature signals detected by RTD sensors are continuously collected to trigger the PID-BP algorithm in the controlling module of host computer software. Then, coolant supply temperature instructions are dynamically calculated and then transmitted to the differentiated multi-loop bath recirculation system to perform. Thus, the left and right screw coolant temperatures of machine feed system can be stabilized according to the obtained instructions above.

On the other hand, screw heat generating part temperatures detected by RTD sensors are used to construct the optimization objective function in Sect. 3.2.2. The detected signals are displayed in monitoring module of host computer software.
3 Theoretical model verification method of active coolant control onto thermal behaviors of precision ball screw unit

3.1 Thermal numerical simulation method of precision ball screw unit

3.1.1 Heat-fluid-solid coupling analytical model

To verify the reliability of the theoretical model proposed in Sect. 2.2.1, it is necessary to numerically simulate temperature characteristics of precision ball screw unit, which are influenced by heat generations of screw-nut pair/screw bearings, heat dissipation of screw circulating coolant, and ambient air convection. The heat-fluid-solid coupling simulation model of precision ball screw unit is established by finite element (FE) method. By solving Eq. (4) [26], the heat transfer process and fluid-solid coupling heat transfer can be obtained:

\[
\frac{\partial}{\partial t} \left( \rho_{\text{oil,sol}} H_{\text{en}} \right) + \nabla \cdot \left[ \rho_{\text{oil,sol}} \nabla T + \left( \frac{\vec{v} \cdot \nabla \vec{v}}{\tau} \right) \right] = \nabla \cdot \left( k_{\text{oil,sol}} \nabla T \right) + S_h
\]

For Eq. (4), \( \rho_{\text{oil,sol}} \) is the density of coolant oil or solid structure (kg/m\(^3\)), \( k_{\text{oil,sol}} \) is the thermal conductivity of coolant oil or solid structure (W/(m·K)), \( H_{\text{en}} \) is the energy content per unit mass (J), \( p \) is the pressure (Pa), \( \vec{v} \) is the velocity vector/stress tensor, \( S_h \) is the heat generation power of volumetric heat source (W), \( \nabla \cdot \left( \frac{\vec{v} \cdot \nabla \vec{v}}{\tau} \right) \) is the viscous power dissipation of flowing coolant (W), and \( \nabla \cdot \left( k \nabla T \right) \) is the heat transfer among solid, flowing coolant and ambient air (W).

Meanwhile, the flow field is obtained by FE method. Since the coolant is in a laminar flow state and is assumed to be a steady-state viscous incompressible fluid, the flow field is calculated by solving Eq. (5):

\[
\begin{aligned}
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} &= 0 \\
\frac{\partial}{\partial t} \left( \rho_{\text{oil}} \vec{v} \right) + \nabla \left( \rho_{\text{oil}} \vec{v} \vec{v} \right) &= -\nabla p + \nabla \left( \frac{\tau \cdot \vec{v}}{\tau} \right)
\end{aligned}
\]

Fig. 5 Screw coolant channels equipped with differentiated multi-loops bath recirculation system
In Eq. (5), $u/v/w$ is the coolant flowing velocity on X/Y/Z direction (m/s), and $\rho_{oil}$ is the density of coolant oil (kg/m$^3$).

Based on this mathematical model above, the transient temperature behaviors of precision ball screw unit can be solved by numerical simulation.

### 3.1.2 Numerical simulation method

For the transient heat-fluid-solid coupling simulation of precision ball screw unit, its geometry model is constructed in ANSYS. Then, SOLID5 unit is adopted for meshing the bearing balls and screw/nut structures of precision ball screw unit. SOLID70 unit is adopted for meshing other structures. A total of 41803 nodes and 174867 grid units are generated, respectively. FLUID116 unit, which for heat conduction and fluid transmission between two nodes, is selected as the coolant fluid unit for meshing. The surface effect unit between the coolant and inner wall of screw coolant channel is set as SURF152 to realize the convective heat transfer effect in simulation. Based on the structural meshing of precision ball screw unit, physical parameters of its solid structure and fluid regions are defined according to Table 1.

Specially, in order to realize the full stroke reciprocating motion of screw nut along the screw shaft in transient thermal simulation, the following setting is adopted: Firstly, because the duration required for the precision ball screw

| Physical parameters | Density / kg·m$^{-3}$ | Specific heat capacity / J·(kg·$^\circ$C)$^{-1}$ | Coefficient of thermal conductivity / W·(m$^2$·$^\circ$C)$^{-1}$ |
|---------------------|------------------------|-----------------------------------------------|-----------------------------------------------|
| Screw / screw nut / bearings (GCr15) | 7800 | 460 | 40.11 |
| Motor-bearing seat / bearing seat (HT300) | 7300 | 523 | 47 |
| Coolant (5# spindle oil) | 851 | 1851 | 0.144 |

Fig. 6 Active coolant control platform for thermal behaviors of precision ball screw unit

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unit to reach its structural thermal stability in operation is empirically 2 h, 7200 s is selected as the total time length of its transient heat-fluid-solid coupling simulation. In addition, owing to the screw nut reciprocating at 9 m/min during each experiment (Sect. 4) in this paper, the substep length of one-way relative movement of screw-nut pair is calculated as 6 s, with the screw stroke length being considered. ANSYS Parametric Design Language (APDL) is used to define different displacement endpoint coordinates of screw nut for each substep in transient simulation. Based on the method above, the cyclic reciprocating linear motion of screw-nut pair is realized in transient simulation.

For the meshed simulation model, heat generation loads of screw-nut pair/bearing groups are loaded according to Fig. 7, and convective heat transfer coefficients of ambient air and recirculating coolant are then loaded onto the outer surfaces of screw structure and inner wall of coolant channel respectively. The time-varying ambient temperature is considered for the simulation modeling according to its measured data. Most vitally, to simulate actual structural thermal behaviors of precision ball screw unit under different coolant control strategies, the coolant supply temperature data tested in experiments are utilized as screw coolant inlet temperature conditions for simulations.

For the transient thermal simulation of precision ball screw unit, heat generation and convective heat transfer coefficients should be calculated and corrected by the following method.

### 3.2 Thermal load modeling and optimization correction method

#### 3.2.1 Thermal load modeling

**Screw bearings** While the screw bearings are in motion, friction heat was generated by the relative movements between the various parts of the bearing. The heat can be computed by Eq. (6) [27]:

$$ Q_b = 1.047 \times 10^{-4} n (M_0 + M_1) $$

(6)

In Eq. (6), friction torque $M_0$ (N·m) brought by bearing lubricant viscosity and friction torque $M_1$ (N·m) caused by bearing applied force can be calculated by Eqs. (7) and (8):

$$ M_0 = \begin{cases} 10^{-7} f_0 \left( \nu_0 n \right)^{2/3} D_m^3, & \nu_0 n \geq 2000 \\ 160 \times 10^{-7} f_0 D_m^3, & \nu_0 n < 2000 \end{cases} $$

(7)

In Eq. (7), $f_0$ is a coefficient related to the bearing type and lubrication method, and $\nu_0$ is the kinematic viscosity of the lubricant under working temperature (m²/s).

$$ M_1 = f_1 F_\beta D_m $$

(8)

In Eq. (8), $f_1$ is a coefficient related to the bearing type and load, $F_\beta$ is the bearing load (N), and $D_m$ is the mean diameter of the bearing (mm).

![Fig. 7 Heat generation loads for FE simulation of precision ball screw unit](image)
Screw-nut pair  When the precision ball screw unit is in operation, the screw-nut pair will generate heat due to its internal friction effect. The heat can be determined by Eq. (9) [28] and loaded into the simulation modeling of precision ball screw unit.

\[ Q = 0.1047nM_Z \quad (9) \]

In Eq. (9), \( n \) is the rotational speed of ball screw, and \( M_Z \) is the friction moment of screw-nut pair (N·m), which can be obtained from Eqs. (10)–(12):

\[ M_Z = M_D + M_p \quad (10) \]

\[ M_D = \frac{F_aP_h}{2\pi\eta} \quad (11) \]

\[ M_p = \frac{F_aP_h}{2\pi\eta} (1 - \eta^2) \quad (12) \]

In Eqs. (10)–(12), \( M_D \) and \( M_p \) are respectively driving moment and resistance moment of screw-nut pair; \( F_a \) is the total axial load of the screw (kN); \( F_p \) is the axial preload of the screw-nut pair (kN); \( P_h \) is the lead of screw (mm); and \( \eta \) is the transmission efficiency of the screw-nut pair.

**Coefficient empirical modeling of ambient and coolant heat convections**  The forced convective heat transfer coefficient \( h_f \) (W/(m²·K)) can be obtained by Eq. (13) [29]:

\[ h_f = \frac{N_uK^*}{d} \quad (13) \]

In Eq. (13), \( K^* \) is the thermal conductivity of fluid, and \( d \) is the set size of solid structure. \( N_u \) is the Nusselt number.

For the ambient air convection occurring at outer surfaces of a long cylinder (screw shaft), the Nusselt number \( N_u \) is computed from Reynolds number \( Re \) and Prandtl number \( Pr \):

\[ Nu = 0.133 Re^{\frac{1}{3}} Pr^{\frac{1}{3}} \quad (14) \]

In Eq. (14):

\[ Re = \frac{u_{air}d}{v_{air}} \quad (15) \]

\[ Pr = \frac{c_{air}v_{air}}{K^*} \quad (16) \]

For Eqs. (15) and (16), \( u_{air} \) is the air velocity, \( v_{air} \) is the air kinematic viscosity, and \( c_{air} \) is the air specific heat capacitance.

For the coolant convection occurring inside a tube structure (screw coolant channel), the Nusselt number \( N_u \) is defined as:

\[ N_u = 0.15Re^{0.33} Pr^{0.43} Gr^{0.1} \cdot (Pr/Pr_w)^{0.25} \cdot K \]

In Eq. (17), \( Re \) is the Reynods number, \( Pr \) is the Prandtl number, \( Gr \) is the Grashof number, \( Pr_w \) is the Prandtl number of contact surface, and \( K \) is the correction coefficient.

In addition, stationary surfaces of precision ball screw unit mainly interact with ambient air by natural convection and its heat transfer coefficient \( h = 9.7 \) W/m²·K is provided by Reference [29].

### 3.2.2 Thermal load optimization and correction method

Generally, thermal simulation loads obtained by empirical formula have errors compared with their actual values. Therefore, based on the simulation model above, genetic algorithm is adopted to comprehensively optimize and modify heat generation values of bearing groups, screw-nut pair, and convection heat transfer coefficients. Their modified values are taken as the thermal loads, for accurate thermal simulation model of precision ball screw unit. The optimization method is described in Fig. 8.

As described in Fig. 8, the empirical values of heat generating parts and convection heat transfer coefficients are used as initial values of design variables. These values are adopted for heat-fluid-solid coupling simulation of precision ball screw unit. Thus multi-physical field models of heat transfer, fluid and structural mechanics in transient simulation are considered as the constraint conditions. The overall errors between simulated structural temperatures of precision ball screw unit and their corresponding experimental data are designed as the fitness function, and the objective function is to minimize these overall errors. That means thermal load values will be continuously updated by genetic algorithm until the overall errors meet the requirement. With this optimization and correction process, the exact thermal loads and simulated structural temperature of precision ball screw unit are obtained.

### 4 Experimental verification of the advantages of active coolant control strategy in correcting thermal elongation of screw shaft

#### 4.1 Experimental method

##### 4.1.1 Monitoring method onto thermal elongation of screw shaft

In this paper, the shaft thermal elongation of precision ball screw unit can be experimentally reflected according to the thermal variations of the positioning errors of machine feed.
system (Grating encoder is closed), which is monitored by the laser interferometer in Fig. 9.

From the initial moment of each experiment, positioning errors of machine feed system are tested by laser interferometer every hour for the 2-h operation. Then, the differences from the detected values at 1-h/2-h moments to the initial moment are calculated respectively, to obtain the thermal variations of the machine positioning errors at these 2 moments. According to engineering experience, thermal variations above are mainly attributed to thermal elongations of screw shaft, which can be influenced by the applications of different screw coolant control strategies.
4.1.2 Design of comparative experiments

In order to verify the effectiveness and advantages of the proposed active coolant control strategy in correcting the thermal elongations of screw shaft, comparative experiments are necessary: the precision ball screw unit is operated under the proposed active coolant control strategy and the traditional ambient temperature tracking strategy respectively.

Besides, both of experiments were carried out under the same working conditions: (1) Worktable moving speed of machine feed system is 9 m/min; (2) Each experiment lasts for 2 h (7200 s); (3) Ambient temperature is 17 °C initially, and then increase slowly by 2 °C during the whole operation; (4) Coolant supply flow rate for each precision ball screw unit is 7.5 L/min.

4.2 Experimental results and discussions

4.2.1 Accurate screw structural temperature rises based on simulation load correction

After the correction procedure in Sect. 3.2, obtained loading values and their corresponding loading positions for the thermal simulation model of precision ball screw unit are listed in Table 2.

Based on these corrected thermal loads, simulated temperature rises of screw heat generating parts are obtained under the active coolant control and ambient temperature tracking strategies respectively. These simulated temperatures are compared with their corresponding measured values in experiments, which is shown in Fig. 10. It can be seen from it that the simulated curves and the experimental curves are very close to each other under both 2 strategies respectively. Therefore, it can be concluded that established simulation models can accurately reflect actual thermal behaviors of precision ball screw unit, which provides the possibility to observe its structural temperature to verify the theoretical model in Sect. 2.2.1.

![Laser interferometer for monitoring thermal elongation of screw shaft](image)

**Table 2** Thermal loads/boundary conditions and their loading positions for transient FE thermal simulation modeling of precision ball screw unit

| Loading position | Loading value |
|------------------|---------------|
| Heat generation rate / W·m⁻³ | Screw-nut pair 652654 |
| Convection heat transfer coefficient of ambient air / W·(m²·C⁻¹) | Bearings 1350307 |
| Convection heat transfer coefficient of circulating coolant / W·(m²·C⁻¹) | Screw outer surface 37.4 |
| | Nut outer surface 9.7 |
| | Bearing seat outer surface 9.7 |
| | Inner wall of coolant channel 357 |
4.2.2 Structural temperature discussions of precision ball screw unit (theoretical model verification of active coolant control strategy)

The accurate simulated structural temperature rises of precision ball screw unit obtained above are compared with screw coolant temperature rises detected by RTD sensors. As illustrated in Fig. 11, this comparison is for both the active coolant control strategy and ambient temperature tracking strategy: The structural temperatures of precision ball screw unit are very close to those of coolants, which proves the reliability of the theoretical model proposed in Sect. 2.2.1 (Eq. 2).

It can be observed from Fig. 11a, b that coolant temperature is always slightly lower than the screw structural temperature. That is because the time-increasing ambient temperature and heat generations of screw-nut pair/bearings have the heating effect onto screw shaft and cause its temperature rise.
To make screw shaft temperature approach to coolant temperature, recirculating coolant has the cooling effect onto it. Owing to the intensive heat convention effect of recirculation coolant, screw shaft temperatures can be stabilized in time by real-time heat dissipations of coolant.

In addition, as shown in Fig. 11a, with the ambient temperature rising from 17 to 19 °C, the structural and coolant temperatures of precision ball screw unit remain approximately at their initial values. However, in Fig. 11b, they continue to rise following the ambient temperature rising. This fact indicates that the screw structural temperature caused by the ambient temperature tracking strategy is seriously affected by the time-variations of ambient temperature, but the active coolant control strategy is more effective in resisting thermal influence from variations of ambient temperature onto screw structural temperature.
4.2.3 Thermal elongation discussions of screw shaft (advantage verification of active coolant control strategy)

Thermal variations of positioning errors of machine feed system generated by the active coolant control strategy and the ambient temperature tracking strategy are detected by the method in Sect. 4.1.1. They can reflect the shaft thermal elongations of precision ball screw unit caused by these 2 strategies.

As illustrated in Fig. 12, thermal variations of machine positioning error caused by the active coolant control strategy are smaller than 10 μm, while that caused by ambient temperature tracking strategy continues to increase with time and is significantly greater than the former. This is attributed to the structural temperature difference of precision ball screw unit, which is conveyed by Fig. 11: Its structural temperature caused by the active coolant control strategy is more stable than that caused by the ambient temperature tracking strategy.

It can be concluded that the proposed active coolant control strategy is more advantageous than traditional one, in correcting shaft elongation of precision ball screw unit and ensuring accuracy stabilization of machine feed system.
5 Conclusions

In order to resist thermal disturbances from internal heat generations and external ambient temperature change of precision ball screw unit onto its structural thermal behaviors, an active coolant control strategy is proposed in this paper. This method controls the coolant temperature of precision ball screw unit to keep stable, thus to stabilize the screw shaft temperature and correct its thermal elongation. The conclusions of this study are as follows:

1. Compared with the traditional ambient temperature tracking method, the proposed active coolant control method is more advantageous in structural temperature stabilization and thermal elongation correction of precision ball screw unit. This is verified by comparative experiments.

2. The theoretical model for the active coolant control strategy is verified to be reliable by the experimental and simulation results: For the slender and long tubular structure of screw shaft, the screw shaft temperature is approximately equal to its recirculating coolant temperature, owing to the intensive coolant forced thermal convection onto screw shaft.

Author contribution Teng Liu proposed and described the active coolant control strategy for thermal behaviors of precision ball screw unit, based on a premise hypothesis: For the slender and long tubular structure of screw shaft, the screw shaft temperature is approximately equal to its recirculating coolant temperature. Chentao Li finished the finite element simulation modeling about thermal behaviors of precision ball screw unit, and then performed the contrasting experiments for this study. The aim is to verify the reliability of the premise hypothesis above and the advantages of the active coolant strategy. Meanwhile, he finished the handwriting of the manuscript as a whole. Yifan Zhang constructed the controlling algorithm for this study, and then finished the data analyses about experimental and simulation results. Weigu Gao gave Teng Liu the significant guidance about the thermal simulation modeling method of precision ball screw unit. Zhikai Fu finished the construction of experimental platform. Jianjun Zhang designed the logical structure of the whole manuscript. Dawei Zhang gave crucial comments onto this work for improving its technical route.

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Data availability Data generated or analyzed in this study are available.

Declarations

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Consent to participate All authors are consent to participate in the author team of this submitted manuscript.

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