Comprehensive compensation method for thermal error of vertical drilling center
Cheng Ming Kang, Chun Yu Zhao, Kuo Liu, Tie Jun Li, and Bo Yang

Abstract: To eliminate the influence of thermally induced error from a machine tool on machining accuracy, a comprehensive error compensation method for thermal displacement of the screw shaft and spindle is put forward. Based on a heat transfer mechanism and experimental analysis, a model of screw thermal expansion error is built. Modeling of spindle thermal growth that depends on speed variations is also proposed. Thermal tests for studying thermal behavior of the spindle and screw axis are carried out on the vertical drilling center TC500R. Finally, the compensation effect of the robust model is validated via experimental tests and machining. Experimental results show that thermal displacement variations are controlled within 2 μm when the compensation system is activated. The suggested model can achieve high accuracy and good applicability in different moving states. Machining results indicate that dimensional accuracy of the workpiece is significantly improved after implementation of compensation. Feasibility of the thermal error compensation system is satisfactory in applications for drilling operations.

Key words: screw shaft, spindle, comprehensive error compensation method, robust.

Résumé : Pour éliminer l’influence de l’erreur induite thermiquement de la machine-outil sur la précision de l’usinage, une méthode complète de compensation d’erreur pour le déplacement thermique de l’arbre à vis et la broche est proposée. Basé sur le mécanisme de transfert de chaleur et l’analyse expérimentale, le modèle de l’erreur de dilatation thermique de l’arbre est construit. De même, la modélisation de la croissance thermique de la broche en fonction des variations de vitesse est proposée. Ensuite, les essais thermiques pour étudier le comportement thermique de la broche et de l’axe de la vis sont effectués sur le centre de forage vertical TC500R. Enfin, l’effet de compensation du modèle robuste est validé par des essais expérimentaux et des usinages. Les résultats expérimentaux montrent que les variations de déplacement thermique sont contrôlées en moins de 2 μm lorsque le système de compensation est activé. Le modèle proposé peut atteindre une grande précision et une bonne applicabilité de différents états de mouvement. Les résultats d’usinage indiquent que la précision dimensionnelle de la pièce est nettement améliorée après la mise en œuvre de la compensation. La faisabilité du système de compensation des erreurs thermiques peut satisfaire lors de l’opération de forage. [Traduit par la Rédaction]

Mots-clés : arbre à vis, broche, méthode complète de compensation d’erreur, robuste.

1. Introduction

To supply products with fine quality and high precision, errors in the machining process should be reduced. Errors that affect accuracy of a machining tool are classified as geometric errors of machining components, errors induced by heat, and errors induced by cutting force. Among error sources, thermal errors are a major contributor, accounting for as much as 40%–70% of total errors (e.g., Bryan 1990; Ramesh et al. 2000; Mayr et al. 2012; Yang et al. 2015). Thermal errors of a machining tool vary with time and are nonlinear.

Manufacturers adopt primarily two strategies to minimize thermal errors: error avoidance and error compensation (Ni 1997; Yang 1998). The purpose of error avoidance is to reduce the thermal deformation of machining tools during the design or assembly phase, by adopting cooling systems or using symmetric structures or thermally insensitive materials (Creighton
et al. 2010). Although error avoidance can control machining tool errors to some degree, production costs increase dramatically. Hence, error avoidance is not a widely used or cost-effective method for enhancing machining accuracy. Error compensation is a “soft technique” that aims to create an opposite error to eliminate the original thermal error (Han et al. 2013). The thermal error compensation method has advantages of diverse applications and lower cost.

Of all factors contributing to thermal deformation of machining tools, thermal errors of the screw shaft and spindle play a significant role. The source of spindle thermal growth is heat generation caused by bearing rotation, motor heating, and ambient temperature variation. Similarly, friction of nut and screw, rotation friction of bearings, and the effect of ambient temperature are major sources of screw thermal expansion. The complete thermal error of machining tools is calculated from superposition of screw thermal expansion error (TEE) and spindle thermal growth error (TGE). Use of the error compensation method to eliminate these two types of thermal error is the subject of current research.

Many researchers have applied mathematical methods for thermal error modeling by directly mapping temperature data of the critical machine elements to the thermal error. These mathematical modeling techniques include artificial neural networks (Zhang and Yang 2011; Jin and Wang 2012), multiple linear regression (Pajor and Zaplata 2011; Lei and Rui 2012), gray models (e.g., Yan and Yang 2009; Zhang et al. 2012), support vector machines (e.g., Ramesh et al. 2002; Lin et al. 2009), time series models (e.g., Li et al. 2006; Shu et al. 2012), and thermal mode (Zhu et al. 2008). Wu et al. (2011) presented a method based on multivariate linear regression to implement screw axial expansion compensation. Huang et al. (2014) introduced a combined thermal error model to compensate for radial thermal drift of the spindle, integrating a genetic algorithm (GA) to optimize initial weights and thresholds of a neural network (BP). Average compensation rate is improved from 89.03% to 93.155% with the GA BP model. Yang et al. (2015) built a spindle thermal error model using a least squares support vector machine. These compensation methods obtain good results but suffer from the following problems.

1. Poor robustness. Most of these compensation methods are data-driven models, which require sufficient data to represent the input–output relationships associated with the process. The primary disadvantage of a data-driven model is that when the moving state of a machining tool in actual machining differs from that of the modeling tests, predictions are worse, especially with multiple linear regression methods.

2. Condition limitations. Many methods only function in particular conditions. For instance, the artificial neural network method has a worse prediction effect if incomplete input and output information is used. The time series method needs test data under various speeds to improve accuracy of the error model.

3. Position limitations. The machining structure has limited space to set up equipment for thermal error testing. For example, sensors cannot directly measure the temperatures of ball screws owing to the moving nut.

4. Economy and reliability. These compensation methods require numerous sensors to achieve higher prediction accuracy, which are expensive. Moreover, sensors must be protected from coolant and chips to maintain system reliability.

To develop a practical model with high accuracy and strong robustness, a novel modeling method for comprehensive thermal displacement of the screw axis and spindle is proposed in this paper. A real-time mathematical model of screw and spindle thermal deformation is established through mechanistic and thermal analysis. Then, thermal characteristic tests of the screw axis and spindle are designed and conducted on a drilling machine. Results are used to evaluate the thermal model. Finally, experimental tests and machining are performed for further verification of the effectiveness of this error modeling, measurement, and compensation method.

2. Thermal error model establish and result analysis

2.1. Combination errors of spindle and servo shaft

Figure 1 shows the comprehensive thermal displacement of the spindle and screw shaft. Thermal error of the machining tool is influenced by both TGE and TEE.
terms; when the directions of spindle TGE and screw TEE are the same, the axial thermal error of the machine tool will be aggravated. Hence, these two kinds of thermal errors should be compensated together.

The comprehensive thermal displacement is a function not only of spindle speed, but also of screw shaft position. The comprehensive thermal displacement model of the spindle and screw shaft can be depicted as

$$E_{\text{sup}}(z,S) = E_{\text{screw}} + E_{\text{cfe}}$$

The modeling process for thermal displacement of the screw shaft and the spindle is introduced in Sections 2.2 and 2.3, respectively.

$$V(T) = \left[ \frac{z_1 - z_0}{\Delta T} + \frac{z_2 - z_1}{\Delta T} + \cdots + \frac{z_i - z_{i-1}}{\Delta T} + \cdots + \frac{z_N - z_{N-1}}{\Delta T} \right] / K$$

The feed frequency can be written as

$$C(T) = \frac{K}{N}$$

**Figure 2** shows that the positioning errors of the screw shaft obey a stable exponential decrease during cool-down phase. An exponential model can be obtained to describe contraction of a screw due to heat dissipation.

$$Q_r(T) = k \left[ \xi_{\text{screw}}(T-1) \right]^h$$

As the ball screw experiences natural cooling, only friction heat is dissipated to the open air, which results in screw shrinkage (as shown in Fig. 3). Through the eq. (2) transition, the thermal characteristic of the screw shaft during the free cooling process is

$$\xi_{\text{screw}}(T) = \xi_{\text{screw}}(t_0) - \left[ Q_r(t_1) + Q_r(t_2) + \cdots + Q_r(t_j) \right]$$

**2.2. Modeling of screw axis**

In general, sources of heat generation induce thermal deformation of the ball screw system, which influences the positioning precision of a machining tool. The thermal deformation of the screw axis is related to the energy that heats it. Heat generation caused by friction is dependent upon feed rate and leads to thermal extension of the screw (Li et al. 2014). The stroke range of a screw is short and its movement intermittent during actual machining. Feed frequency is used in real-time thermal extension determination. At the same time, part of the produced heat flows out the screw via natural convection, which causes the screw to contract. The thermal expansion error model is formulated as

$$\xi_{\text{screw}}(T) = \xi_{\text{screw}}(T-1) + Q_r(T) - Q_r(T)$$

From **Fig. 2**, it is not difficult to see that a screw displacement variation trend is in keeping with the law of the natural exponential function. An exponential growth model is defined to describe the thermal expansion of a screw by using the average feed speed and feed frequency.

$$Q_r(T) = \lambda \left[ z_i V(T) \right]^\tau [C(T)]^r$$

When the nut moves along its whole stroke, the average feed rate and feed frequency is determined by the positional change of the Z-axis. The average feed rate is calculated by eq. (4).

$$E_{\text{cfe}}(T) = \lambda \xi_{\text{screw}}(T)$$

where $t_j (j = 1, 2, \cdots, m)$ is the data collection time during the screw experiment.

**Figure 2** presents the screw thermal error variation under different positions of the Z-axis; it is not only related to the mean feed rate and feed frequency but also affected by the axis position. Therefore, an exponential model with respect to the axis position is employed to describe the positional displacement of a screw.
match the two values is through the least squares of the differences between them. The optimization algorithm is written in MATLAB software, and optimum objective function is defined as

$$\min[F(\lambda, \kappa, r, s, h, \tau)] = \sum_{u=1}^{U} \sum_{v=1}^{V} \left(E_{fe}(u, T) - E_{cfe}(u, T)\right)^2$$

where $E_{fe}(u, T)$ denotes the experimental data of the $u$th test point at the $v$th test and $E_{cfe}(u, T)$ denotes the estimated error of the $u$th test point at the $v$th test.

Figure 4 presents the comparison of measured and simulated values of thermal deformation of the screw shaft. The fitting curve matches measured errors well during warm-up and cooldown phases. Therefore, the accuracy of the exponential model makes it suitable for use in practical applications.

2.3. Modeling of spindle

Thermal error induced by the spindle is composed of radial thermal drift error and axial thermal growth error. In this paper, we assume that the spindle is rigid and does not bend, so the radial thermal error of the spindle can be ignored. Figure 5 shows the thermal characteristics of the spindle depend on spindle speed. Because of this, the thermal growth model of the spindle considers the spindle speed as an input variable.
The expression for thermal growth of the spindle during the heating process is described by eq. (10).

\[
\delta_{\text{spindle}}(T) = \delta_{\text{spindle}}(T - 1) + Q_{\text{spindle}}(T) - q_{\text{spindle}}(T)
\]

To eliminate the effect of variation with time in the spindle speed, the mean speed could be calculated as

\[
S(T) = \frac{S_1}{N} + \frac{S_2}{N} + \cdots + \frac{S_i}{N} \quad i = 1, 2, \ldots, N
\]

When the spindle is rotated, heat generation at representative portions causes the spindle to thermally deform. The results from the thermal characterization tests of the spindle at the various rotation speeds are used to develop a spindle thermal extension that is exponential in nature, as in eq. (12) and similar to one proposed in Kim et al. (2004).

\[
Q_{\text{spindle}}(T) = \alpha[S(T)]^n
\]

During the machining process, heat transfers from the spindle into the ambient air. The contraction of the spindle due to heat dissipation is calculated as

\[
q_{\text{spindle}}(T) = \eta(\delta_{\text{spindle}}(T - 1))^f
\]

The spindle is warmed until interrupted to cool freely. No more heat flows into spindle, and the residual friction heat is gradually dissipated into the ambient surroundings. According to eq. (10), the thermal distortion model of a spindle when cooled is

\[
\delta_{\text{spindle}}(T) = \delta_{\text{spindle}}(t_k) - \left( \delta_{\text{spindle}}(t_1) + \delta_{\text{spindle}}(t_2) + \cdots + \delta_{\text{spindle}}(t_k) \right)
\]

where \( t_k \) is cool time and \( t_k = n\Delta t \) (\( k = 1, 2, \ldots, n \)).

The relative positional deviation between the spindle and workpiece is induced by thermal deformation of the spindle, which can be determined by measured screw data. Therefore, spindle thermal growth could be measured as screw position displacement. The thermal growth of a spindle related to axis location and thermal characteristics is represented by eq. (15).

\[
E_{\text{cse}}(T) = Z^2 \delta_{\text{spindle}}(T)
\]

The necessary parameters are identified by minimizing the differences between the test curve data and the estimated values of the model curve. The optimum objective function can be obtained as

\[
\min[F(a,\eta,w,e,r)] = \sum_{T=t}^{K} (E_{\text{tse}}(T) - E_{\text{cse}}(T))^2
\]

where \( E_{\text{tse}} \) is the tested thermal error.

Figure 6 presents the modeling results for spindle thermal growth under various rotating speeds. The predicted values from the error model agree well with experimental values during machining tool operation.

3. Testing procedure

To investigate thermal deformation of the spindle and ball screw shaft, experiments were carried on a vertical drilling center TC500R. The spindle is driven by belt and spindle speeds up to 20000 r/min. The feed drive system chosen is half-closed-loop control and the maximum feed rate is 48 m/min. The up end of the ball screw is fixed, and the down end is supporting. The control system of the machining tool uses FANUC i-Mate.

3.1. Screw axis test

The thermally induced positioning error of the ball screw is tested using a laser interferometer XL80 manufactured by Renishaw Company, UK. The parameter “expansion compensation of material” in the Renishaw software is set as 20 °C to cancel the ambient temperature compensation function of the software. The real-time position of the Z-axis is collected by the computer, with Visual C++ used to develop the FOCUS program, at a sampling interval of 50 ms.

To study thermal change in active length of the ball screw, the reference origin of the machine is set to be the starting point for this measurement and positioning errors are measured every 70 mm in the entire stroke. The test procedure is as follows.

1. Let the Z-axis move up 150 mm as the commanded position for this measurement.
2. Move the Z-axis in the stroke range of 0–280 mm for 10 min at the feed rate of 10000 mm/min.
3. Stop moving and test the positioning error of the Z-axis.
4. Repeat steps (2) and (3) four times.
5. Let the Z-axis stop at the 10 mm position for free cooling. The positioning error is measured four times at intervals of 10 min.

Figure 3 shows the test results for the Z-axis. The position displacement of the ball screw at all the test points varies with time, and the positioning error curves change little in shape.

Error tests are conducted for \( z = 50 \) mm in the same manner.

3.2. Spindle test

The thermal growth of the spindle is tested using a spindle error analyzer CPL290 manufactured by Lion Precision Corporation, USA. The displacement sensors are fixed on the worktable and aimed at the precision ball motion, as shown in Fig. 7. A computer with Visual C++ used to develop the FOCUS program is utilized to collect the real-time rotating speed at a sampling period of 50 ms.

The spindle thermal characteristics are assessed at speeds of 500 and 1500 r/min. In each test, the spindle rotates at a preset speed for 2.5 h and then remains stopped for 3.5 h. The sample period for spindle thermal error is set at 10 s. Results are plotted in Fig. 5. Higher rotating speed is associated with higher thermal growth. In contrast, it could be observed from the error diagram that error values appear to be positive first, which is interpreted as the test bar moving downwards. As heat generation and heat dissipation reach thermal equilibrium, the increase of the spindle elongation slows down. When the spindle is suspended, it starts to shrink by giving off its heat.

4. Compensation strategy and verification

4.1. Compensation strategy

Here we validate the effect of the thermal compensation with the XL80 laser interferometer. For this, the real-time spindle speed and screw position need be read from the computer numerical control (CNC) through the Ethernet cable, and the real-time compensation values need be input to the Z-axis of the vertical drilling center. The external mechanical coordinate offset (EMCO) is used to write the offset values for the FANUC 0i-Mate CNC (FANUC 2003). The schematic diagram of real-time thermal error compensation is given in Fig. 8.

The thermal error compensation system is developed based on EMCO, which is made up of hardware and software platforms. The hardware platform is composed of the error acquisition unit and the thermal compensator. The software platform implements the modeling, data acquisition, CNC communication, and real-time thermal error compensation. The software interface for real-time thermal error compensation is shown in Fig. 9.

4.2. Experimental verification

To verify the effectiveness of the modeling for comprehensive thermal growth of the ball screw shaft and spindle, compensation experiments are performed on the TC500R. Figure 10 is a photograph of the experimental device, showing the spectroscope installed at the end of the worktable and the reflector mounted on the spindle. The laser interferometer XL80 records the relative error of spindle and worktable in the \( z \)-direction.

The procedure for experimental tests is (1) record the tool position to a set axis position at this measurement; (2) let the Z-axis and spindle move according to the path listed in Table 1; and (3) stop and measure the positioning error of the Z-axis every 10 min before and after compensation.

The experimental results are shown in Fig. 11, where “N” is the error before compensation and “Y” is the residual error after compensation.
Figure 11 shows that comprehensive thermally induced errors of the ball screw and spindle after compensation are greatly decreased, from more than 25 μm to 2 μm or less, which demonstrates that the predicted accuracy of the presented model is high. Note that the residual errors with compensation are very small, even when the motion information changes according to the parameters listed in Table 1. Thus, the strong robustness of the comprehensive error model is demonstrated.

4.3. Machining verification

Machining with and without compensation is conducted to validate the feasibility of the compensation system. Several test specimens with and without compensation are milled the upper surface of a rectangular plate, as shown in Fig. 12. The rectangular workpiece is steel and its size is 150 mm × 115 mm × 30 mm. The machining procedure is as follows.

1. Let a φ140 disc milling cutter mill the upper surface to guarantee side surface finish and flatness, as shown in Fig. 13a.
2. Mill Hole 1 with a milling depth of 5 μm using a φ12 disc 4-edge milling cutter. Open compensator and drill Hole 2 with the same depth as Hole 1.
3. Move the worktable to the left side. Let the Z-axis and spindle run according to the path presented in Fig. 14. One hole is drilled without compensation; the other hole is drilled with compensation.
4. Repeat step 3 three times until holes 5–10 are machined.
5. Warm up stop and move the worktable 25 mm along the Y-direction. Drill Hole 11 to 15 mm depth without compensation. Open compensator and

Table 1. Parameters of compensation test.

<table>
<thead>
<tr>
<th>State</th>
<th>Time (min)</th>
<th>Servo axis Speed (mm/min)</th>
<th>Range (mm)</th>
<th>Spindle Speed (r/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>State 1</td>
<td>10</td>
<td>5000</td>
<td>10–290</td>
<td>1000</td>
</tr>
<tr>
<td>State 2</td>
<td>10</td>
<td>6500</td>
<td>50–290</td>
<td>1500</td>
</tr>
<tr>
<td>State 3</td>
<td>10</td>
<td>5000</td>
<td>60–270</td>
<td>2000</td>
</tr>
<tr>
<td>State 4</td>
<td>10</td>
<td>6000</td>
<td>30–280</td>
<td>4000</td>
</tr>
<tr>
<td>State 5</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 11. Thermal error compensation results. [Colour online.]
drill Hole 12 to the right side. Drill the remaining holes in the same manner as in Fig. 14.

The workpieces machined pre- and post-compensation are shown in Fig. 13b. Figure 13b shows that the micron-scale errors in the Z-axis of a vertical drilling center are easily observed by the naked eye. Moreover, the specimens with compensation have good consistency in a ring-shaped profile. The dimensional accuracy is further examined for Holes 13–20 under machining with and without activation of the thermal error compensation system, as listed in Table 2. As is shown, the size variations of the machined holes are reduced from 10 μm (before compensation) to 2 μm (after compensation). The accuracy of workpieces is improved by more than 70%. The results verify the feasibility of this real-time compensation system for minimizing thermally induced errors in actual machining applications.

5. Conclusions

This article proposes a comprehensive compensation method for thermally induced errors of the screw axis and spindle. The compensation effects are validated by both experiment and machining. The advantages of the compensation method can be summarized as follows.

1. The comprehensive thermal error model of the ball screw and spindle established in this article can achieve a good compensation performance in terms of robustness and accuracy.
2. The comprehensive thermal errors of the ball screw and spindle are offset together. Experimental results reveal that stable accuracy of the proposed model can be achieved even if movement of the machine tool changes irregularly. Machining results reveal the dimensional accuracy is decreased from 10 μm to 2 μm under the activated compensation system. Feasibility of the thermal
Error compensation system is satisfactory in applications for drilling operations.

3. The comprehensive compensation method is cost-effective because it only uses a displacement sensor to function.

4. The test efficiency for thermal errors of the ball screw and spindle is high, as first-transition displacements can be predicted for the ball screw and spindle.

Therefore, the compensation method can be widely applied to CNC machining tools in workshops with no temperature controls.

Acknowledgements

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### List of Symbols

- $C$: average moving frequency
- $E_{cse}$: spindle position displacement value
- $E_{cfe}$: ball screw position displacement value
- $h$: coefficient of exponential model about heat dissipation
- $K$: number of data with moving speed at sampling time
- $N$: total number of screw position at sampling time
- $Q_e$: ball screw displacement caused by heat generation
- $Q_r$: ball screw displacement caused by heat dissipation
- $Q_{spindle}$: spindle displacement due to heat generation
- $q_{spindle}$: spindle displacement due to heat dissipation
- $r, s$: coefficient of exponential model for heat production
- $S_i$: spindle rotation speed
- $T$: time
- $V$: average moving speed
- $w$: coefficient of exponential model for heat generation
- $z_i$: current position of screw axis
- $\Delta T$: sampling time for measured data
- $\alpha$: heat generation coefficient of spindle
- $\delta_{spindle}(T)$: spindle thermal growth model curve
- $\delta_{spindle}(t_0)$: spindle initial error in cooldown phase
- $\varepsilon$: coefficient of exponential model for heat dissipation
- $\zeta_{screw}(T)$: ball screw thermal expansion model curve
- $\zeta_{screw}(t_0)$: screw initial error in cooldown phase
- $\eta$: heat dissipation coefficient of spindle
- $\kappa$: heat dissipation coefficient of screw
- $\lambda$: heat production coefficient of screw