Research Article

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Thermally stimulated artificial muscles: Bio-inspired approach to reduce thermal deformation of ball screws based on inner-embedded CFRP

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Abstract: Ball screws are the indispensable machine tool components and, as such, influence the positional accuracy of machine tools. The accuracy stability of machine tools is affected by thermal deformation of ball screws resulting from the increase in temperature. Inspired by the distinctive artificial muscle heat behavior, a bio-inspired ball screw was proposed. The proposed ball screw was based on the inner-embedded carbon fiber-reinforced plastic (CFRP), which restrains the axial expansion through the thermal contraction of CFRP. Additionally, a thermal conductor was mounted between the screw shaft and CFRP to improve the thermal conduction condition. Furthermore, both the simulation analysis and comparative experiments were carried out to compare the bio-inspired ball screw with the standard one. Two working conditions were considered to evaluate the effectiveness of the novel design, primarily in terms of reducing thermal deformation. Both results show that the proposed approach is effective and can be applied to reduce the thermal deformation of ball screws.

Keywords: ball screw, CFRP, artificial muscles, contraction, thermal deformation

1 Introduction

Ball screws are known for their high efficiency, good stiffness, and long lifetime. As such, they are widely used when there is a need to transform rotation into linear motion, for example, in machine tool feed drives. However, ball screws are sensitive to temperature changes, which cause deformations in the axial direction. Said deformations are generating a thermal error in motion drive systems, reducing their positional accuracy. Li et al. [1] analyzed thermal characteristic of ball screw feed drive system based on finite difference method considering the moving heat source. Liu et al. [2] proposed an optimization method for determining thermal boundary conditions to improve the simulation accuracy of the traditional transient thermal characteristics analysis model of the ball screw feed drive system. Shi et al. [3] conducted theoretical modeling and experimental study on thermal error of ball screws along with heat generation characteristics. After analyzing all the factors, it was found that thermal error is responsible for approximately 30 to 50% of total machine tool errors, while the value is up to 70% in precision machining [4]. Thus, studying thermal errors in ball screw systems has an important role in reducing the thermal deformation and thus improving the machining accuracy, especially in high-speed machine tools. To mitigate the problem at hand, inspired by thermally stimulated artificial muscles, a novel ball screw design based on inner-embedded CFRP was designed and presented in this paper. Thermally conductive material was mounted between the screw and CFRP to improve their heat transfer performance. The effectiveness of the design was validated using both finite element analysis and experiments. A schematic representation of the design is shown in Graphical abstract.

Thermal error compensation is an effective method to address the thermal deformation issue in machine tools, and an accurate and robust thermal error modeling is necessary for the implementation of error compensation [5]. Guo et al. [6] predicted thermal deformation of ball

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screws by finite element analysis, which is an effective method in the prediction domain. Xie et al. [7] carried out a finite element analysis on simplified composite sandwich panel to compare with the experimental results. The finite element results showed a good agreement with the experimental results in predicting the load displacement curve. Li et al. [8] proposed a new inverse random model to predict thermal error, while considering the randomness of influencing factors. This model combined the stochastic theory, genetic algorithm, and radial basis function neural network. Shi et al. [9] explored the relationship between thermal error and axial deformation by carrying out several experiments on the machine tool. They established the theoretical model of thermal error by employing fuzzy clustering and linear regression methods to predict thermally induced errors in the ball screw feed drive system. Furthermore, Li et al. [10] proposed a real-time prediction method for thermal errors in screw systems under various operating conditions; an adaptive moving thermal network model was used. Zhang et al. [11] developed a position error prediction model for ball screws based on the mounting conditions and validated its error compensation effectiveness. Yang et al. [12] employed Elman neural networks to conduct the thermal error modeling considering complex operating condition of the high-precision feed system. Ye et al. [13] proposed a thermal error regression modeling method for determining the thermal deformation coefficient of the moving shaft of a machine tool.

All of the above-presented studies yielded practical methods for thermal error modeling and prediction of its influence on the ball screw feeding system. Furthermore, thermal deformation compensation was proven to be effective in mitigating the ball screw thermal deformation. Xu et al. [14] studied component heat generation, compensation method, thermal model, mathematic model, and calculation method. As a result, the authors proposed a ball screw thermal error compensation system without the temperature or positioning feedback. Zapłata and Pajor [15] presented a method for compensation of thermal errors based on the partial differential equation (PDE) model of ball screw temperature distribution. Li et al. [16] used an exponential algorithm to predict the thermal variation of the ball screw; they developed a real-time compensation system to be used in machine tools. Ma et al. [17] proposed a thermal error analytical modeling method, and the effectiveness of thermal error prediction and compensation is verified. In all of the above-referenced studies, a model with high accuracy and robustness is required; however, it is difficult to hold the thermal error model robustness under complex working conditions.

For this reason, methods for reducing thermal deformation are studied by many researchers. Xu et al. [18] proposed an air-cooling ball screw system to reduce the thermal deformation of ball screws and the effectiveness was also validated. Further, they studied the methods for reducing thermal deformation of ball screws by including liquid cooling to control the increase in temperature [19]. However, those systems were complicated and lacked reliability. Several studies on reducing thermal deformation by using special materials were also carried out. One such material is CFRP, which has a high elastic modulus and strength and is insensitive to changes in temperature [20]. Nakonieczny et al. [21] reviewed that the carbon fibers have the main property of easy shape formation which allows obtaining even very complicated shapes and makes the application of carbon fibers attractive. Ge et al. [22] designed a new type of high-speed motorized spindle with CFRP to reduce thermal deformation, and the experimental and numerical results have shown that the decrease reached 97% compared to the structure without CFRP. Further, they also used the CFRP in the machine tool part to reduce the thermal deformation of machine tool. The thermal deformation of machine tool could be reduced by 93% [23]. Moreover, Gao et al. [24] designed a novel ball screw based on CFRP to improve accuracy; however, the resulting design is difficult to apply in machine tools due to the large size at the two ends. Additionally, the good heat transfer performance between the screw and CFRP cannot be guaranteed. Thus, a more suitable ball screw design is necessary to reduce the thermal deformation.

In performance improvement design, nature does always give plenty of inspiration and bionics has inspired and created many inventions with great performance. Lee et al. [25] designed a three-dimensional cactus stem-inspired water harvesting system with directional transport of absorbed fog. This bio-inspired design could aid in developing effective three-dimensional plant-inspired fog collectors. Dash and Prabahara [26] summarized nano resistive memory devices and their applications and presented battery-like cells as artificial synapse in brain-inspired computing. In this paper, an artificial muscle reaction was studied when stimulated by heat. Using its unique performance as a guide, the thermal behavior of the ball screw was improved by combining the CFRP, which has a negative thermal expansion coefficient, with the screw. In this paper, the ball screw structure needed to apply an axial load on the screw was designed using CFRP. Moreover, the thermal conduction condition between the screw and the CFRP was improved by using a thermally conductive material. The proposed

bio-inspired ball screw based on inner-embedded CFRP was shown to be more successful in reducing thermal deformation.

2 Ball screw design based on inner-embedded CFRP

In this study, the biomimetic approach was adopted after the investigation of artificial muscle functional principles and characteristics. The unique characteristics were then applied to reduce the thermal deformation of ball screws, resulting in a novel bio-inspired ball screw design based on inner-embedded CFRP.

2.1 Characteristic of the artificial muscle

Artificial muscles – materials that change size or shape when exposed to a stimulus – are attractive for applications in robotics, sensors, and control technologies. Their primary advantages are large force and motion while remaining compact and lightweight [27]. There are various driving methods for artificial muscle fibers. Based on the structure characteristics, composition, and properties of the fiber driving material, the artificial muscle fibers can be driven by several stimuli including temperature difference, adsorption/infiltration of solvent or vapor, electrochemical double-layer charge injection, and air pressure [28].

Hashim et al. [29] presented that the carbon nanotube has excellent mechanical properties with elastic modulus 1 TPa, tensile strength 150 GPa, and low thermal expansion coefficient. Therefore, it can be used as an artificial muscle material. Lima et al. [30] described a hybrid carbon nanotube yarn muscle (Figure 1) with great strength and movement speed, which was actuated by heating. Heating resulted in a phase transition and volume expansion of the guest material (Paraffin waxes), changing the yarn length. The geometric model of the described artificial muscle is a helical structure, enabling

Figure 1: A schematic of carbon nanotube yarn muscle contraction.

both torsional rotation and tensile contraction. When the artificial muscle is exposed to heat, wax confined to the nanosized pores of a multiwall nanotube yarn expands, driving a yarn volume increase that contracts its length. The combination of the volume increase with the length decrease is produced by the twisted, helical nature of the yarn formed by twist-spinning the nanotubes together [31].

The artificial muscle in Figure 1 has negative thermal expansion property. Inspired by this artificial muscle, the length of which decreases stimulated by heat, this unique characteristic was adopted for two reasons. The first is to reduce the thermal deformation of ball screws, and second, to improve the positional accuracy stability of machine tool further. Therefore, the CFRP was selected to reduce the thermal deformation of ball screws due to its special characteristics, which include excellent specific strength and rigidity, low weight [32], and negative thermal expansion coefficient. In theory, the positive thermal expansion of the steel can be reduced or even negated completely by the negative thermal expansion of the CFRP. Thus, it can be applied to design a new type of ball screw, aiming to reduce thermal deformation.

2.2 Design of bio-inspired ball screws

Simionescu et al. [33] presented that carbon-based composites and structures have good and stable conductivity and favorable chemistry and structure, which make the

Figure 2: Structure of ball screw based on inner-embedded CFRP.

Figure 3: Schematic diagram of thermal contraction mechanism in bio-inspired ball screw.

carbon fibers represent one of the most pursued paths. CFRP, a type of advanced material, has been widely applied in various fields to meet the increasing demand for structural materials. Newcomb [34] described the carbon fiber as a unique material with a wide range of thermophysical properties that can be tailored to the desired application. Thus, a novel ball screw based on inner-embedded CFRP with a negative thermal expansion coefficient was designed (see Figure 2). The proposed novel ball screw is made of steel, thermally conductive phase change material, and CFRP. The fiber direction is consistent with the axial direction of the ball screw; therefore, the axial force is applied as the steel expands in the axial direction. To improve the heat transfer at the interface between screw and CFRP, thermally conductive phase change material with a heat transfer coefficient of $5 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ was mounted in-between. More heat can be transferred to CFRP effectively by using the thermally conductive material. The filler in the ball screw center is a composite material with a low elastic modulus, used to support the CFRP and reduce the CFRP bending

Table 1: Ball screw parameters

Parameters	Value
Nominal diameter (d_o)	32 mm
Length (l)	1,220 mm
Material	GCr15

deformation. The thermal contraction mechanism of the novel ball screw is shown in Figure 3. When the steel temperature rises, the standard ball screw shaft expands in the axial direction until the thermal balance is reached. However, the ball screw designed in this paper reacts differently; when stimulated by the heat, the heat is transferred from the steel to the CFRP rapidly through the thermally conductive phase change material. Due to the specific CFRP thermal characteristics, the ball screw is contracted, reducing the thermal deformation.

3 Thermal deformation analysis using FEM

A range of properties can be predicted in modeling and simulation using a variety of analysis methods. Lau *et al.* [35] reviewed the molecular dynamics simulations on nano-engineering of construction materials including fiber-reinforced polymers. The challenges were also provided. Alhijazi *et al.* [36] presented a review on finite element analysis of natural fibers composites and indicated that finite element method (FEM) is a powerful method to study the property of materials. Therefore, to verify the effectiveness of the ball screw based on inner-embedded CFRP, simulation analysis of the thermal deformation

Figure 4: FE model of ball screw based on inner-embedded CFRP: (a) isometric view and (b) orthographic view.

Table 2: Thermal parameters of ball screws under different rotational speeds

Rotational speed (rpm)	Nut heat generation (W)	Heat transfer coefficient ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)	Fixed bearing heat generation (W)	Support bearing heat generation (W)
1,100	18.16	34.80	3.93	3.68
1,400	23.12	40.87	5.87	5.49

was carried out. Both ball screw models (inner-embedded CFRP and the standard) were established and analyzed using the FEM, and the results were compared.

3.1 FE model of ball screws

To save time and reduce calculation costs, the screw geometry was simplified as a shaft. Based on a certain type of ball screw (Table 1), models of ball screws based on inner-embedded CFRP and the standard ball screw were established, as illustrated in Figure 4. Three materials were defined as solid elements in the FE model. Ball

screws were approximated as a typical thermodynamic system, and the heat transfer coefficient was determined according to ref. [37]; and heat generation of bearings was referred from ref. [38]; and heat generation of nut was referred from ref. [39]; and the material properties of ball screws were referred from ref. [40]. In the ball screw feed driving system, the bearings and nuts are generally identified as the main heat sources, primarily due to friction between the moving components. Jian et al. [41] presented bio-inspired design, analysis, and optimization, motivated by insights from nature, which generally require high computational expense. To accelerate the analysis process, some measures should be taken. The

Figure 5: Simulation results of two types of ball screw at 1,100 rpm; temperature distribution of the bio-inspired (a), and standard ball screw (b); thermal deformation of the bio-inspired (c), and standard ball screw (d).

Figure 6: Simulation results of two types of ball screw at 1,400 rpm; temperature distribution of the bio-inspired (a), and standard ball screw (b); thermal deformation of the bio-inspired (c), and standard ball screw (d).

sequential coupling method was adopted to determine the thermal deformation of both ball screw types using thermal-structure coupling analysis [42].

The ambient temperature was selected as the initial simulation temperature, along with the rotational speeds of 1,100 and 1,400 rpm. The thermal parameters of ball screws are shown in Table 2 and were used to define the boundary conditions and heat loads of both types of ball screw. Thermal deformation results of the standard ball screw and the bio-inspired were obtained and compared at two rotational speeds using FEM.

3.2 FE model results

After establishing the finite element model and determining thermal parameters, the reciprocating cycle heat source was applied to simulate the nut-generated heat flow movement. Temperature distribution and thermal deformation were calculated at the rotational speeds of

1,100 and 1,400 rpm, respectively, using thermal-structure coupling analysis. The results for the two types of ball screws were compared and shown in Figures 5 and 6.

Based on the analysis results, it was concluded that increases in temperature and thermal deformation are correlated with the increase in rotational speed, which is consistent with ref. [43]. The maximum temperature of both FE models has not much difference under each of the working conditions. However, the thermal deformation of the bio-inspired design was 17.8 and 17.9% lower at 1,100 and 1,400 rpm, respectively. It indicates from the simulation that the thermal performance of bio-inspired design is better than the standard one.

4 Experiment study

Experiments were carried out using electric heating simulation to compare the standard ball screw and ball screw

Figure 7: Experimental setup: (a) ball screw based on inner-embedded CFRP; (b) standard ball screw; (c) experimental data visualization interface.

based on the inner-embedded CFRP. The aim was to investigate the CFRP effectiveness in terms of reducing thermal deformation. To reduce both the costs and time, a simplified experimental ball screw model with the CFRP mounted inside and thread groove ignored [44] was designed and manufactured. Simultaneously, a shaft with the same size was manufactured to enable the comparison.

4.1 Experimental procedure

To validate the effectiveness of this method, both ball screws tests were carried out on the self-designed test bench, which allowed for collection and comparison of both the temperature and thermal deformation results (see Figure 7). Heating sheets were installed on the shaft surface to simulate frictional heat resulting from the nut

Figure 8: Arrangement of sensors and heating sheets.

Table 3: Experimental instrument properties

Type	Product description	Accuracy
Heating sheets	XH-RJ101012, Xinghe, Suqian, China	None
DC power supply	HY1711-5S, Yaguang, Huaian, China	None
Temperature sensors	KYW-TC, Kunlunyuanyang, Beijing, China	$\pm 0.05^{\circ}\text{C}$
Temperature inspection instrument	Kunlunyuanyang, Beijing, China	$\pm 0.05\%$ F.S
Eddy current displacement sensor	ML33-01-00-03, Milang, Shenzhen, China	$0.05\text{ }\mu\text{m}$
Displacement inspection instrument	XSAE-CHVB1M2V0, Milang, Shenzhen, China	$\pm 0.05\%$ F.S

and bearing. Heating sheets were powered by the DC power supply. The temperature was measured at three points located on the screw shaft surface using three temperature sensors (Figure 8). The thermal deformation was measured using the eddy current displacement sensor

at the end of the shaft. The properties of all the instruments are shown in Table 3.

Experiments on both the proposed and standard ball screw were carried out using identical operating conditions, which allowed for the comparison of temperature

Figure 9: Comparison of temperature rise at various points for the 22 V supply voltage: (a) point T1; (b) point T2; (c) point T3.

and deformation. Both the temperature data and thermal deformation information were collected continuously and visualized by the LABVIEW software.

Two voltages, 22 and 25 V, were used as the heating sheet inputs. Next, experiments were carried out at the ambient temperature, which was also monitored. Once the thermal deformation changed less than $2\mu\text{m}$ during five minutes, it was considered that the system has reached thermal balance.

4.2 Experimental results

The temperature increases at measurement points and the resulting thermal deformations under two operating conditions are shown in Figures 9–11. As shown in Figures 9 and 10, the maximum temperature errors between two types of ball screws are below 10% at the

supply voltages of 22 and 25 V. It is concluded that there is not much difference between the two types of ball screw in terms of temperature rise.

Figure 11 compares the thermal deformations of the two types of ball screw. The thermal deformation of the ball screw with inner-embedded CFRP has decreased by 25.71% (at 22 V) and 21.14% (at 25 V) compared to its standard counterpart, which means the thermal performance of the ball screw is improved.

It is evident that the ball screw based on inner-embedded CFRP reduces thermal deformation without affecting temperature rise. Thus, it can be concluded that thermal characteristics and positional accuracy stability of ball screws can be improved by employing this bio-inspired design. This proposed method can be also applied to reduce the thermal deformation of other components of machine tools (see Figure 12), such as spindles, frames of machine tools, and so on.

(a)

(b)

(c)

Figure 10: Comparison of temperature rise at various points for the 25 V supply voltage: (a) point T1; (b) point T2; (c) point T3.

Figure 11: Thermal deformation comparison under various supply voltages: (a) 22 V; (b) 25 V.

Figure 12: Potential application of the proposed research: (a) simplified ball screw based on inner-embedded CFRP; (b) spindle housing with CFRP [22]; (c) rectangular structure in machine tool with CFRP [23].

5 Conclusion

In this paper, a novel ball screw design was proposed aiming to reduce thermal deformation. The proposed design based on inner-embedded CFRP was inspired by a thermally stimulated artificial muscle. Thermally conductive material was installed between the screw and CFRP to improve their heat transfer performance. Simulation

analysis and comparative experiments were carried out. It was concluded that the ball screw based on inner-embedded CFRP has a promising performance in reducing thermal deformation. Therefore, the effectiveness of this method was validated both theoretically and experimentally.

In the future, the ball screw structure based on inner-embedded CFRP will be realized considering its practical

engineering standards. The authors aim to validate the effectiveness of this design in engineering practice.

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