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REGULAR PAPER

Thermal–Mechanical Coupling Analysis and Experimental Study on CNC Machine Tool Feed Mechanism

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Abstract
As the CNC machine tool feed mechanism is affected by joint action of heat and load during the working process, thermal–mechanical coupling analysis and experimental research on CNC machine tool feed mechanism are conducted. On the basis of exploring the thermal–mechanical coupling effect of CNC machine tool feed mechanism, a thermal–mechanical coupling dynamic analysis method is proposed through combining multi-step finite element simulation with temperature field experiment. According to the proposed method, the transient and steady-state simulation analysis on CNC machine tool feed mechanism are conducted and conclusions obtained are as follows, before the whole feed mechanism reaches thermal balance state, the thermal–mechanical coupling effect makes the deformation of the feed mechanism increase with the temperature rising. The correctness of the proposed thermal–mechanical coupling dynamic analysis method was verified by the contrastive analysis of the experiments. Therefore, in the process of CNC machine tool feed mechanism's analysis and design, the influence of thermal–mechanical coupling effect on dynamic performance should be considered.

Keywords CNC machine tool · Feed mechanism · Temperature field · Thermal–mechanical coupling

1 Introduction

With the booming development of modern manufacturing industries, the increasing demand for processing various complicated parts and components promotes the rapid development of the CNC machine tool. Feed mechanism is an important part of CNC machine tool, and its dynamic performance is the focus and difficulty of the research in the field of machine tool design, which has great influence on the machining accuracy of machine tool. During the working process of the CNC machine tool, the thermal–mechanical coupling effect is generated in the feed mechanism under the action of heat and load, which will affect deformation and dynamic performance of the feed mechanism. Therefore, the research on analytical technique of thermal–mechanical coupling of feed mechanism plays an important role in improving machining accuracy and work stability of CNC machine tool and improving the level of the advanced manufacturing technology.

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The analysis of dynamic performance and the optimal design of feed mechanism of the machine tool are based on its dynamic model. Therefore, many scholars pay more attention to the modeling methods of the feed mechanism. Younkin [1] applied the CAD/CAE simulation technology to establish a numerical simulation model of the machine tool feed mechanism to analyze and predict the dynamic performance of the feed mechanism. Altintas et al. [2] carried out the dynamics analysis of the transmission and guide mechanisms of feed mechanism of a machine tool and realized the connection between two mechanisms and the dynamic performance of the feed mechanism, furthermore, he established a dynamic analysis model of the feed mechanism with the finite element method and advised a multi-body dynamics modeling analysis on feed mechanism in the further research. Tounsi et al. [3] proposed a dynamic modeling method based on time series for the feed mechanism of CNC machine tool and the precision of this model was verified by experiments, and this model is applied to predict acceleration response characteristics in working process. Based on the above analysis, it is necessary to study further how to improve the dynamic characteristics of the system through optimization of structural parameters. Zaeh et al. [4] analyzed the dynamic performance of the machine tool feed mechanism and established a model of feed mechanism with the finite element method, which provided a basis for the design optimization of feed mechanism.

Nowadays, the design and manufacturing technology of machine tool has a trend toward high speed, high efficiency and high precision [5], the problem of thermal deformation becomes more and more serious [6]. Moreover, the rapid development of computing and testing technology promotes the further theoretical research on the thermal deformation of machine tool feed mechanism. Liu et al. [7] proposed a new robust modeling method based on the heat transfer theory, and the procedure of the thermal tests for a feed drive system was presented. Horejš [8] established a numerical simulation model of the thermal characteristics of a feed mechanism with consideration of the influence of unsteady heat sources through the finite element analysis of the ball screw of feed mechanism and verified the accuracy of the model by experiments. Gomez-Acedo et al. [9] took a CNC machine tool as the research object, and he found that the temperature rise in Z axis and X axis of the feed mechanism is an important factor that influences the thermal deformation of the CNC machine tool through the thermal characteristic analysis of simulation and experiment. Lee et al. [10] analyzed the influence laws of friction coefficient of the sliding guide of the machine tool feed mechanism on the thermal deformation with the finite element method and provided a theoretical basis for realizing rapid movement for the guide of feed mechanism. Wu and Kung [11] took a machine tool feed mechanism as the research object and analyzed its heat source distribution, and the finite element model established by him can be applied to predict the thermal characteristics of the feed mechanism.

The existing research methods are usually studied respectively for the mechanical performance and thermal performance of the feed mechanism, accordingly, the previous analysis of the dynamic performance of the feed mechanism is not comprehensive enough, therefore, it is difficult to further improve the comprehensive performance of the feed mechanism and study profoundly the effect of thermal–mechanical coupling on dynamic characteristics of feed mechanism. In order to solve the above problems, this paper deeply studies the thermal–mechanical coupling mechanism of the feed mechanism of CNC machine tool and systematically analyzes the dynamic performance and its variation laws under the influence of thermal–mechanical coupling effect during the operation process of CNC machine tool feed mechanism. A thermal–mechanical coupling dynamic analysis method is proposed through multi-time finite element simulation in this paper. The transient and steady-state simulation of thermal–mechanical coupling is carried out by taking the feed mechanism of the CNC machine tool as an example. The correctness of the proposed thermal–mechanical coupling dynamic analysis method was verified by the contrastive analysis of the thermal–mechanical coupling experiments.

2 Thermal–Mechanical Coupling Dynamic Analysis Method of Feed Mechanism

The dynamic performance analysis of the thermal–mechanical coupling of the CNC machine tool feed mechanism is involved in multidisciplinary research. During the working process of the feed mechanism, the structural field generated by load is coupled with the temperature field generated by heat, which will affect the mechanical properties of the feed mechanism and further influence its dynamic characteristics.

In the process of feed movement of the CNC machine tool feed mechanism, there exists generation and transmission of heat in its servo motor, screw support bearings, screw–nut drive mechanism. If heat can not be emitted in time, it will lead to continuous temperature rise in moving parts such as lead screw or nut of feed mechanism. As a result, the vibration resistance of feed mechanism will be lowered and the dynamic characteristics will be aggravated [12], accordingly, it is difficult to guarantee the normal operation of feed mechanism. Excessive temperature rise can also cause thermal–mechanical coupling deformation of the structure [13] so that the transmission accuracy and dynamic performance of feed mechanism will be reduced and the machining accuracy of machine tool will be affected.

During the working process of feed mechanism of CNC machine tool, the heating of various heat sources leads to the change of temperature field in the internal structure of feed mechanism. Some of mechanical properties parameters of material will vary as the temperature of feed mechanism rises. In addition, thermal–mechanical coupling stress and deformation in the internal structure caused by cutting loads will affect the dynamic performance of the feed mechanism structure and further affect the dynamic characteristic amplitude. With the consideration of the influence of thermal–mechanical coupling on the dynamic performance of the feed mechanism, the following factors must be analyzed: (1) the effect of temperature rise on the mechanical properties of the feed mechanism; (2) the effect of thermal–mechanical coupling stress and deformation of feed mechanism structure on dynamic characteristics.

It is seen that the dynamic performance of the CNC machine tool feed mechanism is related to the change of structure and temperature load under the effect of thermal–mechanical coupling. Therefore, it is necessary to analyze the temperature field first in the dynamic analysis of the thermal–mechanical coupling of the CNC machine tool feed mechanism. Figure 1 shows the flow of dynamic analysis of the CNC machine tool feed mechanism.

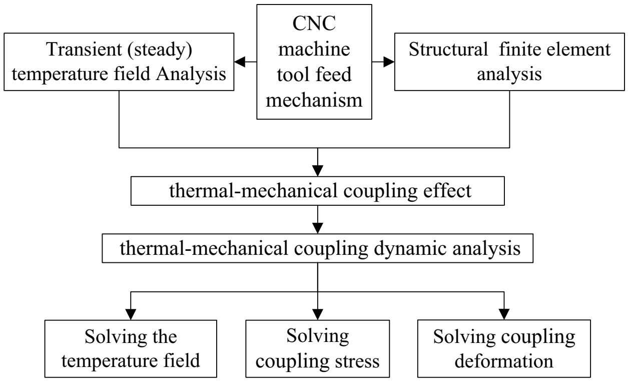


Fig. 1 Dynamic analysis process of feed mechanism

When CNC machine feed mechanism works, it is affected by both heat and load. The uneven heating of each part causes the feed mechanism to form a temperature field. The temperature rise generated by heat makes internal structure expand, which causes the generation of thermal stress of CNC machine tool feed mechanism. The thermal stress interacts with the mechanical stress, which causes the generation of thermal–mechanical coupling stress of the feed mechanism. The change of temperature field of CNC machine tool feed mechanism also generates thermal strain inside the feed mechanism structure. The thermal strain interacts with the mechanical strain of to generate thermal–mechanical coupling strain, which causes the generation of thermal–mechanical coupling deformation of the feed mechanism. As shown in Fig. 1, Firstly, the simulation model of the CNC machine feed mechanism is established. Secondly, the structural finite element analysis and thermal analysis on the CNC machine feed mechanism are performed separately. Thirdly, the thermal–mechanical coupling effect and mechanism of the CNC machine feed mechanism are explored. Fourthly, the thermal–mechanical coupling dynamic analysis is performed to solve temperature field, thermal–mechanical coupling stress and thermal–mechanical coupling deformation of the CNC machine feed mechanism.

The transient temperature field of feed mechanism structure of the CNC machine tool can be solved by the combination of the thermal transient boundary conditions and the initial temperature field with the consideration of the thermal properties parameters (thermal expansion coefficient, thermal conductivity, specific heat capacity) of the material. Then the thermal–mechanical coupling stress of the structure can be solved by taking the obtained transient temperature field at some moment as the thermal load with the consideration of the mechanical properties of the material (Elastic modulus and Poisson's ratio). Finally, the dynamic performance parameters of thermal–mechanical coupling of the CNC machine tool feed mechanism can be solved by taking thermal–mechanical coupling stress as prestress with the consideration of mechanical properties (such as density, elastic modulus and Poisson's ratio) of the material.

The dynamic characteristics are always generated along with heating during the working process of the CNC machine tool feed mechanism in the cutting state [14]. Based on the above discussion of the thermal–mechanical coupling mechanism, the dynamic performance parameters of the feed mechanism are related to the variation of the temperature field because the change of temperature field of the CNC machine tool feed mechanism will bring the change of structural field which also affects the dynamic characteristics of the feed mechanism structure. In reverse, the dynamic characteristics of the feed mechanism structure will also have little impact on the temperature field. Therefore, this paper focuses on the dynamic characteristics of the thermal–mechanical coupling and mainly considers the influence due to change of temperature field on the dynamic characteristics of the feed mechanism. The feed mechanism of CNC machine tool in this paper has a complex structure of carriage and ball screw drive mechanism, and it is quite complicated to analyze the dynamic characteristics of thermal–mechanical coupling with the only theoretical method. Therefore, more intuitively, the finite element analysis method is applied here to solve dynamic performance parameters with the combination of computer numerical simulation technology.

Based on the above thermal–mechanical coupling mechanism of the CNC machine tool feed mechanism, the dynamic characteristics of thermal–mechanical coupling in this paper is unidirectional according to the interaction between the dynamic characteristics and temperature field because the structure field has little impact on the temperature field [15]. The transient thermal analysis is carried out before temperature field reaches steady state during the working process of CNC machine tool feed mechanism. As for the dynamic characteristics analysis, since the variation laws over time of exterior excitation are unpredictable, therefore, this paper mainly focuses on the thermal–mechanical coupling analysis of the CNC machine tool feed mechanism.

Based on the above theoretical analysis, as for the thermal–mechanical coupling relationship in the working process of CNC machine tool feed mechanism, it is enough to simply consider the unidirectional coupling from the temperature field to the structure field. The dynamic analysis method of thermal–mechanical coupling of feed mechanism is that the temperature load of each node is output after transient analysis of the temperature field has been completed in each time step and then is loaded into the node of the feed mechanism structure. The change of temperature field of CNC machine tool feed mechanism also affects the strain of structure and generates, temperature load which will affect the dynamic performance of the feed mechanism structure [16]. The dynamics analysis in each time step belongs to the thermal–mechanical coupling analysis. However, it is involved in a series of independent dynamic characteristics analysis with different temperature field, and there is no coupling effect between each pair of steps.

The transient thermal–mechanical coupling of the CNC machine tool feed mechanism is a systematic process in which each step should follow the clear sequence. The simulation model of thermal–mechanical coupling is used for dynamic characteristic analysis in each step. The result of the dynamic characteristics analysis of the thermal–mechanical coupling is also variable because the model of each transient step is related to the temperature load and acceleration. As for the thermal–mechanical coupling effect of the CNC machine tool feed mechanism in this paper, its coupling is generated when the temperature field affects the structure field with temperature load serving as the carrier. Then, a transient analysis should be carried out for the temperature field of feed mechanism, and several relatively independent thermal–mechanical coupling analysis should be carried out for the structure field. The steady state analysis should be carried out for the temperature field of feed mechanism after the CNC machine tool feed mechanism reaches the stage of thermal steady state. In sum, the main task is to study the influence of the thermal–mechanical coupling effect on the dynamic performance of the structure.

3 Thermal–Mechanical Coupling Simulation Modeling and Analysis of Feed Mechanism

This paper takes the Y-axis feed mechanism of a CNC machine tool as the research object under the action of thermal–mechanical coupling effect during the working process. The CNC machine tool is shown in Fig. 2, and the *Y*-axis feed mechanism is shown in Fig. 3. Based on the above theoretical basis and analysis method, we carry out simulation

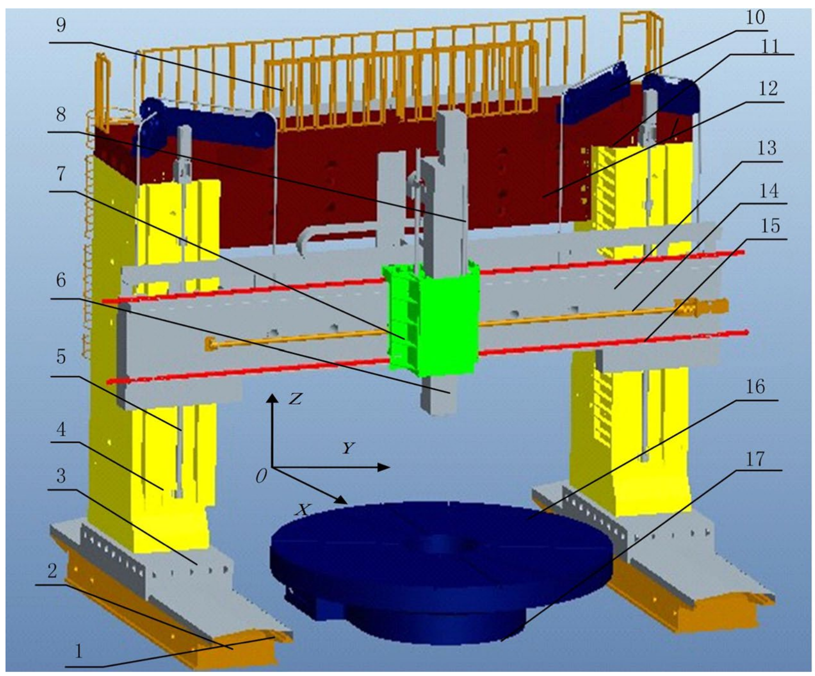


Fig. 2 CNC machine tool

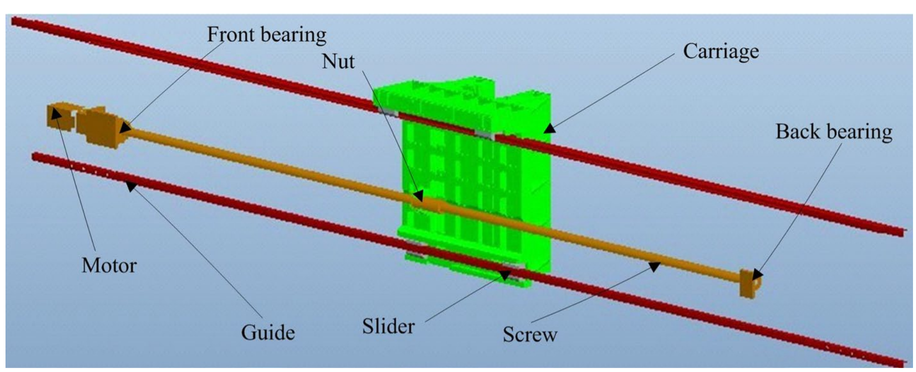


Fig. 3 *Y*-axis feed mechanism

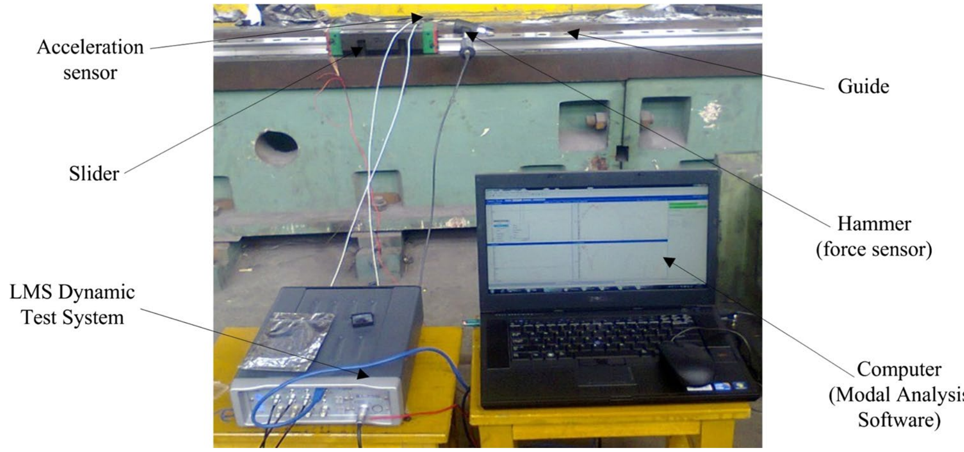


Fig. 4 Dynamic experimental site of guide mechanism

modeling of the dynamic characteristics analysis and the temperature field analysis of feed mechanism and do experiments on the physical prototype of feed mechanism. The obtained boundary conditions and parameters can be used to improve the simulation model further, and then another simulation model can be obtained for the thermal–mechanical coupling analysis. Based on the established simulation model, the transient analysis and steady state analysis of the feed mechanism of CNC machine tool are respectively carried out to study the connection between thermal–mechanical coupling effect and dynamic performance.

3.1 Thermal–Mechanical Coupling Simulation Modeling of Feed Mechanism

Three-dimensional parametric design software Pro/E is applied here to establish the geometric model of carriage, bearing, bearing seat and screw nut pairs and complete the virtual assembly of CNC machine tool feed mechanism structure. The miniature features of the model should be properly simplified to improve the efficiency of the analysis [17]. The model is converted to IGES format first and then is imported into the finite element analysis software ANSYS for meshing, and then the simulation model of the feed mechanism can be obtained by setting the material properties, constraints and boundary conditions.

1. The type of selected element: the Solid70 element is used for both the carriage and the ball screw drive. This type of element is a hexahedral element with 8 nodes and each node has degrees of freedom of temperature, which is suitable for 3D transient or steady-state thermal analysis of structure.
2. The modeling of the joint: the parameters of guide–slider joint and screw–nut joint have a great influence on the dynamic characteristics of the feed mechanism. The spring-damping element of ANSYS software-Combin14 is used to simulate during the process of simulation modeling. The parameters of guide–slider joint are obtained by dynamic experimental analysis. The experimental site is shown in Fig. 4, and the data obtained from the experiment is analyzed and computed to get the parameters shown in Table 1. The model of spring-damping is shown in Fig. 5. Ball screw–nut pair has a great influence on the transmission accuracy of the feed mechanism, and it is not suitable for dynamic experiments to obtain the parameters of the joint. The equivalent contact stiffness of screw–nut pairs is 2×10^{8} N/m and the equivalent contact damping is 1157 Ns/m, which is calculated by referring to the machine design data.
3. To set the boundary conditions: The front and rear ends of the bearing base and the rolling guide are fixed with

Table 1 Guide–slider joint parameters

Direction	Contact stiffness (N/m)	Contact damping (Ns/m)
Normal	5.05×10^{8}	1829
Tangential	1.45×10^{8}	836

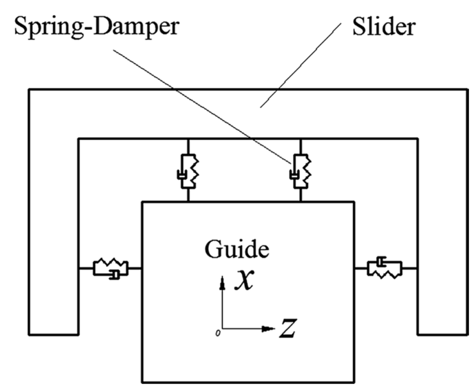


Fig. 5 Spring-damper

constraints on the beam of CNC machine tool in the finite element simulation model of the CNC machine tool feed mechanism. As the bearing seat and the beam are contacted fixedly through the bolt, the temperature of the contact position should be set as the environment temperature. The feed mechanism is in contact with the air in a closed laboratory, so the convection coefficient of the outer surface of the carriage, ball screw shaft, nut and bearing is set as the convection coefficient between iron and still air [18], which is defined as 20 W/(m^2 K) in feed mechanism's simulation model.

4. To set material properties: to set the elastic modulus, Poisson's Ratio, and density for the finite element simulation model of the feed mechanism. The material parameters of each part of the feed mechanism are shown in Table 2.
5. To set the heat sources: the main heat sources [19, 20] of the CNC machine tool feed mechanism are as follows: (1) the generation of heat of motor, (2) the generation of heat by friction between bearings and ball screw, (3) the generation of heat by friction between the ball screw and the nut, (4) the generation of heat by friction between rolling guide and the slider, (5) the friction heat generated by the square ram motioning. As shown in Fig. 6, there are five main heat sources in the CNC machine tool feed mechanism, which are marked respectively as follows: $H_1(t)$, $H_2(t)$, $H_3(t)$, H_4 (t) and $H_5(t)$.

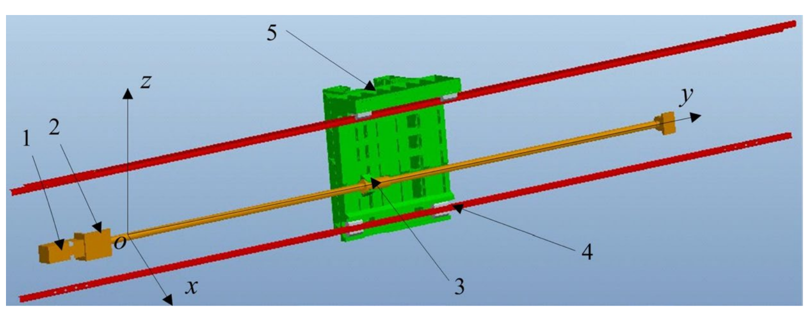
The specific heat, heat transfer coefficient and density of the feed mechanism are set according to Table 3. The material of the carriage is HT300. The ball screw and nut are made of GCr15. During the thermal–mechanical coupling simulation modeling stage of the feed mechanism, the values of thermal property are set according to the material parameters firstly. Simulation and experiment on CNC machine tool feed mechanism are carried out in the laboratory synchronously. The simulation results are compared with the experimental results repeatedly, so the reasons of errors are found out, and then the values of thermal property of thermal–mechanical coupling simulation model of the feed mechanism are corrected opportunely.

6. To divide the model grid: with the application of intelligent meshing function of ANSYS software and manual intervention [21], the precision of the grid is controlled according to the complexity of the 3-D model of the feed mechanism for the simulation analysis. Timoshenko Beam Elements [22] are used to simulate ball screws and rolling guides. The solid elements are used to simulate the carriage, slider, nut, bearing and bearing seat.

Table 2 Material properties of the feed mechanism

Parts	Material	Density (kg/m^3)	Modulus of elasticity (25 °C) (GPa)	Poisson's ratio (25 °C)
Carriage	HT300	7300	143	0.27
Screw–nut pair	GCr15	7830	219	0.3
Guide–slider pair	GCr15	7830	219	0.3
Bearing	SUJ2	7810	212	0.29
Bearing seat, end cover	HT250	7300	130	0.27
Internal septum, inner frame of seal ring	45# steel	7850	206	0.3
Clamping sets, spring seal ring	65Mn	7800	206	0.29
Coupling	Titanium alloy	4500	105	0.34
Seal ring	Silicon rubber	1100	0.006	0.48

Fig. 6 Distribution of heat source in the feed mechanism



1- heat source $H_1(t)$, 2- heat source $H_2(t)$, 3- heat source $H_3(t)$, 4- heat source $H_4(t)$, 5- heat source $H_5(t)$

Table 3 Material thermal parameters of feed mechanism

Parts	Material	Thermal expansion coefficient (20–200 °C) (/K)	Specific heat (25 °C) [J/(kg K)]	Thermal conductivity (25 °C) [W/(m °C)]
Carriage	HT300	1.12×10^{-5}	510	45
Screw–nut pair	GCr15	1.2×10^{-5}	460	44
Guide–slider pair	GCr15	1.2×10^{-5}	460	44
Bearing	SUJ2	1.18×10^{-5}	552.66	37
Bearing seat, end cover	HT250	0.92×10^{-5}	543	56
Internal septum, inner frame of seal ring	45# steel	0.91×10^{-5}	461	53
Clamping Sets, spring seal ring	65Mn	1.11×10^{-5}	474	42
Coupling	Titanium alloy	0.8×10^{-5}	544	16
Seal ring	Silicon rubber	1.85×10^{-5}	1285	0.25

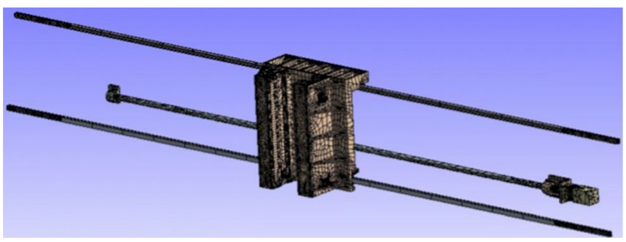


Fig. 7 Finite element simulation model of feed mechanism

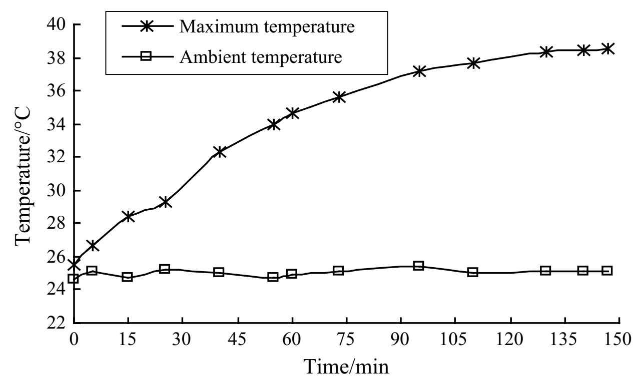


Fig. 8 The change course of temperature rise of feed mechanism

The CNC machine tool feed mechanism's parts are modeled in according to the actual size accurately, and the material thermal parameters are set in according to Tables 2 and 3. The guide–slider joint parameters are set in according to Table 1. The constraint form of the CNC machine tool feed mechanism's model is set in according to the actual situation. The finite element mesh model of thermal–mechanical coupling of the feed mechanism of CNC Machine Tool is obtained as shown in Fig. 7 after the completion of the meshing and pre-treatment of the finite element analysis. The whole model has 141,959 elements, 271,630 nodes and 24 Combin14 springs.

3.2 Transient Analysis of Thermal–Mechanical Coupling in Feed Mechanism

The transient analysis of the time step is defined as 5 min in the transient analysis of thermal–mechanical coupling of CNC machine tool feed mechanism. The relationship between temperature and time is shown in Fig. 8 in this process.

The external load is 5000 N in the simulation analysis of transient thermal–mechanical coupling of the CNC machine tool feed mechanism. The acceleration and thermal load of the trailing plate of the CNC machine tool feed mechanism are shown in Table 4 in each step of transient thermal–mechanical coupling. In order to comprehensively explore the influence of thermal–mechanical coupling effect on the dynamic characteristics of feed mechanism, four time nodes are selected which are shown in Table 5 for transient analysis of thermal–mechanical coupling. During the transient analysis, the thermal–mechanical coupling deformation of the CNC machine tool feed mechanism is shown in Figs. 9, 10, 11 and 12. After completing the transient thermal–mechanical coupling analysis, the vibration amplitude analysis result of the CNC machine feed mechanism obtained is shown in Fig. 13.

Although Figs. 9, 10, 11 and 12 are quite similar, the maximum thermal–mechanical coupling deformation of each Figure is very different from each other. The maximum thermal–mechanical coupling deformations of Figs. 9, 10, 11 and 12 are 0.025284 mm, 0.026874 mm, 0.028906 mm and 0.030756 mm respectively, which increase gradually. The entire thermal–mechanical coupling simulation time of the CNC machine feed mechanism is 150 min. During the thermal–mechanical coupling simulation analysis process of the feed mechanism, the rotational speed of the lead screw is continuously increased, and the heat generation

Table 4 Thermal–mechanical coupling parameters

Time step	Time	Acceleration (m/s^2)	Load caused by temperature rise (N)
0	0	58.97	0
1	5	51.36	32.6
2	10	−485	69
3	15	38.29	95.7
4	20	−30.12	127.8
5	25	243	159.6
6	30	−17.58	180.2
7	35	141	215
8	40	−12.74	250.7
9	45	11.35	281.1
10	50	−10.29	319
11	55	9.53	351.3
12	60	−8.67	382.5
13	65	7.19	411.2
14	70	−6.62	448
15	75	−5.48	475.1
16	80	56	508.2
17	85	−93	539.1
18	90	37	571.4
19	95	2.71	606
20	100	−2.01	639
21	105	1.59	655.3
22	110	−0.93	696.6
23	115	0.63	728.1
24	120	−0.48	759.4
25	125	0.34	792.1
26	130	−0.19	827.6
27	135	0.06	859.3
28	140	−0.03	891.5
29	145	0.02	922
30	150	−0.01	956.7

Table 5 The extracted time steps of thermal–mechanical coupling

Time step	4	8	16	24
Operation hours (min)	20	40	80	120
Screw speed (rpm)	300	600	900	1200

and load of the feed mechanism are becoming larger and larger, which further leads to the thermal–mechanical coupling effect more and more significant. The gradual significant thermal–mechanical coupling effect makes the thermal–mechanical coupling deformation of the CNC machine feed mechanism larger and larger.

In summary, during the thermal–mechanical coupling transient phase of the feed mechanism, the

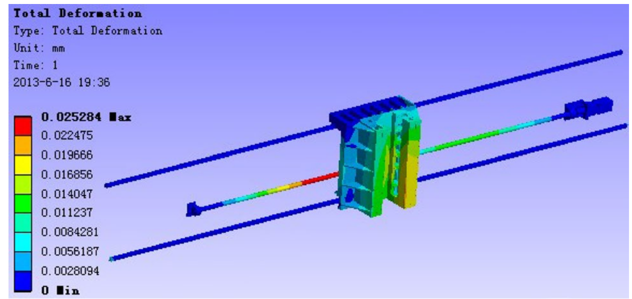


Fig. 9 Deformation of the feed mechanism in step 4

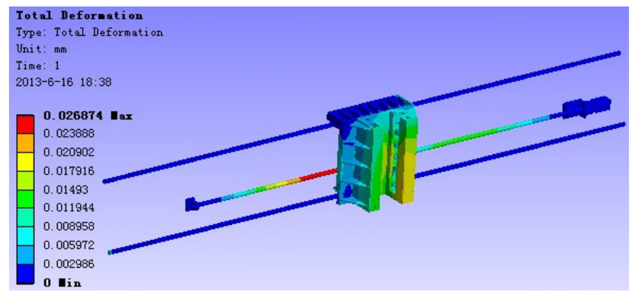


Fig. 10 Deformation of the feed mechanism in step 8

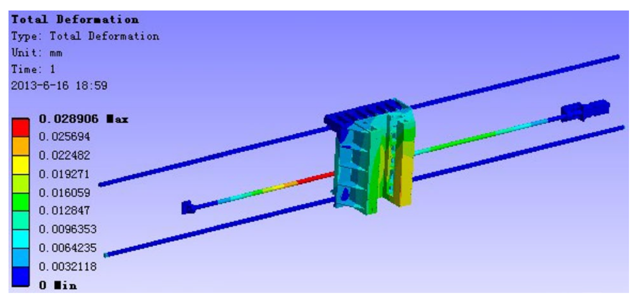


Fig. 11 Deformation of the feed mechanism in step 16

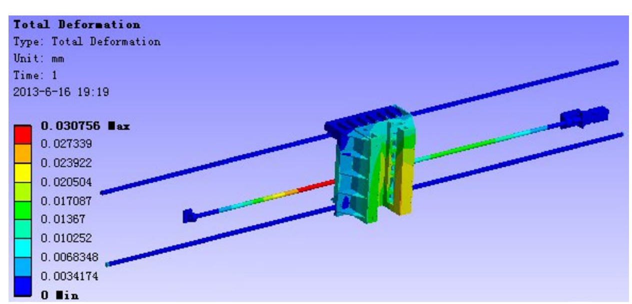


Fig. 12 Deformation of the feed mechanism in step 24

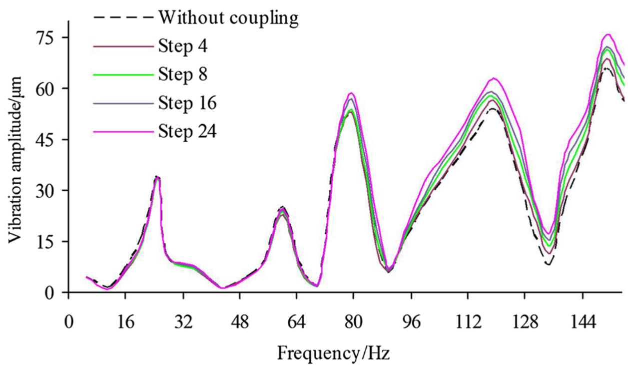


Fig. 13 Comparison of vibration amplitude results

thermal–mechanical coupling effect causes a dynamic change in the deformation of the feed mechanism and leads in maximum deformation gradual increase.

As can be seen from Fig. 8, during the operation of CNC machine tool, the temperature inside the feed mechanism continues to rise with the extension of time, but the amplitude of the rise is reduced. The temperature field of the feed mechanism tends to be in a state of thermal equilibrium.

It is known from Figs. 9, 10, 11 and 12 that temperature rise and load will increase with the revolving speed of ball screw accelerated along with the time which strengthens the thermal–mechanical coupling effect and worsens the deformation of feed mechanism continuously. This is because the heat source of the feed mechanism is mainly from the cutting heat transmitted by the square ram-spindle system and the heat generated by the rotation of the ball screw–nut joint. Before the whole feed mechanism reaches the heat balance, the temperature of feed mechanism rises continuously and the impact of thermal–mechanical coupling effect becomes larger. This shows that the influence of thermal–mechanical coupling effect on dynamic characteristics should be considered in the process of optimal design of CNC machine tool feed mechanism.

The analysis on Fig. 13 and Table 5 shows that the change rules of vibration amplitude of the CNC machine tool feed mechanism are as follows: as the temperature of the feed mechanism increases, the vibration amplitude response curves rise to varying degrees; while the frequency reaches a higher frequency range, the above phenomenon is even more obvious; the maximum increase rate of the vibration amplitude of feed mechanism due to thermal–mechanical coupling can nearly reach 18%, which is compared with the condition without considering thermal–mechanical coupling effect; the vibration of the feed system is aggravated due to the thermal–mechanical coupling effect. Therefore, the thermal–mechanical coupling effect which is related to the temperature rise has impact on the dynamic characteristics of feed mechanism.

3.3 Steady State Analysis of Thermal–Mechanical Coupling in Feed Mechanism

When the thermal–mechanical coupling of feed mechanism of the gantry machine reaches steady state, the revolving speed of ball screw is 1200 rpm, and the ambient temperature is 25 °C. The dynamic analysis is respectively conducted under two different conditions-with and without consideration of the thermal–mechanical coupling effect. The distribution results of temperature field which are obtained by steady state thermal analysis are shown in Figs. 14 and 15.

We can draw the following conclusion from the analysis of steady-state simulation results of the thermal–mechanical coupling of feed mechanism of the CNC machine tool.

The dynamic characteristics of the CNC machine tool feed mechanism result in the uneven deformation of the structure and the change of temperature field of feed mechanism, which will affect the thermal deformation of the feed mechanism and the time of reaching thermal steady state.

The temperature of the CNC machine tool feed mechanism in the thermal–mechanical coupling steady state is higher than that without consideration of coupling condition. This is because the load of the structure and the rotation of the ball screw lead to the increase of the friction load and the heat from heat sources. This shows that the load and

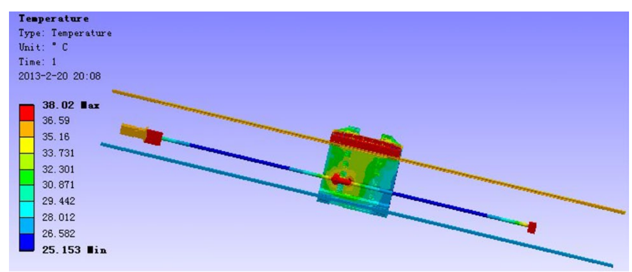


Fig. 14 Temperature field of feed mechanism with consideration of coupling condition

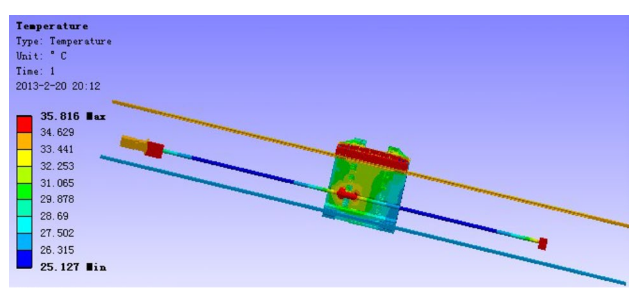


Fig. 15 Temperature field of the feed mechanism without consideration of coupling condition

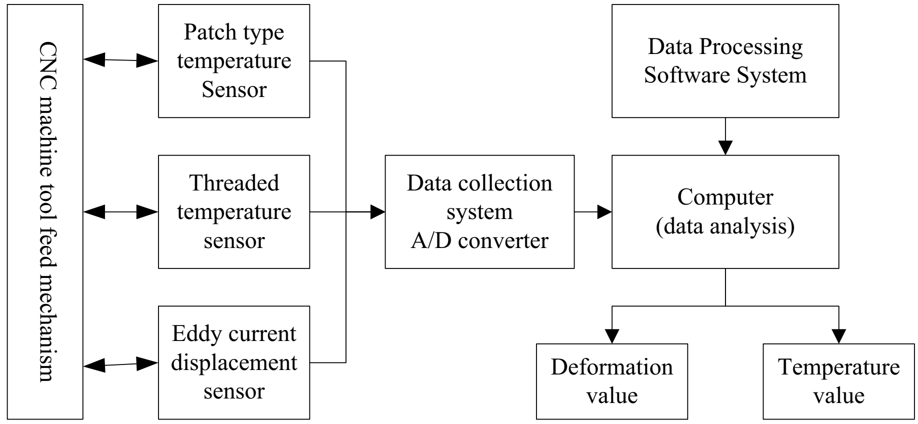


Fig. 16 Experimental test system

Table 6 Points of measuring temperature and serial numbers of sensors

Sensor location	Drive motor	Front bearing	Nut	Rear bearing	Carriage	Guide seat	Surroundings
Test point code	T1	T2	T3	T4	T5	T6	T7

heat of the feed mechanism influence each other and affect the dynamic performance of the feed mechanism together.

In sum, the thermal–mechanical coupling effect has an impact on the dynamic performance in the working process of the CNC machine tool feed mechanism. Therefore, it is necessary to carry out the multi-objective optimization design based on the thermal–mechanical coupling for the CNC machine tool feed mechanism.

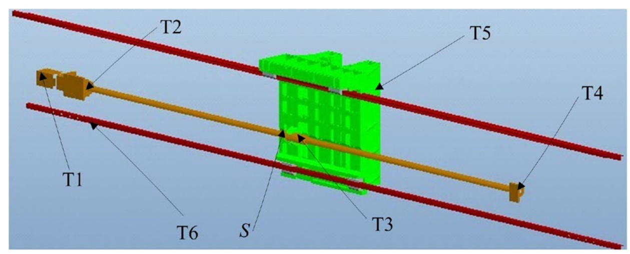


Fig. 17 Distribution of measuring points of sensors in the feed mechanism

4 Experimental Study on Thermal–Mechanical Coupling of Feed Mechanism

4.1 Experimental Purposes

The temperature distribution and the thermal–mechanical coupling deformation are analyzed according to the results from the experiments carried out under the cutting conditions of the CNC machine tool. A contrastive analysis is carried out by comparing those results and the above calculated results of the thermal–mechanical coupling simulation model, which is used for the study on the impact of thermal–mechanical coupling effect on the deformation of feed mechanism, and the verification of feasibility of the dynamic analysis method of the thermal–mechanical coupling.

4.2 Experimental Settings and Conditions

The experiment object is the feed mechanism of CNC machine tool manufactured by Wuxi Qiaolian CNC Machine Co., Ltd. The experimental test system is shown in Fig. 16. The temperature sensors are mainly installed in the position of drive motor, front bearing, rear bearing, guide seat, carriage and the joint part of nut and others parts of the feed mechanism. Besides, a temperature sensor is set to measure the environment temperature of the workshop. During the experiment, the points of measuring temperature and the sensor serial numbers are shown in Table 6, and the distribution of the sensors in the feed mechanism is shown in Fig. 17. The thermal–mechanical coupling deformation should be detected which is caused by the thermal–mechanical coupling effect generated in the experimental process of the CNC machine tool feed mechanism. Eddy current displacement sensor s is used to detect deformation and collect data. The deformation detection device is shown in Fig. 18. The temperature field detection device is shown in Fig. 19.

4.3 Experimental Methods and Processes

The load experiment can reflect the working performance of feed mechanism of the machine tool more accurately than the no-load experiment [23]. Because the feed mechanism of the machine tool receives the action of stress and heat at the same time in the load conditions, the thermal–mechanical

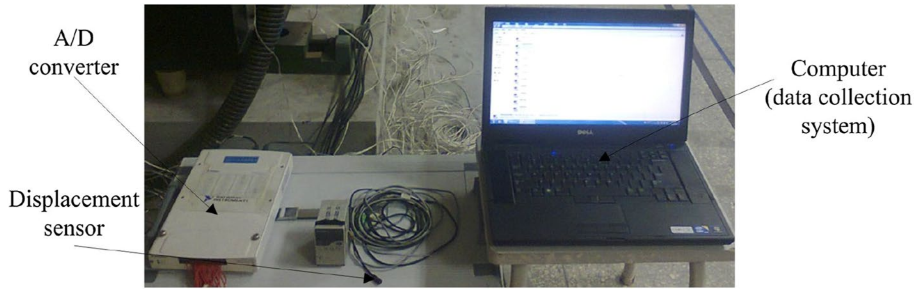


Fig. 18 Experimental device for deformation detection

Fig. 19 Multi-channel temperature detection system

coupling effect of it can be analyzed for the feed mechanism. The load conditions used in this experiment are listed as follow: The CNC machine tool is used to machine the surface of a large work piece; the test site is shown in Fig. 20. The drive motor of the feed mechanism is kept working continuously at a constant speed; The revolving speed of ball screw of feed mechanism is 1200 r/min; The front and rear bearings of the feed mechanism are all preloaded and lubricated by dilute oil; The environment temperature is kept stably at 25 °C. Under these conditions, a carbide end mill is used for the machine tool with a rake angle of 15° and a diameter of 10 mm, and the cutting parameters are shown in Table 7. During the operation of the feed mechanism, the change of temperature and the deformation of thermal–mechanical coupling can be obtained through the experimental test system. A contrastive analysis is carried out between the above results in the steady-state test and those of the FEA simulation model in order to explore the relationship between temperature field and deformation distribution.

4.4 Experimental Results and Analysis

The change course of temperature over time is shown in Fig. 21 at each measurement point of the CNC machine tool feed mechanism, and the data obtained from each test point is collated and analyzed after the completion of experiments. A contrastive analysis is carried out between the results of above experiments and the experimental results in a steady state under no-load condition with the same revolving speed of lead screw, and the maximum values of temperature of testing points at T1, T2, T3, T4 and the maximum values of deformation at *s* point can be obtained which are shown in Table 8.

It can be seen from the data in Table 8 that the temperature rise of each testing point under load conditions is larger

Table 7 Cutting parameters

Cutting parameters	Radial cutting depth (mm)	Axial depth of cut (mm)	Cutting speed (m/min)	Cutting load (N)
Value	2	0.5	230	5000

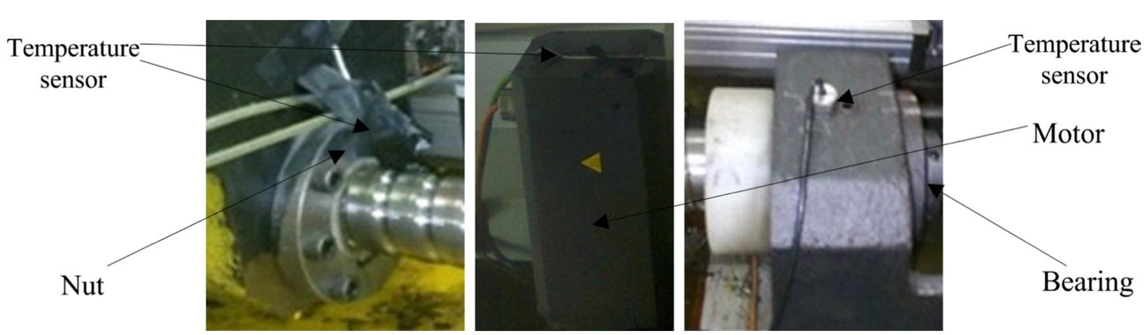


Fig. 20 Experimental test site

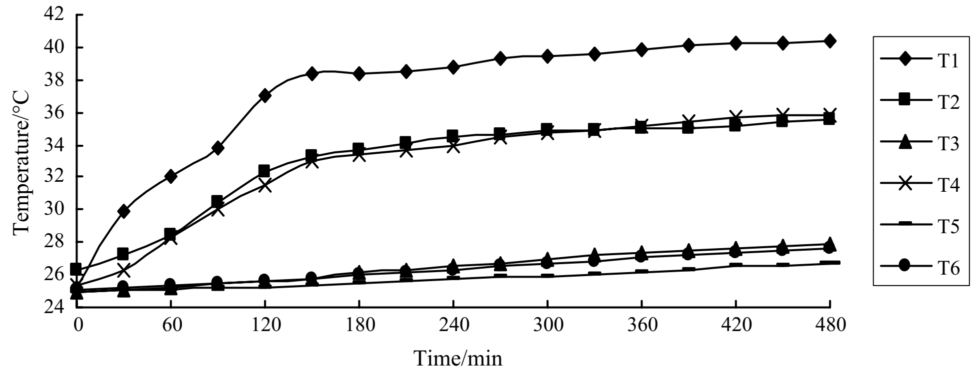


Fig. 21 Temperature change process

Table 8 Comparison of experimental results of machine tool under no-load and load conditions

Test point code	T1	T2	T3	T4	*s*
Parameter index	Temperature (°C)	Temperature (°C)	Temperature (°C)	Temperature (°C)	Deformation (μm)
Machine tool no-load	36.1	32.7	26.4	32.8	8.5
Machine tool loading	40.3	35.5	27.9	35.9	27.9

than that under no-load conditions with the same revolving speed of ball screw (1200 rpm). This is because the increase of friction at each contact point due to the loaded cutting load transmitted to the feed mechanism will result in the increase of heat and temperature rise. In addition, when the machine tool works under load conditions, its feed mechanism are influenced by stress and heat from heat sources simultaneously, the deformation of the feed mechanism caused by thermal–mechanical coupling effect is increased larger than that under no-load conditions. Therefore, when analyzing and designing the feed mechanism of CNC machine tool, we should consider not only the deformation due to stress or heat but also the influence of thermal–mechanical coupling effect on structural deformation.

Under the same working conditions as the above experiments, the thermal–mechanical coupling is analyzed and calculated according to the simulation model of the CNC machine tool feed mechanism established in the previous article, and then the corresponding data in Table 9 can be obtained when the thermal–mechanical coupling experiment lasts for 300 min.

The CNC machine tool feed mechanism's thermal–mechanical coupling state is under loaded motion conditions, but the CNC machine tool feed mechanism's state without thermal–mechanical coupling is under no-loaded motion conditions. Therefore, the experimental values with the thermal–mechanical coupling and without thermal–mechanical coupling in Table 9 are different.

It can be seen from Table 9 that the relative errors are not large between the experimental values of the temperature and deformation at each measuring point and the calculated values according to the simulation model. It is another evidence to prove that the proposed simulation model and analysis method of thermal–mechanical coupling is reasonable and feasible for the CNC machine tool feed mechanism.

Table 9 Comparison of experimental and simulation results

Sensor code	Parameter index	Thermal–mechanical coupling			Case without consideration of coupling		
		Experimental value	Calculated	Deviation (%)	Experimental value	Calculated	Deviation (%)
T1	Temperature (°C)	39.4	41.5	5.33	36.1	37.9	5.14
T2	Temperature (°C)	38	37.2	6.89	31.2	31	6.21
T3	Temperature (°C)	26.9	28.7	6.69	25.3	26.8	5.88
T4	Temperature (°C)	37	32.3	−6.9	30.8	29.1	−5.84
T5	Temperature (°C)	25.9	27.1	4.63	25.8	26.9	4.26
T6	Temperature (°C)	26.8	25.5	−4.85	26.2	29	−4.93
s	Deformation (μm)	25.9	24	−5.79	20.8	19.8	−4.81

5 Conclusion

Taking into account the influence of load and heat on CNC machine tool feed mechanism during the working process, the thermal–mechanical coupling effect and its mechanism is explored. On the basis of thermal–mechanical coupling effect, the thermal–mechanical coupling model of CNC machine tool feed mechanism is established. A thermal–mechanical coupling dynamic analysis method is proposed through combining multi-step finite element simulation with temperature field experiment. According to the method proposed, the thermal–mechanical coupling simulation analysis on CNC machine tool feed mechanism is conducted. The results obtained show that the influence of thermal–mechanical coupling effect on dynamic characteristics should be considered in the optimal design process of CNC machine tool feed mechanism.

The inherent relationship between thermal–mechanical coupling and dynamic performance of the CNC machine tool feed mechanism is analyzed in depth in this paper. A numerical simulation method is proposed to solve the dynamic problem of thermal–mechanical coupling. The influence of thermal–mechanical coupling effect on the stress and deformation of the feed mechanism is analyzed through the transient analysis and solution to the thermal–mechanical coupling, The change laws of the temperature field of the feed mechanism are explored through the steady-state analysis of the thermal–mechanical coupling when the temperature of the ball screw is increased due to its rotation. Based on above study, the measures are given to improve the dynamic performance of the feed mechanism, which can provide a theoretical basis for the multi-objective optimization design of the CNC machine tool feed mechanism.

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