Analysis and Research of Thermal Error of Numerical Control Machine Tool Spindle System and its Compensation Technology

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***Abstract* — The thermal error is one of the most important factors affecting the precision of numerical control machine tools. Spindle system, as the key part of numerical control machine tool, its thermal deformation error is one of the important factors leading to machine tool thermal deformation error. Therefore, so the precision degree of spindle system, to a great extent, decides the machining accuracy of numerical control machine tools. This paper, through using the finite element analysis method, at the same time, taking the experimental results into consideration, analyzed and designed the thermal characteristics of numerical control machine tool spindle system. Besides, it achieved real-time compensation to the thermal error of spindle system.**

Keywords - Spindle System; Optimum Temperature Measuring Points; Orthogonal Finite Element Method (fem), 840 D Secondary Development.

I. INTRODUCTION

Machine tool manufacturing industry is the foundation of national industry, and it directly affects automation level of the state industrial sector equipment, labor productivity and the realization of national defense modernization. With the rapid development of production, science and technology, machine tool is increasingly developing towards the direction of high speed, high efficiency, high precision and automation. Because of the fact that the high speed precision of numerical control machine tools, on the production, featured by high flexibility, high precision, high speed, high efficiency and high reliability, is widely applied in automobile, motorcycle, textile, instrumentation, aerospace, machinery, machine tools etc, nearly on all walks of life. Therefore its position becomes more and more important. At present, the machine tool structure's dynamic optimization design technology has already been widely used in all kinds of researches of new machine tools, yet, the Chinese machine tool industry has still been using the outdated, traditional and static design method, which make the machine tool designed perform poor with heavy structure, low speed accuracy, long design cycle and high manufacturing costs. These problems make the domestic machine tool unable to compete with foreign machine tool machine tool in high-grade level. With China's accession to the WTO, in facing of more formidable competitors the situation of Chinese machine tool manufacturing industry will become more and more serious. Therefore, Chinese machine tool manufacturing enterprises must change the old traditional design method, with advanced design and manufacturing method as technical support, to improve the design and manufacture level, and actively participate in the competition in the new market environment.

Modern manufacturing industry has higher and higher requirements on the quality of mechanical products, so it is quite important to improve the machining precision of the machine tool. Thermal error is one of the most important factors affecting the accuracy of machine tools. The external and internal heat source of machine tool would cause thermal interference to machine tool leading to thermal deformation in machine tool, finally result in thermal error. The machine tool errors include mainly the geometric error, thermal error and cutting force error, among which, the thermal error accounts for 40% to 70% of the total machine tool error. Thermal error greatly impact on the dimensional precision of high precision mechanical products, which will further affect the product processing quality, production efficiency and cost. With the development of manufacturing technology, geometric error of machine tool has been well solved. Therefore, the thermal error becomes the most main factor affecting the machining accuracy of machine tool, which is also the most difficult problem to be solved. A large number of studies have shown that the thermal deformation error of the spindle system is an important factor leading to machine tool thermal deformation error, therefore, the analysis and design of thermal characteristics of spindle system is very important for the accuracy guarantee of numerical control machine tool, besides, it is also one of the key technologies the high speed and high precision machine tools must take into consideration.

II. THE FINITE UNIT METHOD AGAINST TEMPERATURE FIELD PROBLEM

A. Heat Conduction Differential Equation of Temperature Field

Temperature field refers to the temperature distribution of the object at certain point, the general equation is $T = f(x, y, z, \tau)$, which means the temperature T on certain point of the object. It will change with the change of its space location (x, y, z) and time $dxdydz$. To study the temperature field, the first thing to do is find a differential equation to describe the above equation. In the research of rectangular coordinate system, the infinitesimal body in heat-conduct-internal solid object body presents transient thermal balance. In order to reduce the complexity of the problem, here, we only talk about solid and static fluids assuming that the object is continuous and homogeneous. Assume that $dxdydz$ is an infinitesimal body extracted from object, and the three sides of the infinitesimal body parallel to the x, y, z axis, as shown in figure 1.

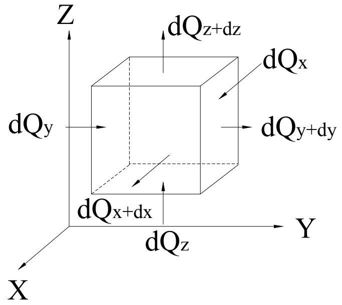

Figure 1. Infinitesimal body's thermal conductivity

Based on the law of energy's conservation and transformation, we analyze the heat balance in infinitesimal body. Assume that during the period $T_a = T(\Gamma, t)$, the net heat in infinitesimal body is $T_a = T(\Gamma, t)$, and the calorific value of inner heat source is $T_a = T(\Gamma, t)$, and the increment of thermodynamics in the body is $T_a = T(\Gamma, t)$, then we can get the following equation:

$T_a = T(\Gamma, t)$ (1)

During the time period $T_a = T(\Gamma, t)$, the heat for import passed by surface x is

$T_a = T(\Gamma, t)$ (2)

The surface heat passed by the surface $T_a = T(\Gamma, t)$ is

$T_a = T(\Gamma, t)$ (3)

In the x direction, the imported and exported net heat is

$T_a = T(\Gamma, t)$ (4)

Similarly, in the y and z directions, the net heat of infinitesimal body is

$T_a = T(\Gamma, t)$ (5)

$T_a = T(\Gamma, t)$ (6)

The imported net heat of three directions is

$T_a = T(\Gamma, t)$ (7)

In the above equation, $T_a = T(\Gamma, t)$, $T_a = T(\Gamma, t)$ and $T_a = T(\Gamma, t)$ are the heat flux vectors respectively in the x，y and z direction. According to Fourier's law, put equation (6) into equation (1), we can get

$T_a = T(\Gamma, t)$ (8)

During the time period $T_a = T(\Gamma, t)$， the calorific value of infinitesimal body is

$T_a = T(\Gamma, t)$ (9)

In the above equation, $T_a = T(\Gamma, t)$ represents the heat (W/m3) got by per unit volume in per unit time, and during the time period $T_a = T(\Gamma, t)$, the increased thermodynamic energy in infinitesimal body is

$T_a = T(\Gamma, t)$ (10)

In the above equation, $T_a = T(\Gamma, t)$ represents the material density (kg/m3);

$T_a = T(\Gamma, t)$ represents material specific heat (J/kg, ℃).

And put equations (8), (9) and (10) into equation (4), we can get

$T_a = T(\Gamma, t)$ (11)

The equation (11) is known as the heat conduction differential equation, it represents the changes of object's temperature along with time and space.

B. The Boundary Conditions of Thermal Process

The First Kind of Boundary Condition----the Known Temperature Boundary

$T_a = T(\Gamma, t)$ （on the boundary of $T_a = T(\Gamma, t)$ ） (12a)

Each temperatures point on the boundary of the temperature field changes with the time with explicit function, when calculating the temperature field, the temperature on the boundary has already been known, which is called the first kind of boundary condition.

The Second Kind of Boundary Condition ---- the Known Heat Flux Boundary

In convective heat transfer, if the difference between the boundary temperature and environmental temperature on the surface is a known function, then the boundary condition become the known heat flux. Because the boundary heat flux is continuous, then we can get

$T_a = T(\Gamma, t)$ （on the boundary of $T_a = T(\Gamma, t)$ ） (12b)

In the equation, $T_a = T(\Gamma, t)$ represents the given heat flow on the boundary;

$T_a = T(\Gamma, t)$, $T_a = T(\Gamma, t)$ and $T_a = T(\Gamma, t)$ are the cosines in the direction outside the boundary normal.

The third kind boundary condition----the convective heat transfer boundary

There exists a convective heat transfer within the fluid having temperature differences or at the junction of fluid and solid, which is caused by the energy transfer of micro group in macro fluid motion molecules. It can be represented in equation as

$T_a = T(\Gamma, t)$ （on the boundary of $T_a = T(\Gamma, t)$ ） (13)

In the above equation, h represents the convection coefficient (W/m2, ℃);

$T_a = T(\Gamma, t)$ represents the environment temperature, if there is natural convection; or the adiabatic wall temperature of boundary layer, if there is forced convection.

The above equation shows that when there is contact between the solid surface and the fluid (such as air), through heat flow density on the solid surface, the temperature on the solid surface T is in directly proportion with the temperature of fluid T0. This is a common solid fluid boundary, which we called as the third kind boundary condition.

In the above three kinds of boundary conditions, the first kind boundary condition is forced boundary condition, the second and third boundary conditions are natural boundary conditions.

III. THE CALCULATION OF HEAT SOURCE AND CALORIFIC VALUE ABOUT MACHINE TOOL SPINDLE SYSTEM

A. The Heat Source of Machine Tool Spindle System

The machine tool is affected by a variety of heat sources in the process of work. The heat quantity generated by the heat source passes to the machine tool by many kinds of different ways to make the machine tool get thermal deformation.

First of all, the prime motor. In the process of implementing energy conversion, due to internal friction and other factors it leads to energy loss and converts into heat. The energy dissipation parts from electric motors, pumps and other mechanical power source in the process of work convert into heat energy. The heat quantity generated by them delivers to the machine tool through the transmission parts, pressure oil, and so on.

Secondly, the moving parts. Bearing, gear pair, guide pair, clutch and so on will generate heat in the process of movement because of the friction. They will make the heat be transferred to other places by the lubricating oil. Especially the lubricating oil pool in the inside of the lathe bed will form a large heat source. It will have great influence on the thermal deformation of the lathe bed. It mainly causes the phenomena, such as the warp of lathe bed, the bending of guide rail and so on.

Thirdly, cutting. The mechanism of cutting is material extrusion. In the process of cutting, due to the change of material shape it generates heat. It is commonly known as the cutting heat. This part of heat is transferred to the lathe bed bythe cutting and lubricating liquid.

The spindle system of machine tool has two main sources: the cutting heat and the friction heat from the bearing. Because the cutting heat can be taken away by cutting and coolant timely, we only consider the friction heat of bearing here.

B. The Calculation of Calorific value of spindle system bearing

The calorific value of bearing is caused by the friction torque of bearing. The calorific value of rolling bearing can be calculated by the following equation

$v_0 n$ (14)

In the equation, n refers to rotational speed of bearing, r/min

M refers to bearing frictional torque, N • m

$v_0 n$

Among them, $v_0 n$ is the item of conformity which determines the starting friction torque and the size of friction torque in slow motion. $v_0 n$ is the velocity item. In the process of high-speed operation the viscous friction resistance of the lubricant plays a main role in $v_0 n$.

In many empirical formulas about the velocity item and the load item, the empirical formula proposed by Palmgren is generally used.

$v_0 n$ (15)

In the equation, $v_0 n$ refers to the coefficient related to bearing type and the load it suffered;

$v_0 n$ refers to the computation load of the bearing friction torque;

$v_0 n$ refers to the pitch diameter of bearing;

We can obtain $v_0 n$ and $v_0 n$ by searching the information.

In the process of calculating $v_0 n$,when the product of the moving viscosity $v_0 n$ of lubricant and the rotational speed $v_0 n$ is $v_0 n$ >2000 cSt • r/min,

$v_0 n$ (16)

When $v_0 n$ <2000 cSt • r/min,

f_0 (17)

In the equation, f_0 refers to empirical constant related to bearing type and lubricating mode;

v_0 refers to the moving viscosity of the lubricant under the working temperature, cSt.

According to the equations above, we get the result that when the spindle runs under the 1000 r/min the calorific value of front and back bearing about the spindle by the calculation are respectively 68.055W and 73.29W.

IV. TEMPERATURE FIELD ANALYSIS OF MACHINE TOOL SPINDLE SYSTEM

A. The Establishment of the Finite Element Analysis Model about Spindle System

We use the finite element analysis software ANSYS10.0 to build the finite element model of the machine tool spindle system. In the process of ANSYS analysis, it includes pre-treatment, solving and post-processing, the three steps. Pre-treatment refers to create solid model and finite element model. The solving process includes loading value, selecting solver and and the solution. Before we solve, we should analyze data examination, including the unified unit, unit type and options, material property properties (When we consider the inertia, we should input material density),quality characteristics of entity model, whether there is a gap in the modelor not and so on. The postprocessor can watch the result of the whole model at a particular moment, and it also can watch the results of the model in different period of time. It is often used to handle transient or dynamic analysis results. When we build the modeling, we should strictly comply with the design size of manufacturer drawings so as to make whole model geometry size be the same with the actual spindle system. In this way it can analyze thermal characteristics which can reflect the spindle system correctly. According to the model characteristics of the spindle system, we adopt entity unit when build the modeling. In the process of building modeling, the bearing is simplified as the ferrule which its inner and outer diameter, and width have the same size with the actual size of bearing. When we make meshing division, we should adopt free partition method. The finite element model of the whole spindle system has 188609 hot entity units SOLID87 and 185 surface units. They are shown as Figure 2.

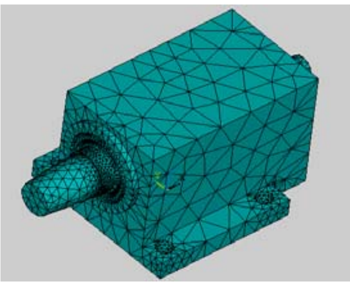

Figure 2 The finite element model of spindle system

B. The Determination of the Boundary Condition of Spindle System

According to the theory of thermodynamics, there are three basic forms for the way of heat transfer. That is to say, the three forms are respectively conduction, convection and radiation. Because the temperature rise of the machine tool spindle system is small, the radiation heat loss can be neglected. Therefore, we only consider heat conduction and convection.

(1) Heat Conductivity Coefficient

According to the materials of spindle system, box body and bearing, we research the related data to get the heat conductivity coefficient of all parts about the spindle system. The information is shown as Table 1.

TABLE 1. THE HEAT CONDUCTIVITY COEFFICIENT OF ALL PARTS ABOUT THE SPINDLE

	Material	**the heat conductivity coefficient(W/m·k)**
box body	HT200	39.2
spindle	38Crsteel	48
bearing	Bearing steel GCr15	40

(2) Convection Coefficient

We adopt Nusselt criterion equation to calculate. Under the condition of forced convection, when the spindle rotates at a certain speed, the convective heat transfer coefficient between air can calculate according to the following formula.

$$\alpha = \frac{N_u k_{fluid}}{d} \quad (18)$$

In the formula, α refers to the convection heat transfer coefficient between parts surface and the air;

k_{fluid} refers to the heat conductivity of air;

Among them, N_u is the Nusselt number. It can be obtained from the following formula.

$$N_u = 0.133 R_e^{2/3} P_r^{1/3} \quad (19)$$

In the formula, R_e refers to Reynolds number(R_e <4.3× 105)

P_r refers to Prandtl number(0.7< P_r <670)

Because the convection conditions of all parts of the spindle system are different, the convection coefficients are also different. And the convection coefficient of the system is difficult to accurately determine. Combined with experience, we know that the convection coefficient adopted in the process of calculating the temperature field about the system actually is 3~5 times of the theoretical calculated value. Therefore, we get the result by calculating in the paper. Under the 1000 r/min of the spindle, the convection coefficients of all parts are shown in Table 2.

TABLE 2. THE CONVECTION COEFFICIENTS OF ALL PARTS ABOUT SPINDLE SYSTEM

	the convection coefficient(W/m2·□)
box body	20
spindle	The outside of box body:400; The inside of box body：80
bearing	20

(3) Other Parameters

According to the materials of all parts about the spindle system, we can determine the thermal boundary conditions and mechanical performance parameters needed in the thermal property analysis of spindle system. The information is shown in Table 3.

TABLE 3. THE PARAMETERS NEEDED IN THE THERMAL ANALYSIS OF SPINDLE SYSTEM

	specific heat capacity J/(kg·k)	**density (kg/m3)**	**coefficient of thermal expansion(1/□)**	**elastic modulus (Pa)**
box body	480	7250	1.0×10-5	1.5×1011
spindle	460	7850	1.12×10-5	2.0×1011
bearing	460	7810	1.12×10-5	2.0×1011

V. THE ESTABLISHMENT OF THE FINITE ELEMENT MODEL ABOUT THE MACHINE TOOL SPINDLE SYSTEM

A. The Finite Element Analysis of the Spindle System after Correction

After we analyze the influence of boundary conditions about the spindle system on the finite element analysis of the spindle, we know the factor A. That is to say, the convection coefficient of the box body has the greatest impact on the analysis results of spindle system. And the larger the value of the factor A is, the lower the obtained temperature value of spindle system is. According to the conclusion mentioned above, we modify the finite element model of machine tool spindle system. The method adopted by us is single factor optimization method. We get the final values of the convection coefficient about spindle system by calculation. The final values are 11.56，150，60 and 10. We use the boundary conditions to load again the spindle system in ANSYS to get the temperature field after the spindle system had run for two hours at the speed of 1000r/min. It is shown as Figure 3.

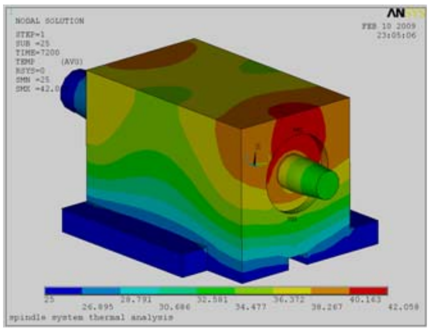

Figure 3. The temperature field distribution of spindle system after modification

B. *The Validation Verification of Spindle System Model after Modification*

Mutual information for the model after modification is calculated to look for the most sensitive point of thermal error. Similarly selecting 15 corresponding nodes on the model to calculate the mutual information of thermal deformation of the 15 nodes and the spindle, as shown in table 4:

TABLE 4 AFTER THE MODEL HAS BEEN MODIFIED, THE MUTUAL INFORMATION OF EACH NODE CALCULATED BY ANSYS IS SHOWN AS THE TABLE.

The temperature sensor (Ti)	Mutual information (knight)	The temperature sensor (Ti)	Mutual information (knight)
T1	1.50788	T9	1.52788
T2	1.50788	T10	1.52788
T3	1.46788	T11	1.50788
T4	1.50788	T12	1.48788
T5	1.46033	T13	1.46033
T6	1.50788	T14	1.50788
T7	1.46033	T15	1.48033
T8	1.46033		

VI THE FINITE ELEMENT CALCULATION AFTER THE STRUCTURE OPTIMIZATION OF SPINDLE SYSTEM

In the analysis of ANSYS towards the spindle system of optimized structure, assume that the spindle speed is 1000 r/min, thus after it has been running for 2 hours, the temperature field and thermal deformation of spindle system diagram we got is shown in figure 4 ~ 5.

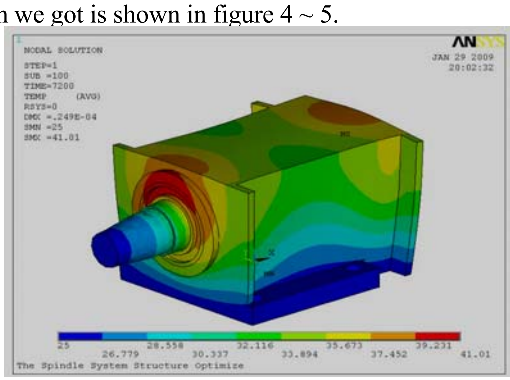

Figure 4. The temperature field distributions after the optimization of spindle system structure

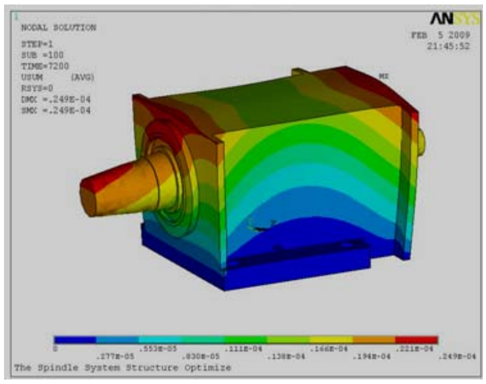

Figure 5. Thermal deformation of spindle system image after optimization

Taking eight nodes of transverse section of A on the front of the bearing, we can get the spindle thermal deformation results. They are shown in Table 5:

TABLE 5. THE THERMAL DEFORMATION OF TRANSVERSE SECTION OF A ON THE FRONT OF THE BEARING AFTER OPTIMIZATION

		The radial displacement (um)		The axial displacement (um)
No	Node number	displacement in Y direction	displacement in Z direction	displacement in X direction
1	52305	1.5451	1.7294	-19.072
2	52310	1.1961	2.6781	-21.2488
3	52314	0.3127	3.1811	-21.2419
4	52318	-0.6881	2.9845	-21.745
5	52322	-1.3176	2.1885	-20.4974
6	52596	-1.0189	0.7548	-18.1832
7	52600	-0.1508	0.278	-17.3936
8	52604	0.8207	0.4628	-17.6894

We compare the thermal deformation situations of spindle system before and after optimization. And the results got are shown in Table 6:

TABLE 6 THERMAL DEFORMATION CONTRAST BEFORE AND AFTER THE OPTIMIZATION OF THESPINDLE SYSTEM

	The radial displacement (um)	The axial displacement (um)
spindle system before optimization	4.7981	4.4720
spindle system after optimization	2.7465	3.8552
the deceasing rate of thermal deformation	42.75 %	13.79 %

VII. CONCLUSION

The spindle system is key component of the numerical control machine tool, and to a great extent, its precision degree decides the machining accuracy of numerical control machine tools. In the process of machining, there are 70% deformation cases of machine tools caused by thermal error. Using the finite element analysis method with the experimental results to analyze the thermal error value of spindle system and improving the machining precision of the machine tool is research content of this paper. There are the main points of this paper:

Combining with the existing calculation theory of temperature field, we use large simulation software-ANSYS to analyze the thermal force coupling in the machining process of spindle system in this paper, and get the temperature field distribution and thermal deformation degree of thermal equilibrium in the working process of main shaft system. And experiments carried on the universal thread grinding machine by the Shanghai machine tool plant verified the effectiveness of this method, and it fixed some parameters in the model to ensure the accuracy of the finite element analysis method.

Based on the information theory method, we propose an optimal heat sensitive point in this paper, namely the optimal selection method of temperature measurement points. In detail, we elaborated the mutual application of mutual information in the choice of the optimal temperature measurement points in this paper, and together with the experimental data analysis it obtained the most sensitive point of the spindle thermal error. At the same time, we took the multiple linear regression method into consideration, and got the thermal error compensation model of the spindle system. After an analysis of the obvious features of model, we ensure the practicability of the thermal error compensation model in this paper.

Through the use of secondary development of Siemens 840 d numerical control's system software OEM, we designed the thermal error compensation software of the main shaft system in this paper. At the same time, we used Visual Basic and VC + + to embed the software in the numerical control system. Finally, we completed communication between the numerical control system and the compensation software, and realized real-time compensation for thermal error of spindle system in the process of processing.

Based on the previous analysis and research to optimize the structure of the spindle system. We focus on the effects of arrangement and the size of box body radiating rib plate on the thermal deformation of the spindle system, and take the actual spindle system installation structure and assembly space into consideration to complete structure optimization in this paper. After optimization, radial line of the spindle dropped by 43%, and the axial line fell by 14%. These things mean that the system has achieved good heat dissipation effect.

REFERENCES

[1] Fraser S., Attia M.H., Osman M.O.. Modeling, Identification and control of thermal deformation of machine tool structures, Part I: Concept of Generalized Modeling. ASME Journal of Manufacturing Science and Engineering, 1998,120(3), pp.623-631.

[2] Fraser S., Attia M.H., Osman M.O.. Modeling, Identification and control of thermal deformation of machine tool structures, Part II: Generalized Transfer Functions. ASME Journal of Manufacturing Science and Engineering, 1998,120(3),pp.623-631.

[3] F. J. Carrion, A. Lozano, M. J. Fabela. Simplified Experimental Calibration for a Tridilosa-type Bridge Finite Element Model. Experimental Mechanics, 1999, 39(4), pp.324-328.

[4] E. H. K. Fung, J. C. K. Chan. ARXModeling and Compensation of Roundness Errors in Taper Turning. The International Journal of Advanced Manufacturing Technology, 2000,16(6),pp.404-412.

[5] Yiding Wang, Guoxiong Zhang, Kee S. Moon. Compensation for the thermal error of a multi-axis machining center. Journal of Materials Processing Technology, 1998(75),pp.45–53.

[6] Zone-Ching Lin, Jia-Shing Chang. The building of spindle thermal displacement model of high speed machine center[J]. The International Journal of Advanced Manufacturing Technology, 2007, 34(5), pp.556-566.

[7] Shuhe Lia, Yiqun Zhang, Guoxiong Zhang. A study of pre-compensation for thermal errors of NC machine tools. International Journal of Machine Tools and Manufacture, 1997,37(12),pp.1715-1719.

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