View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Warwick Research Archives Portal Repository

Original citation:
Liu, Teng, Gao, Weiguo, Tian, Yanling, Zhang, Dawei, Zhang, Yifan and Chang, Wenfen. (2017) Power matching based dissipation strategy onto spindle heat generations. Applied Thermal Engineering, 113. pp. 499-507.

Permanent WRAP URL:
http://wrap.warwick.ac.uk/94048

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions. Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher's statement:
© 2017, Elsevier. Licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International http://creativecommons.org/licenses/by-nc-nd/4.0/

A note on versions:
The version presented here may differ from the published version or, version of record, if you wish to cite this item you are advised to consult the publisher's version. Please see the 'permanent WRAP URL' above for details on accessing the published version and note that access may require a subscription.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk

warwick.ac.uk/lib-publications

Manuscript
Click here to view linked References

Power Matching Based Dissipation Strategy onto Spindle Heat Generations

Teng Liu[1,2], Weiguo Gao[1*], Yanling Tian[1, 5], Dawei Zhang[1], Yifan Zhang[3], and Wenfen Chang[1, 4]

[1] *Key Laboratory of Mechanism Theory and Equipment Design of Ministry of Education, Tianjin University, Tianjin 300354, China*

[2] *School of Mechanical Engineering, Hebei University of Technology, Tianjin 300130, China*

[3] *School of Electrical Engineering and Automation, Tianjin University, Tianjin 300072, China*

[4] *Beijing Precision Machinery & Engineering Research Co., Ltd., Beijing 101312, China*

[5] *School of Engineering, University of Warwick, Coventry, CV4 7AL, UK*

Abstract: To overcome the imbalance between spindle heat generation and dissipation caused by existed spindle cooling strategies, this paper develops a power matching based cooling strategy for motorized spindle unit. Firstly, heat generation, conduction and dissipation are considered for the modeling of spindle structural heat exchange. This modeling methodology conveys that an operating motorized spindle unit will have satisfactory thermal behaviors only if the supply dissipation powers from recirculation coolants are dynamically and respectively equal to their corresponding heat generation powers (mainly from spindle bearings and motor). Based on this principle, the power matching between spindle heat generations and dissipations is realized by the real-time power estimations of spindle heat sources and the modified constant supply cooling powers strategy. It can be ultimately verified by experiments that the power matching based dissipation strategy is more advantageous than existed spindle cooling strategies in dissipation of spindle heat generations and decrease of thermal errors.

Keywords: Power matching, Dissipation strategy, Motorized spindle unit, Heat generation, Thermal error

∗E-mail address of the corresponding author: gaowg@tju.edu.cn

1 Introduction

Motorized spindle unit, being the crucial component of precision machine tools, can realize various machining types such as drilling, milling, grinding and so on. Generally, the motorized spindle unit has a compact structure combining its built-in motor and high speed bearings. This structure provides motorized spindle unit with not only high speed, precision, and rigidity, but also some thermal disturbances on precision machining accuracy and accuracy stability [1]. As illustrated in Fig. 1, there are mainly the motor and bearing power losses in the energy conversion of a motorized spindle unit operating in a constant temperature (20℃) workshop for precision machining [2]. The former includes motor magnet loss, electric loss, mechanical loss and some additional losses, and the latter is mainly attributed to the friction between bearing parts. Generally, the overwhelming majorities of these power losses contribute to the spindle internal heat generations, to cause the spindle thermal deformation errors for machining accuracy degradation. To solve this problem, recirculation coolants are always applied onto the spindle motor and bearings to realize dissipation management onto their heat generations caused by power losses, and to reduce the harmful heat absorbed by spindle structure [3, 4].

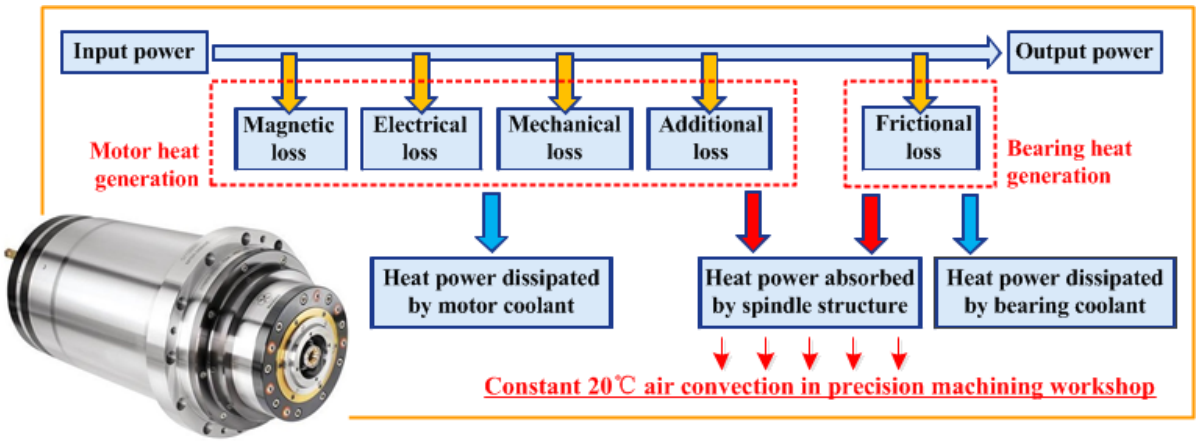


Fig. 1 Energy conversion of an operating motorized spindle unit

However, although recirculation coolants can improve the thermal behaviors of motorized spindle unit, the deficiencies of its traditional uniform and open-loop strategy are being exposed with the rapid evolution of precision machining. As revealed in Fig. 2: On one hand, the traditional strategy for spindle recirculation cooling is based on flow divider to realize parallel coolants from one recirculation cooler, which means different spindle heat generating parts with

various heat generation scales are forced to bear an uniform supply cooling temperature. This can generally result in the heat exchange imbalance of spindle structure. On the other hand, the traditional strategy always has the open-loop temperature control method. Its supply cooling temperature is generally determined based on the preset constant instruction or the ambient temperature tracked by Resistive Thermal Detector (RTD) sensors, and thus it is hardly to be adjusted dynamically according to the spindle time-varying thermal behaviors in operation. This can give rise to the incompleteness and instability of the spindle structural heat dissipation. All these insufficiencies can weaken the effectiveness of traditional cooling strategy for reducing the spindle thermal errors [5, 6].

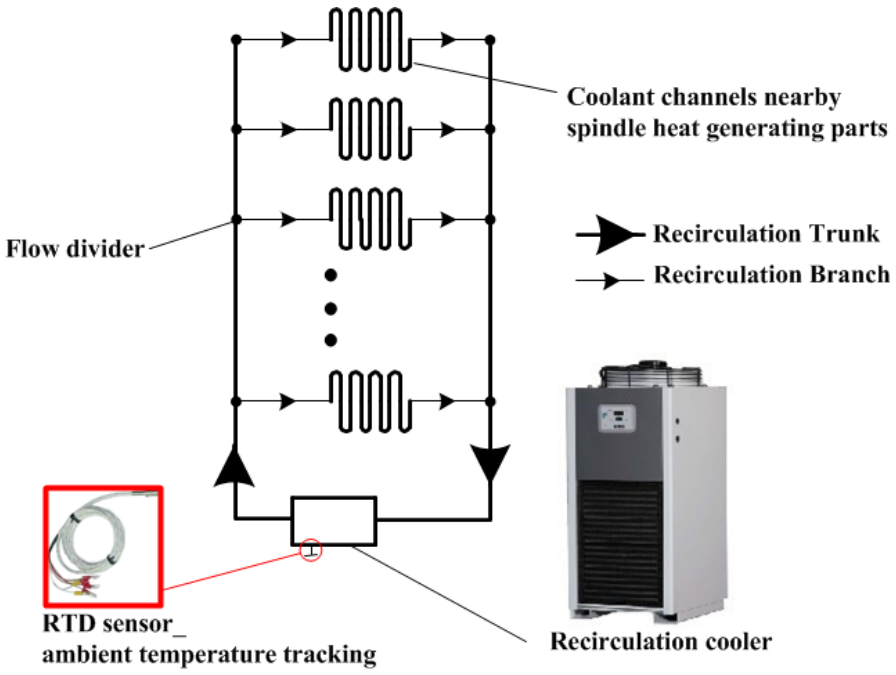


Fig. 2 Principle of traditional strategy for spindle recirculation cooling

To overcome these disadvantages of traditional uniform and open-loop cooling strategy, a differentiated multi-loops bath recirculation system was developed in our previous study [7]. On this basis, being the preliminary attempt to differentiated and closed-loop dissipation strategy for spindle internal heat generations, the constant supply cooling powers strategy was proposed. This strategy was experimentally verified to be more efficient in improving the spindle thermal behaviors than traditional strategy. However, from the perspective of spindle energy exchange, this strategy can reach the time-averaged spindle cooling effect exclusively, but hardly realize

the real-time and accurate dissipations onto the spindle time-variant heat generations, which are closely related to spindle working conditions.

For the realization of the real-time power matching between spindle heat generations and dissipations, this paper makes modifications based on constant supply cooling powers strategy, to construct a power matching based dissipation strategy for internal heat generations of motorized spindle unit. This strategy can realize the sufficient dissipations of spindle internal heat generations, for further improvements of spindle accuracy and accuracy stability. The remainder of the paper is organized as follows: Section 2 establishes the models of the theoretical interaction among structural heat generations, dissipations and conductions of the operating motorized spindle unit, and then obtains the relationships with other spindle thermal behaviors. Based on these analyses, Section 3 proposes the realization method of the power matching based dissipation strategy for spindle heat generations. Section 4 analyzes the methods and results of the advantageous verification experiments for the developed power matching based spindle cooling strategy. Section 5 gives the conclusions of the whole study.

2 Theoretical model for power matching based dissipation strategy for spindle internal heat generations

In this section, the general interaction of the internal heat generation, dissipation and conduction of an operating motorized spindle unit is analyzed, and then the theoretical association with spindle thermal deformation behaviors is investigated, finally the theoretical guidance for the power matching based dissipation strategy for spindle internal heat generation is formed.

2.1 Spindle structural heat exchange - thermal deformation modeling

The physical structure of a typical type of motorized spindle unit is illustrated in Fig. 3: Its main heat sources (heat generating parts) are front bearings, back bearing and built-in motor of the spindle. Meanwhile, 3 coolant channels are designed around these heat sources respectively to realize recirculation cooling effects for dissipations of their heat generations. When the motorized spindle unit is operating in a constant 20℃ workshop, its heat conductions Φ_{con} (W) are closely associated with its heat generations Φ_{gen} (W) and dissipations Φ_{coo} (W), which is

described in Fig. 4. Then according to energy conservation law, the spindle temperature distribution can be calculated as [8]:

$$\sum \Phi = \Phi_{\text{gen}} - \Phi_{\text{coo}} + \Phi_{\text{con}} = c_{\text{T}} \frac{\mathrm{d}T}{\mathrm{d}\tau} \tag{1}$$

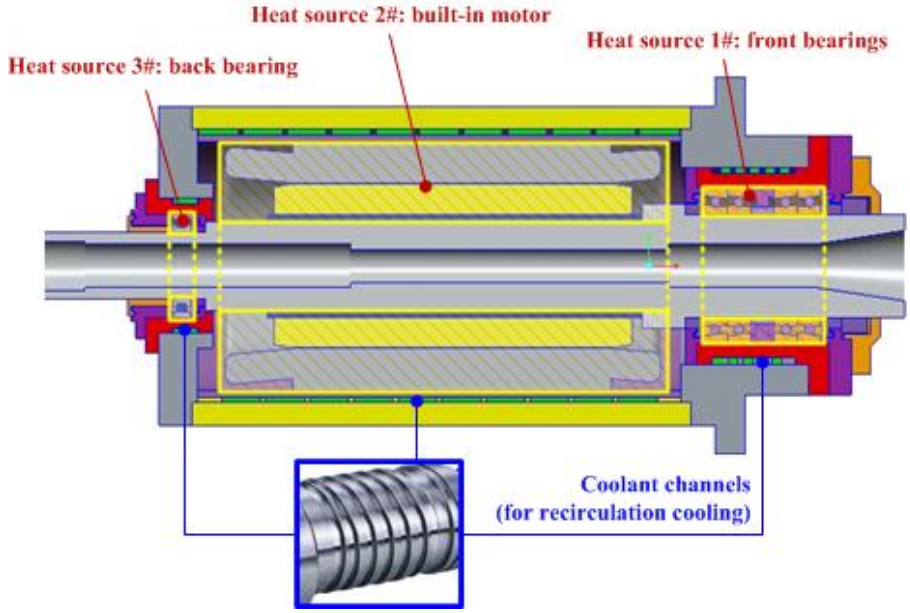


Fig. 3 Design of spindle heat sources and coolant channels

In equation (1), c_{T} is heat capacitance (J/℃), and the heat conduction (Φ_{con}) through a cross section of spindle continuous material is [9]:

$$\Phi_{\text{con}} = \lambda S \frac{\mathrm{d}T}{\mathrm{d}x} \tag{2}$$

In equation (2), S is the area perpendicular to the direction of heat flux (m^2); λ is the thermal conductivity (W/(m•℃)).

Being the source for spindle thermal errors, thermal deformation of the spindle structure is analyzed based on the thermal deformation ΔL of one dimensional rod with constraints:

$$\begin{cases} \Delta L=\alpha L\left(T_i-T_{i-1}\right)+\dfrac{\sigma L}{E} \\ \Delta L=\dfrac{-P}{j} \\ P=A\sigma \end{cases} \tag{3}$$

In equation (3), L is the original length (m); T_i and T_{i-1} are the temperatures at τ_i moment and τ_{i-1} moment (℃); α is the thermal expansion coefficient (℃$^{-1}$); σ, P, E, j and A are the stress (MPa), the axial force (N), the modulus of elasticity (N/m^2), the axial stiffness (N/m) and the area of the cross section (m^2) respectively. Then equation (3) can be simplified as:

$$\Delta L=\frac{\alpha L\left(T_i-T_{i-1}\right)}{1+\dfrac{jL}{AE}} \tag{4}$$

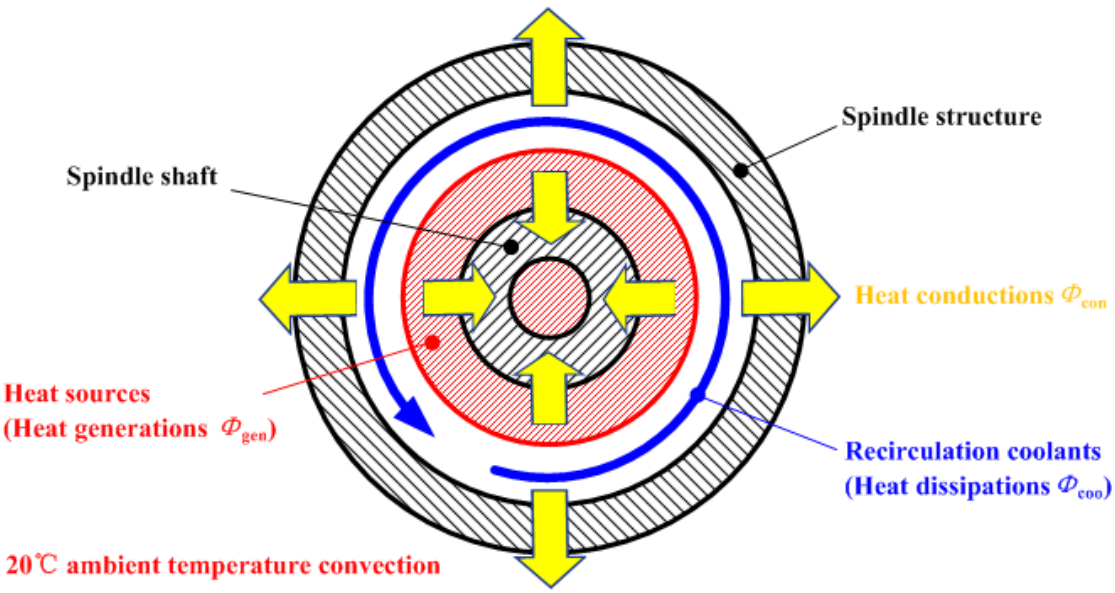


Fig. 4 Association of spindle heat generations, dissipations and conductions

2.2 Heat power measures for constantly least thermal deformation of spindle structure

For the improvement of precision machining accuracy and accuracy stability, the least thermal errors of operating motorized spindle unit can be realized consistently by the avoidance

of spindle structural thermal deformation. According to equation (4), the thermal deformation of spindle structure can be theoretically equal to zero only if the spindle temperature meets:

$$T_i - T_{i-1} \cong \frac{\mathrm{d}T}{\mathrm{d}\tau} = 0 \tag{5}$$

It is assumed that motorized spindle unit has the structure-averaged temperature distribution (=20℃ ambient temperature) at the initial state of spindle operation, which means:

$$\frac{\mathrm{d}T}{\mathrm{d}x} = 0 \tag{6}$$

Equations (5) - (6) can be substituted into Equations (1) - (2) to obtain heat power measures for persistent realization of structure-averaged spindle temperature distribution, at any operating moment τ:

$$\Phi_{\mathrm{gen}} = \Phi_{\mathrm{coo}} \tag{7}$$

Equation (7) clarifies the core principle of the power matching based dissipation strategy for internal heat generations of operating motorized spindle unit, which will be developed and introduced in Section 3. Generally, the spindle internal heat generations Φ_{gen} in equation (7) have time-variant scales, because they are directly affected by the spindle working conditions including rotation speed and cutting loads. Therefore, the realization of real-time power matching between spindle heat generations and dissipations must be based on the differentiated and closed-loop cooling strategy for the motorized spindle unit in operation.

3 Realization method of power matching based dissipation strategy for spindle internal heat generations

From precision machining perspectives, spindle thermal deformation errors are expected to be persistently eliminated for the satisfactory accuracy and accuracy stability, during precision machining activities. According to the conclusion in Section 2 that the least spindle thermal errors can be realized by the method of real-time and accurate dissipations of the spindle internal heat generations, the power matching based dissipation strategy for spindle internal heat generations has been developed, and its realization method is depicted in Fig. 5: On one

hand, the real-time heat power estimations of spindle bearings and motor are performed during spindle operation. On the other hand, to guarantee the real-time power matching between spindle heat generations and dissipations, the estimated heat power values are adopted for the real-time calculations about the required supply cooling powers of recirculation coolants, according to equation (7). The power matching between spindle heat generations and dissipations is mainly realized based on CNC communication - computation technology, and the calculated dissipation power values are implemented by the modified constant supply cooling powers strategy [7] for the motorized spindle unit.

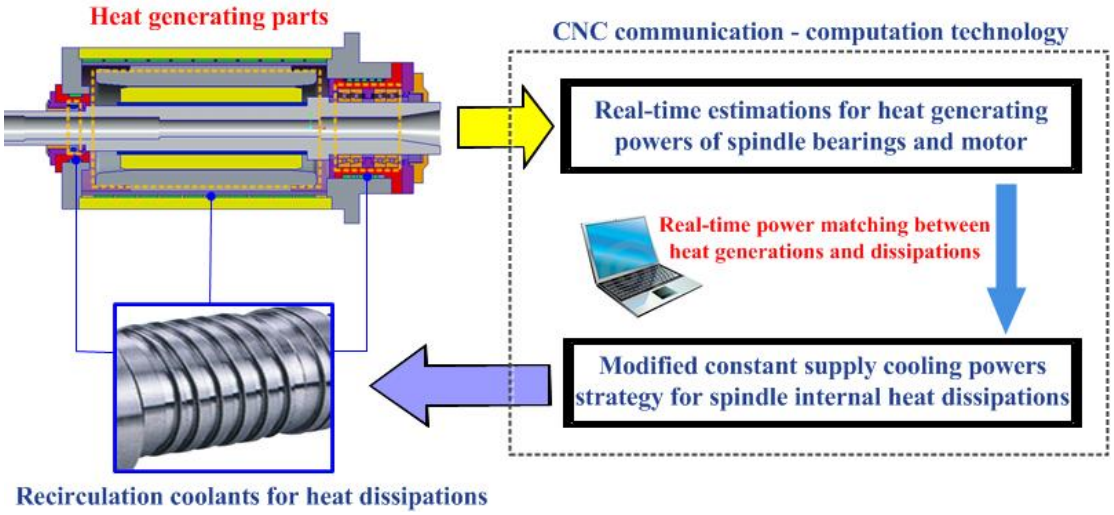


Fig. 5 Realization method of power matching based dissipation strategy onto spindle internal heat generations

3.1 Real-time power estimations of spindle internal heat generations

3.1.1 Power modeling of spindle internal heat generations

Heat power models of spindle bearings and motor are vital for real-time power estimation of spindle internal heat generations, which is required by the implementation of power matching based dissipation strategy. The heat power models of bearings and motor are established based on their published methods respectively.

(i) Spindle bearings

Generally, the spindle bearing heat is generated in bearing contact areas due to the frictions between balls and inner and outer races [10, 11]. Then the heat power Φ_b (W) modeling of both spindle front bearings and back bearing (in Fig. 3) can be determined by the following method:

$$\Phi_b = 1.047 \times 10^{-4} n(M_0 + M_1) \tag{8}$$

In equation (8), n (r/min) is spindle rotating velocity, friction torque M_0 (Nmm) brought by bearing lubricant viscosity and friction torque M_1 (Nmm) caused by bearing applied force can be calculated respectively as:

$$M_0 = \begin{cases} 10^{-7} f_0 (\nu_0 n)^{2/3} D_m{}^3, \nu_0 n \geq 2000 \\ 160 \times 10^{-7} f_0 D_m{}^3, \nu_0 n < 2000 \end{cases} \tag{9}$$

$$M_1 = f_1 F_\beta D_m \tag{10}$$

In equations (9)-(10), f_0, f_1 are parameters related to the type, structure, force and lubrication of bearings; F_β (N) is the load determined by the magnitude and direction of the force onto bearings; ν_0 (cSt) is the kinematic viscosity of lubricant; D_m (m) is the diameter of pitch circle.

It can be concluded by the modeling method that, heat powers of spindle bearings are directly affected by spindle rotation speed and bearing loads, which is time-variant during the spindle operation. Meanwhile, the bearing preload, type, structure, size and lubrication, which are known and regarded as unchanged, also impact the scale of bearing heat generations.

(ii) Spindle motor

Heat generation power Φ_m (W) of spindle motor is mainly attributed to its magnet loss P_h (W), electric loss P_{CU} (W) and mechanical loss P_f (W), with additional loss being ignored:

$$\Phi_m = P_h + P_{CU} + P_f \tag{11}$$

For equation (11), the magnet loss P_h (W) contains hysteresis loss P_t (W) and eddy current loss P (W), and they can be calculated by:

$$\begin{cases} P_t = CfB_{max}{}^2 \\ P = \dfrac{\pi^2 t^2 \left(fB_{max} \right)^2}{6\rho\gamma_c} \end{cases} \tag{12}$$

In equation (12), C is a constant value related to electrical steel grades; f (s^{-1}) is magnetizing frequency; B_{max} (T) is the maximum magnetic flux density; t (m) is the thickness of silicon steel sheet; γ_c (kg/m^3) and ρ (Ωm) are the density and electrical resistivity of iron core respectively.

Besides, the electric loss P_{CU} (W) in equation (11) can be calculated by:

$$P_{CU} = \frac{I^2 \rho_C L}{S} \tag{13}$$

In equation (13), I (A) is the current; ρ_C (Ωm), L (m) and S (m^2) are the resistivity, length, sectional area of a conductor.

Finally, the calculation method of mechanical loss P_f (W) in equation (11) is:

$$P_f = \pi C' \rho_{air} \omega^3 R_f{}^4 L_f \tag{14}$$

In equation (14), C' is the frictional coefficient; R_f (m) and L_f (m) are outer radius and length of rotor; ω (rad/s) is the angular velocity of rotor; ρ_{air} (kg/m^3) is the density of air.

During the spindle operation, time-variant factors influencing the motor heat generation scale mainly include spindle rotation speed and electricity. Besides, there are still some time-invariant factors, such as motor physical properties and structural scales, contributing to heat generation modeling of spindle motor.

3.1.2 Realization of real-time power estimations of spindle internal heat generations

It can be concluded from Section 3.1.1 that, the power modeling of spindle heat sources must be done based on required parameters. Some of them are time-variant during the spindle operation, and the others are not. As shown in Fig. 6, the former must be monitored by CNC communication technology, and the latter can be preset in the host computer software, for the

realization of real-time power modeling of spindle internal heat generations. Generally, the power modeling values of spindle heat sources have obvious inconsistencies with real ones. Therefore, power modeling values of spindle heat sources must be corrected to finish their real-time power estimations. The correction method is given as follows:

$$\Phi_{gen} = k \bullet \Phi_{b(m)} + b \tag{15}$$

In equation (15), k and b are the proportionality and deviation coefficient respectively for the power modeling corrections of spindle heat sources. The determinations of them must be based on the experimental trial and error method introduced in Section 3.2.3.

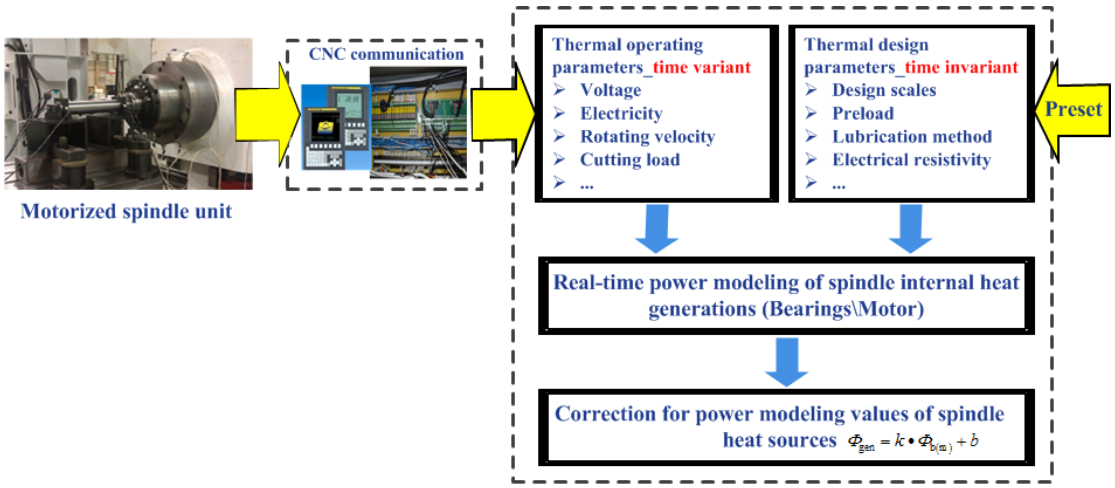


Fig. 6 Realization method of real-time power estimations of spindle internal heat generations

3.2 Real-time power determinations of spindle internal heat dissipations

3.2.1 Power matching based modification onto constant supply cooling powers strategy

It can be observed from Fig. 3 that, in order to realize the dissipations of internal heat generations of operating motorized spindle unit, coolant channels are designed for recirculation coolants being applied nearby spindle heat sources (front bearings, motor and back bearing). Meanwhile, these heat dissipations can bring the real-time coolant temperature rises between outlets and inlets of coolant channels. Then these temperature rises can reflect the real-time power scales Φ_{coo} (W) of the spindle heat dissipations onto heat sources 1#−3# respectively by the following method:

$$\Phi_{\text{coo\_}i} = c\rho Q^i \Delta T_\tau^{\,i},\ i=1,\ 2,\ 3 \tag{16}$$

In equation (16), c (J/(kg·K)), ρ (kg/m^3) and Q (L/min) are special heat, density and supply flow rate of recirculation coolants respectively; ΔT_τ (℃) is real-time coolant temperature rise between outlet and inlet of coolant channel. To be more advantageous than traditional cooling strategy for motorized spindle unit, the constant supply cooling powers strategy [7] was presented in our previous work. This strategy can realize constantly the expected dissipation powers of spindle recirculation coolants. Its principle is based on the differentiated realizations of objective scales of ΔT_τ for different spindle heat sources, with c, ρ and Q being consistent with time.

In this paper, constant supply cooling powers strategy is modified to be associated with the real-time power estimations of spindle internal heat generations, to realize the power matching between spindle heat generations and dissipations. Because of the time-variant property of spindle internal heat generations, real-time calculations of objective dissipation power scales onto spindle heat sources 1#−3# must be based on the equations (7), (15) and (16). Then the real-time calculation strategy for coolant supply temperatures T_{su} (℃) is constructed:

$$\begin{cases} \overline{\Delta T_\tau}^{\,i} = \dfrac{k_i \bullet \Phi_i + b_i}{c\rho Q^i} \\ T^i_{\text{su\_}\tau+1} = T^i_{\text{ou\_}\tau} - \overline{\Delta T_\tau}^{\,i} \end{cases}, i = 1,2,3 \tag{17}$$

In equation (17), T_{su} (℃) and T_{ou} (℃) are the supply (inlet) and outlet temperature for spindle recirculation coolant respectively; $\overline{\Delta T}$ (℃) is the objective coolant temperature rise between outlet and inlet of the coolant channel.

3.2.2 Realization of modified constant supply cooling powers strategy

The presented spindle constant supply cooling powers strategy must be realized based on the previous differentiated multi-loops bath recirculation system. As revealed in Fig.7, 3 coolant channels of motorized spindle unit are equipped with 3 recirculation branches respectively of this system for different coolant supply temperatures onto spindle heat sources.

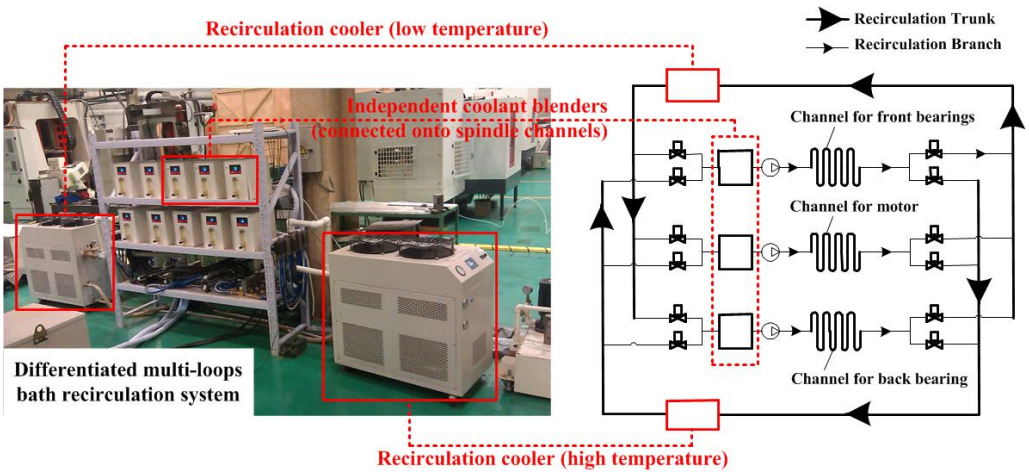


Fig. 7 Spindle coolant channels equipped with differentiated multi-loops bath recirculation system

Meanwhile, Fig. 8 expresses the realization principle of the constant supply cooling power in *i*th recirculation branch (*i*=1, 2, 3): The RTD sensor for coolant outlet temperature detection is used to trigger the real-time calculation in host computer software for the generation of supply temperature instructions. Specially, this calculation must be based on equation (17) with k, b, c, ρ and Q being consistent with time. The aim is to ensure the real-time power matching between spindle internal heat generations and dissipations.

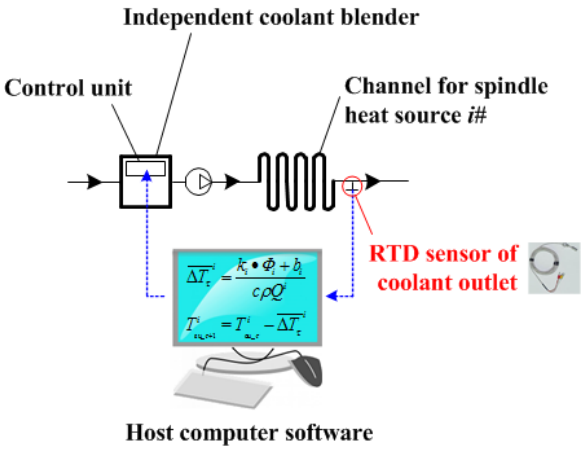


Fig. 8 Realization method of modified constant supply cooling powers strategy in *i*th recirculation branch (*i*=1, 2, 3)

3.2.3 Coefficient determinations for power matching based dissipation strategy for spindle heat generations

In equation (17), the correcting coefficients *k* and *b* must be determined by the experimental trial and error method. It can be concluded from Section 2 that $\Phi_{gen} = \Phi_{coo}$ is the very method realizing $\frac{dT}{d\tau}=0$ for an operating motorized spindle unit. Therefore, the determinations of coefficients *k* and *b* can be conducted by the trial and error method based on a series of spindle experiments. For each experiment, the motorized spindle unit is equipped with the power matching based dissipation strategy with random *k* and *b* values, and forced to have a regular 3000 RPM rotation speed for 5 hours. The aim of these experiments is to find out the approximately appropriate values of correcting coefficients *k* and *b*, which can make the power matching based dissipation strategy ensure persistently $\frac{dT}{d\tau}=0$ during a spindle operation.

4 Verification experiments

For the power matching based dissipation strategy onto the spindle internal heat generations, its advantage in spindle structural heat dissipations is verified by experiments in this section. These experiments are performed with power matching based dissipation strategy and 2 existed spindle cooling strategies respectively.

4.1 Experimental setup

Beside the outlet temperature detections of spindle internal recirculation coolants above, there are some other thermal measurements about motorized spindle unit being adopted. As shown in Fig. 9, the structural temperature and thermal errors of motorized spindle unit were measured by the similar method of our previous study: On one hand, RTD sensors are located nearby spindle heat sources: T_A and T_B are measured for the temperature of front bearings; T_C-T_F stand for the motor temperature; T_G and T_H are used for detecting the back bearing temperature. On the other hand, the spindle thermal errors are detected by the eddy current displacement sensors based on inspection bar, and these sensors must be located according to standard method for the detection of spindle thermal errors [12].

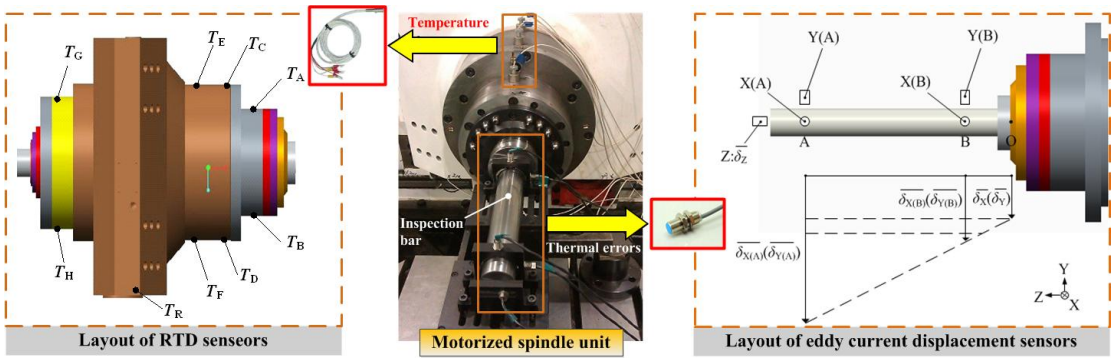


Fig. 9 Sensor layout for evaluations about spindle thermal behaviors

During experimental operations of motorized spindle unit, the detected outlet temperatures and real-time supply temperatures (inlet temperatures) of spindle coolants are monitored for the calculation of spindle dissipation powers onto heat sources 1#-3# respectively by equation (16). Meanwhile, the spindle structural temperatures and thermal errors are detected to evaluate the spindle thermal behaviors.

4.2 Experimental method

In order to verify the advantages of the presented power matching based dissipation strategy for spindle internal heat generations, the motorized spindle unit is operating under 3 different cooling strategies respectively: the traditional strategy (coolant supply temperatures are uniform and always equivalent to ambient temperature), the constant supply cooling powers strategy and the power matching based dissipation strategy.

For all the verification experiments: ① motorized spindle unit is operating from 1000RPM to 5000RPM (increasing step is 1000RPM), and every speed condition lasts for 1 hour; ② the experimental workshop has a constant temperature (T_{am}=20±0.3℃); ③ the density ρ, special heat c and supply flow rate Q of adopted recirculation coolants are 910 kg/m^3, 2090 J/ (kg·K) and 5L/min, respectively.

4.3 Experimental results and discussions

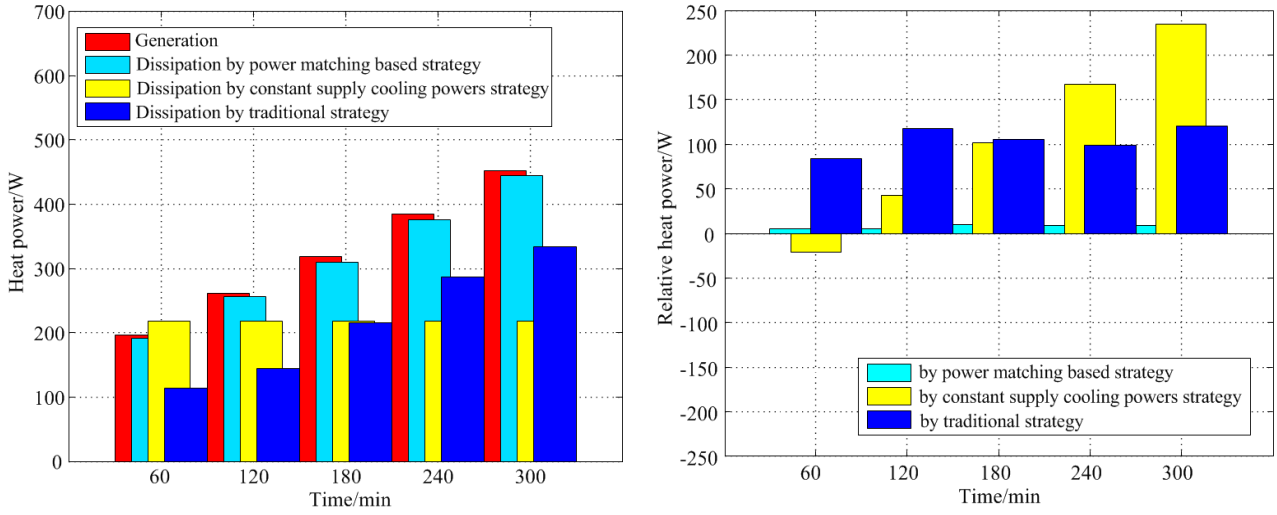
4.3.1 Spindle internal heat generations and dissipations

In order to verify the advantage of the power matching based dissipation strategy in spindle

structural heat exchange, real-time powers of spindle internal heat dissipations onto heat sources 1#-3# under 3 different cooling strategies are calculated based on experimental coolant temperature detections. They are compared with the real-time heat power estimations of corresponding spindle heat sources, under the progressive spindle rotation speed condition.

Fig. 10 (a) illustrates the comparisons of spindle front bearings: 2 existed spindle cooling strategies can hardly meet the real-time power matching requirement from spindle heat generations. For the uniform and open-loop strategy, the heat dissipation power of recirculation coolant has an increasing tendency. Its power values are always lower than the time-variant heat generation powers and higher than zero. Meanwhile, for the constant supply cooling powers strategy, the coolant heat dissipation power has an approximately consistent value. In initial period, the heat dissipation power is slightly higher than heat generation power; but with the increase of spindle rotation speed, the former is lower than the latter. Unlike existed strategies above, the power matching based dissipation strategy can guarantee that the real-time heat dissipation power always approximate to the heat generation power of spindle front bearings, with the progressive spindle rotation speed.

Based on the heat generation-dissipation power comparisons of spindle front bearings in Fig. 10 (a), the real-time power distinctions between the heat generations and dissipations caused by 3 cooling strategies are calculated and compared in Fig. 10 (b). It can be observed that, the uniform and open-loop strategy have a consistently heating effect for spindle structure; under the constant supply cooling powers strategy, the spindle structure is slightly cooled by the front bearings in initial period, but heated subsequently. Specially, under the power matching based dissipation strategy, the heating effect from front bearings is always near to 0 during the spindle operation. This clarifies that the power matching based dissipation strategy can realize effectively the accurate dissipations onto heat generations of spindle front bearings. Actually, this conclusion can also be obtained by comparisons about the spindle motor and back bearing. But the related descriptions have been simplified for the length limit of the paper.



(a) Power comparisons between heat generations and dissipations

(b) Relative power comparisons

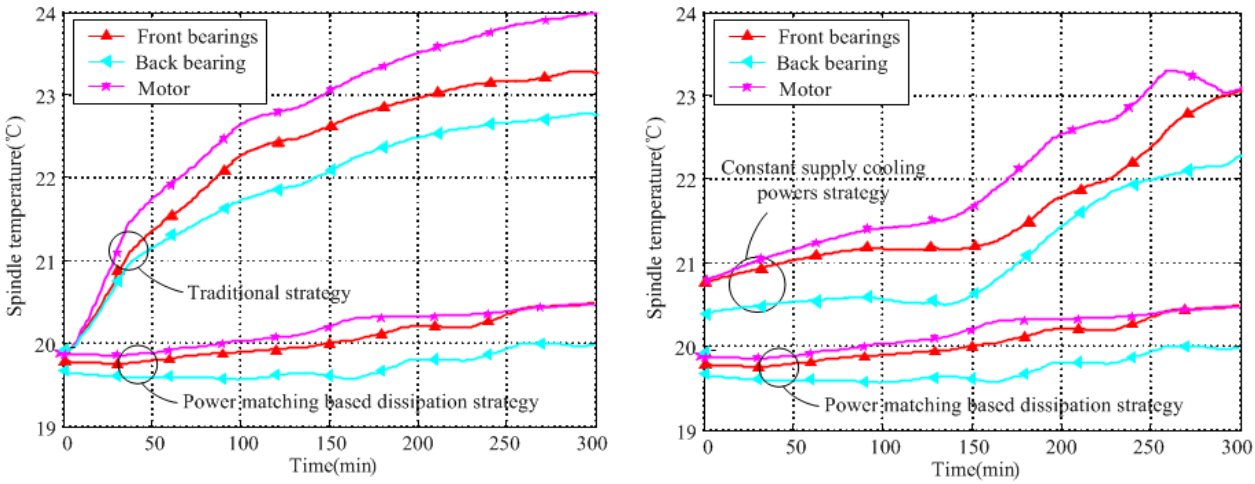
Fig. 10 Experimental heat generation-dissipation power analysis about spindle front bearings

4.3.2 Spindle structural temperatures

Based on the RTD sensors in Fig. 9, the experimental temperature values of spindle front bearings, motor and back bearing can be obtained by the averaging calculations of real-time detections of T_A / T_B, T_C-T_F and T_G / T_H respectively. Because the motorized spindle unit is operating experimentally in a constant 20℃ workshop, the spindle temperature detections nearby heat sources can reflect the behaviors of spindle structural temperatures.

In Figs. 11 (a) and (b), the experimental temperatures of spindle front bearings, motor and back bearing caused by power matching based dissipation strategy are compared with the ones caused by traditional strategy and constant supply cooling powers strategy respectively. Obviously, spindle structural temperatures under 2 existed strategies have irregular and unstable increasing tendencies. The reason is that the power inequality between spindle internal heat generations and dissipations can cause the consistently heating effect for spindle structure. However, the ones caused by power matching based dissipation strategy are more stable and close to ambient temperature (20±0.3℃). This verifies that power matching based dissipation

strategy is more accurate and sufficient than the other 2 strategies in dissipations of spindle internal heat generations.



(a) Compared with traditional uniform, open-loop strategy

(b) Compared with constant supply cooling powers strategy

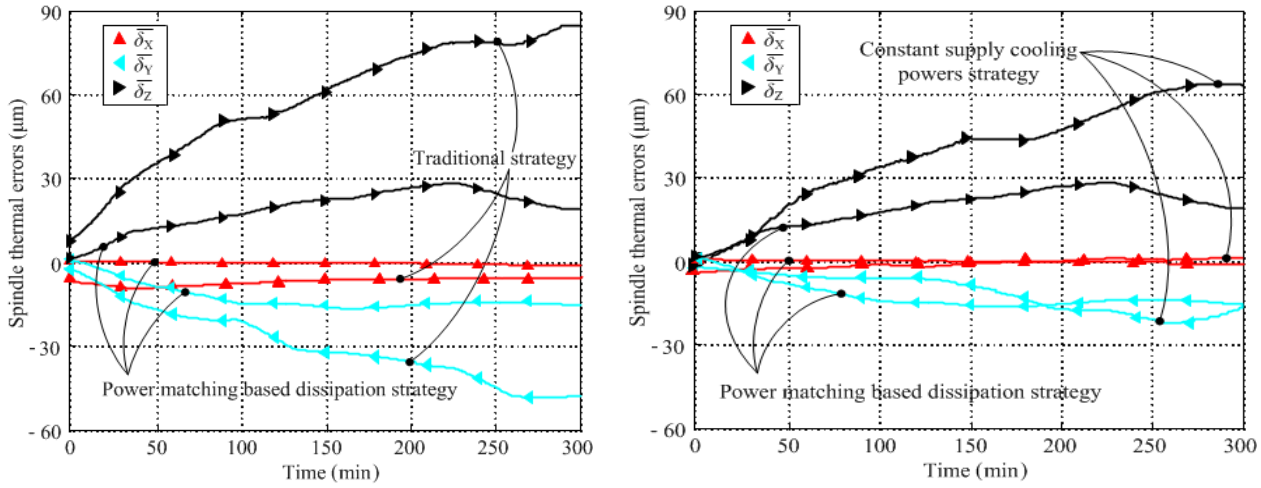
Fig. 11 Experiment comparisons of spindle structural temperatures

4.3.3 Spindle thermal errors

Fig. 9 reveals the geometry relationship between thermal displacements of spindle nose (Point O) and the detected values from eddy current displacement sensors. This relationship results in the calculations of experimental linear thermal errors of motorized spindle unit, based on the detection of the spindle inspection bar.

Figs. 12 (a) and (b) illustrate that the spindle linear thermal errors caused by power matching based dissipation strategy are compared with the ones caused by 2 existed cooling strategies respectively. It can be observed from Fig. 12 that, spindle thermal errors under 2 existed strategies are obviously increasing with time, which is always harmful to spindle accuracy and accuracy stability. This condition is attributed fundamentally to the power inequalities between spindle internal heat generations and dissipations. Meanwhile, thermal errors caused by power matching based dissipation strategy are more stable and near to zero than the ones caused by the other 2 strategies in different degrees. The reducing percentages of steady thermal errors are

listed in Table. 1. It can be concluded from the comparisons that the power matching based dissipation strategy has the advantage in eliminations of spindle thermal errors. This contributes to the improvement of the accuracy and accuracy stability of motorized spindle unit.



(a) Compared with traditional uniform, open-loop strategy

(b) Compared with constant supply cooling powers strategy

Fig. 12 Experiment comparisons of spindle thermal errors

Table 1. Reducing percentages of spindle thermal errors caused by power matching based dissipation strategy

	$\overline{\delta_X}$	$\overline{\delta_Y}$	$\overline{\delta_Z}$
Compared with traditional uniform, open-loop strategy	94.3%	68.8%	67.4%
Compared with constant supply cooling powers strategy	64.9%	31.7%	54.8%

5 Conclusions

This paper mainly introduces a power matching based dissipation strategy for internal heat generations of motorized spindle unit, in order to implement the accurate real-time power matching between spindle heat generations and dissipations. The principle of this strategy is constructed based on the analyses about spindle structural heat generations, dissipations and

conductions. Then this strategy can be realized by real-time power estimations of spindle heat sources and the modified constant supply cooling powers strategy. In summary, conclusions of this paper are as follows:

(1) From the heat transfer perspective, the power inequality between spindle internal heat generations and dissipations is the fundamental reason for the degradation of the accuracy and accuracy stability of a motorized spindle unit, which is operating in a constant temperature (20℃) workshop for precision machining.

(2) Compared with existed spindle cooling strategies, the developed power matching based dissipation strategy has the obvious advantages in the dissipation of spindle internal heat generations, and it is more effective in spindle structural temperature stabilization and thermal errors elimination, which has been verified by experiments.

Acknowledgment

The authors acknowledge the state S & T projects for upmarket NC machine and fundamental manufacturing equipment of China (no. 2013ZX04005-013, no. 2014ZX04014-011, no. 2015ZX04005-001, and no. 2016ZX04004-002, resp.).

References

[1] Weck M, McKeown P, Bonse R, Herbst U. Reduction and compensation of thermal errors in machine tools. CIRP Annals-Manufacturing Technology 1995; 44: 589-598.

[2] Timo S, Simon Z, Konrad W. Method for evaluation of energy efficiency of machine tools. Energy 2015; 93: 1964-1970.

[3] Chou C, DeBra DB. Liquid temperature control for precision tools. CIRP Annals-Manufacturing Technology 1990; 39: 535-543.

[4] Abele E, Altintas Y, Brecher C. Machine tool spindle units. CIRP Annals-Manufacturing Technology 2010; 59: 781-802.

[5] Donmez MA, Hahn MH, Soons JA. A novel cooling system to reduce thermally induced errors of machine tools. CIRP Annals-Manufacturing Technology 2007; 56: 521-524.

[6] Jedrzejewski J, Kwasny W. Study on reducing energy consumption in manufacturing systems. Journal of Machine Engineering 2011; 11: 7-20.

[7] Liu T, Gao, WG, Tian YL, Zhang HJ, Chang WF, Mao K, Zhang DW. A differentiated multi-loops bath recirculation system for precision machine tools. Applied Thermal Engineering 2015; 76c: 54-63.

[8] Bossmanns B, Tu JF. A thermal model for high speed motorized spindles. International Journal of Machine Tools and Manufacture 1999; 39(9):1345–1366.

[9] Harris TA. Rolling bearing analysis, Wiley, New York; 1991.

[10] Jorgensen BR, Shin YC. Dynamics of machine tool spindle/bearing systems under thermal growth. Journal of Tribology 1997; 119 (4): 875–882.

[11] De Lacalle NL, Mentxaka AL. Machine tools for high performance machining, Springer Science & Business Media; 2008.

[12] ISO 230-3 2007. Test code for machine tools-Part 3: Determination of thermal actions