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A tolerance design method for hydrostatic guideways motion accuracy based on error averaging effect

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Abstract

A tolerance design method based on error averaging effect for hydrostatic guideways motion accuracy was proposed in this paper. Firstly, the motion accuracy analysis model was established by average the oil film thickness considering the wavelength, amplitude and phase parameters of guide rails. Then, the guide rails straightness errors were calculated according to the relationship between the motion error and guide rails geometric error parameters, which realize the tolerance design of hydrostatic guideways. Finally, the method was applied to the design of guide rails in open hydrostatic guideways, and the measured motion accuracy results verified the correctness of the method.

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Keywords: tolerance design; hydrostatic guideways; error averaging

1. Introduction

Hydrostatic guideways have wide applications in ultra-precision numerical control machining centers that demand high precision and damping, which is due to its higher motion accuracy, lower friction and better stability characteristics compared with conventional rolling guide. In previous and current design processes of hydrostatic guideways, there were no specified criteria for components tolerance design, and no clearly defined relationship between each other. In general, the tolerance design process mostly depends on the knowledges and experiences from designer's which will makes inappropriate tolerance values. Therefore, reasonably tolerance design of components in hydrostatic guideways for realize the active design towards to the motion accuracy, is of high importance.

2. The state of the art

In recent decades, some researches and explorations have been made on the issue of tolerance design for mechanism and machine elements aside of hydrostatic or aerostatic bearing technology. Lee et al.[1] turned the assemble and design requirement into multivariate constraint conditions, and then solving the probability which met the design and assemble requirements under specific tolerance value by introducing the degree of reliability. Fainguelernt et al.[2] started with the machining capability and proposed a model that translated design tolerance into manufacturing tolerance. Shan et al.[3] researched the geometric error allocation by genetic algorithm, and integrated the method with manufacturing processes during the calculation. Lööf et al.[4] found the tolerance accumulation in the assemble processes will affect the measurement tolerance of the product and hence translated into discrete optimization problems considering cost constraint. According to the aforementioned works, it can be found that the assembly dimension-chain and solution model of a selected mechanism had been conducted, and also the tolerance optimal design method based on degree of reliability was researched.

However, the moving parts and structural elements in hydrostatic bearing were separated by pressured liquid or gas

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film, where the motion accuracy rather than just depending on the tolerance of structural elements. Besides, it was also affected deeply by the pressured liquid or gas film. So, the previous method of tolerance design may not be applicable to hydrostatic bearing, like hydrostatic guideways, towards to the motion accuracy. For this reason, the transitive relation between structural elements tolerance and motion accuracy of moving parts should be researched firstly.

Due to the effect of error averaging, the motion error is smaller than the guiderails geometric error in hydrostatic guideways. The relationship between motion error and guiderails geometric error can be obtained by quantitatively analysis of error averaging. In recent years, a large amount of research studies had been focused on this issue in hydrostatic guideways. Yabe et al. [5] studied the relationship between the sliding accuracy of an externally pressurized gas lubricated pad bearing and machining error of the guide rail. They found that the accuracy was related to the ratio of guide rail profile error wavelength to pad length. Shamoto et al. [6] investigated the relationship between action force of the film on a single pad and the geometric error of a guide rail at various spatial frequencies using finite element analysis. They decreased profile error by lapping rail surfaces, which resulted in improved motion accuracy. Park et al. [7,8] determined the transfer function for a single pad and proposed a machining algorithm based on reverse analysis to improve motion accuracy for hydrostatic table. Ekinci et al. [9,9] analyzed motion errors in aerostatic guideways based on geometric relationship and static equilibrium, and established a model for the quantitative estimation of motion accuracy. Qi et al.[11] established the hydrostatic guideways error averaging model which considering three dimension guide rail geometric error, and researched the effects of guide rails geometric error in length and width direction on the error averaging. Xue et al.[12] established a static analysis model to determine theoretical motion error for closed hydrostatic guideways with four pads, and proposed some suggestions to improve the precision in design process. Also, the quantitative analyses of error averaging in hydrostatic guideways were investigated by previous works of author Zha et al. [13,14], the motion accuracy calculation method and related compensation strategy were proposed.

The conventional approach to improve motion accuracy of a slider is to reduce the profile error of the guide rails by using the manual lapping machining process, which means the tolerance values were changed manually. Shamoto et al. [6] proposed a method to improve guide rails using a transfer function model, which allows the determination of the error averaging coefficient. After which, a reverse analysis approach based on the measured error and lapping information can be used to estimate the profile error of the guide rails[15,16]. Hwang et al. [17] estimated motion errors for X- and Y-stages using the static equilibrium of an aerostatic bearing obtained from the measured profile errors for the guide rails. Similarly, motion straightness for rolling guides can be improved by lapping the guide rails[18]. The previous works of the author Zha et al.[19] improved the motion accuracy of hydrostatic guideways by lapping the guide rails for changing the ratio of pad length to wavelength, but without any specific tolerance design involvement, like the straightness error of guide rails in open hydrostatic guideways, which affect the motion accuracy in specific motion stroke or in the whole motion stroke. However, the design method for wavelength and amplitude parameters, even the phase angle between two guide rails, which decides the tolerance value of guide rails have not been released publicly.

So, it can be found that it is a new way for hydrostatic guideways tolerance design based on the quantitative analysis of the error averaging presented by previous works. The rest of the article was organized as follows: motion accuracy analysis model considering guide rails geometric error based on error averaging effect is presented in Section 3, Section 4 gives the motion accuracy calculation and hence the tolerance design of guide rail, experiment verification was studied in Section 5 and followed discussions in Section 6. With a conclusion the paper closes.

3. Motion error analysis model considering guide rails geometric error

3.1. Description of guide rails geometric error

The pressured lubrication film plays a role of supporting the moving part in hydrostatic guideways. Assuming that the error along the width direction does not change for mathematical description of the guide rails geometric error. So, geometric error for the guide rails can be fitted by using Fourier series, and the function can be expressed as $f_z(y)=E\sin(2\pi/\lambda \cdot y+\varphi)$[20]. Where, E, λ, and φ are amplitude, wavelength and phase angle of guide rail geometric error, respectively. The three parameters affect the tolerance design of the guide rails. They can by represented by straightness error directly, especially the amplitude and wavelength values. As the Fig. 1 shown, the functions of guide rail 1 and 2 were given as $f_{z1}(y)$ and $f_{z2}(y)$, and they have different amplitude and wavelength values. Also, a phase difference existed between these two guide rails. The straightness errors of these two guide rails were s_{e1} and s_{e2}, respectively, which depends strongly on the E and λ.

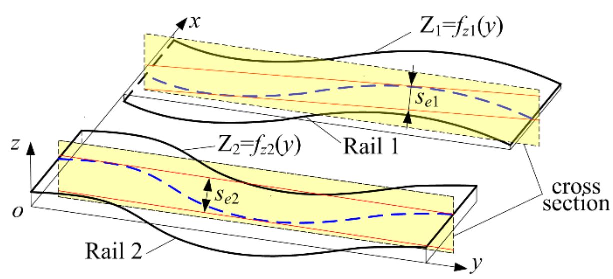
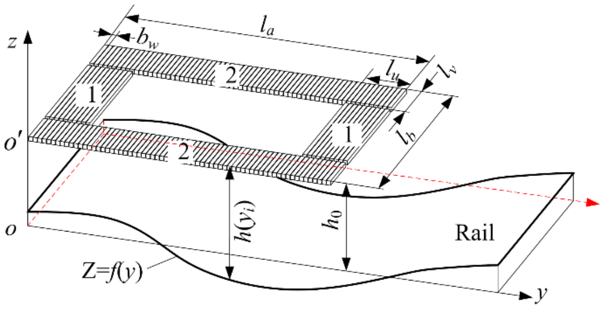


Fig. 1. Geometric error in open hydrostatic guideways

3.2. Motion error analysis model

A pad advancing along the Y direction is shown in Fig. 2. The $z=f_z(y)$ is the function of the actual guide rail with geometric error. The oil film thickness of the land at any coordinate is given by

$h(y)=h_0-f_z(y)$ (1)



1: oil film along width direction, 2: oil film along length direction, l_a: pad length, l_u: land width along pad length direction, l_b: pad width, l_v: land width along pad width direction, b_w: discrete unit width of oil film, h_0: nominal oil film thickness, $f_z(y)$: guide rail geometric error function.

Fig. 2. Guide rail geometric error and pad structure

The oil film of the land along the y direction is divided into N equal elements with length b_w, and A_i is the area of the ith element. Total area of land oil film is A. For the original point o' located at an arbitrary coordinate, the corresponding coordinate of the ith element is y_i and $h(y_i)$ is the oil film thickness for this element. Therefore, average oil film thickness for the whole land is given as

$$h_a(y)=\frac{1}{A}\sum_{i=1}^{N}h(y_i)A_i \tag{2}$$

When o' moves, $\triangle y$ is the displacement along the y direction, volume variations of the oil film 1 and 2 are $\triangle V_1$ and $\triangle V_2$, respectively. From coordinate y_1 to y_2, the variation of average oil film thickness is given as

$$\Delta h_a=\frac{1}{A}\left(\int_{y_1}^{y_2}\Delta V_1+\int_{y_1}^{y_2}\Delta V_2\right) \tag{3}$$

Therefore, average oil film thickness for the whole land of a single pad at coordinate y is represented by

$$h_a(y)=h_a(0)+\Delta h_a\big|_0^y \tag{4}$$

The pressured oil in the pad can be assumed to be an incompressible Newtonian fluid with a constant viscosity, and the oil supply pressure can be considered as a constant value. The flow between the land and the guide rail is assumed as a Poiseuille flow. The nominal oil film thickness $h(y)$ can be substituted by the average oil film thickness. Thus, flow resistance for the whole land is given as,

$$R(y)=\frac{3\eta}{h_a(y)^3\left((l_a-2l_u)/2l_v+(l_b-2l_v)/2l_u\right)} \tag{5}$$

When, resistance of the restrictor is $R_c(y)$, oil pressure in the pocket of the pad is,

$$p_0(y)=\frac{p_s}{R_c(y)/R(y)+1} \tag{6}$$

Therefore, the variation of film reaction force from the original point to coordinate y is,

$$f_e(y)=(p_0(y)-p_0(0))A_e \tag{7}$$

Where, A_e is the effect loading area of the oil film.

3.3. Solving the motion error

Geometric error functions for the two guide rails below pad1 and pad 2, below pad 3 and pad 4 are represented as $z=f_{z1}(y)$ and $z=f_{z2}(y)$, respectively. With pressured oil being supplied, an equivalent static model can be used to describe the open hydrostatic guideways with four pads shown in Fig.3. Pads in the horizontal direction were not contained. The oil film in the hydrostatic guideways is simplified as a linear spring element, so the oil film balance force is given as

$$f_{bj}(y)=f_j(y)-f_{ej}(y)=-k_j(y)\cdot\left[a_je_z(y)+b_j\theta_x\cdot\frac{m}{2}+c_j\theta_y\cdot\frac{n}{2}\right] \tag{8}$$

Where, $e_z(y)$ is the line displacement motion error of the slider in Z direction, θ_x is the pitch angular deviation, θ_y is the roll angular deviation, $f_{ej}(y)$ is the variation of film reaction force for the jth pad when slider advances along Y direction, $f_{bj}(y)$ is the balance force for the jth pad, m is the pads centers spacing along Y direction, n is the pads centers spacing along X direction and a_j、 b_j、 c_j are direction coefficients (j=1~4).

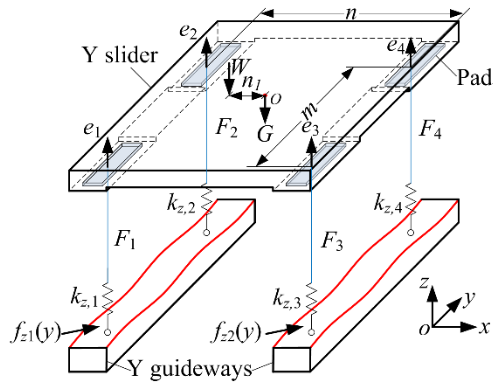


Fig. 3. Equivalent static model of open hydrostatic guideways

The resultant force and moment of the slider must zero when the slider moves to any coordinate. The force equilibrium equation and the moment equilibrium equation are expressed as

$$\begin{cases}\sum_{j=1}^{4}a_jf_j(y)-G-W=0\\ M_x=0\Rightarrow\sum_{j=1}^{4}b_jf_j(y)\frac{m}{2}+W\cdot m_1=0\\ M_y=0\Rightarrow\sum_{j=1}^{4}c_jf_j(y)\frac{n}{2}-W\cdot n_1=0\end{cases} \tag{9}$$

Substitute Eq. (8) into Eq. (9) and e_z is solved as

$$e_z=B_1\cdot A_1\cdot\left(f_{e1}+f_{e2}+f_{e3}+f_{e4}-G-W\right) \tag{10}$$

Where, A is the slider structure parameter matrix, B is the oil film stiffness coefficient matrix, C_m is the direction coefficient matrix, A^- and B^- are the inverse matrix of A and B, respectively. A_1, A_2 and A_3 are column vectors of matrix A^-, B_1, B_2 and B_3 are row vectors of matrix B^-.

$$A=\begin{bmatrix}1 & & \\ & \frac{m}{2} & \\ & & \frac{n}{2}\end{bmatrix}, B=\begin{bmatrix}\sum_{j=1}^{4}k_j & \sum_{j=1}^{4}b_jk_j & \sum_{j=1}^{4}c_jk_j \\ \sum_{j=1}^{4}b_jk_j & \sum_{j=1}^{4}k_j & \sum_{j=1}^{4}b_jc_jk_j \\ \sum_{j=1}^{4}c_jk_j & \sum_{j=1}^{4}b_jc_jk_j & \sum_{j=1}^{4}k_j\end{bmatrix},$$

$$A^-=\begin{bmatrix}A_1 & A_2 & A_3\end{bmatrix}, B^-=\begin{bmatrix}B_1\\ B_2\\ B_3\end{bmatrix}, C_m=\begin{bmatrix}1 & 1 & 1 & 1\\ 1 & -1 & 1 & -1\\ 1 & 1 & -1 & -1\end{bmatrix}$$

4. Tolerance design of guide rails

The straightness error of the guide rails in Fig.2 can be regards as s_{eg}. According to the values of e_z at different positions of the guide rails, the motion error s_{em} of the slider can be calculated by least square method. The ratio of s_{em} and s_{eg} is defined as error averaging coefficient e_{ac}. First of all, the relationship between structural parameters and error averaging coefficient should be researched for design the optimal interval of the wavelength of the guide rails. Assuming that the amplitude of the guide rails in the open hydrostatic guideways have three different values, 2 μm, 4 μm and 6 μm, respectively. The e_{ac} increased as the amplitude value increased, as shown in Fig. 4. The abscissa in Fig. 4 represent the ratio of pad length l_a to wavelength λ of guide rail geometric error. It can be found that the e_{ac} is rather sensitive to the l_a which is smaller than λ. So, the value of λ in a range of 0.2 and 2 is the main consideration when designing the tolerance of guide rails.

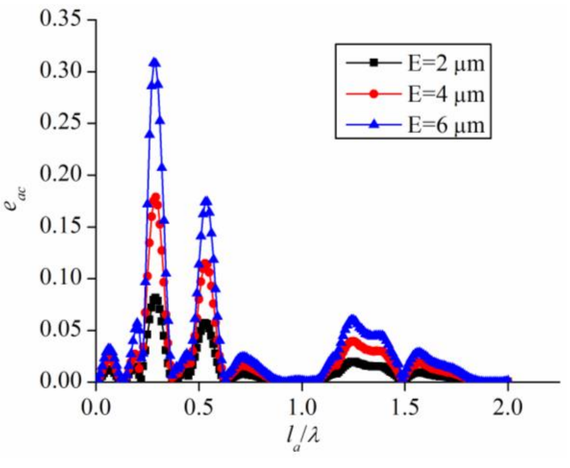


Fig. 4. Relationship between l_a/λ and error averaging coefficient e_{ac}

The relationship between wavelength λ and motion error of slide under different amplitude values in open hydrostatic guideways were shown in Fig. 5, where the phase difference $\Delta\varphi$ was set to zero. Larger motion error will be induced by larger amplitude value, and it increased rapidly at two intervals, [0.65, 0.9] and [1.1, 1.7]. For example, the motion error should be smaller than 3 μm within 1200 mm stroke in open hydrostatic guideways, the length of guide rails was about 1800 mm at least, and the 4 μm amplitude value can met the requirement under any circumstances without considering the phase difference $\Delta\varphi$ between two guide rails.

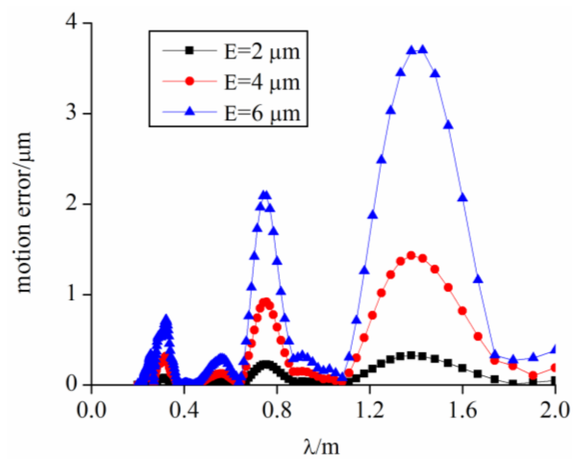


Fig. 5. Relationship between wavelength λ and motion error

In Fig. 6, the relationship between phase difference $\Delta\varphi$ and motion error was shown, where the value of the guide rails amplitude was equal to 4 μm. It can be found that larger motion error always happened, in the majority of cases, as the value of phase difference $\Delta\varphi$ increased.

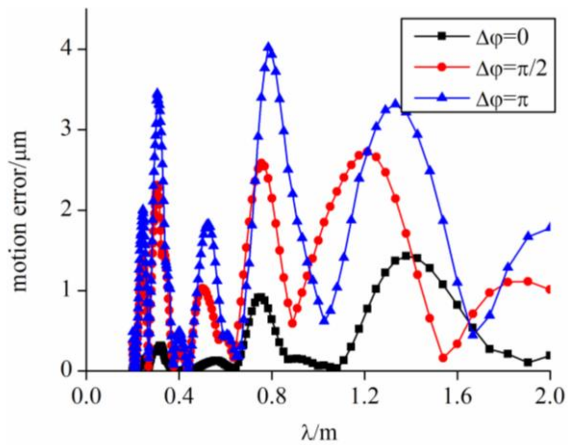


Fig. 6. Relationship between phase difference $\Delta\varphi$ and motion error

So, for the tolerance design of the guide rails in open hydrostatic guideways in order to satisfy the motion error which less than 3 μm within stroke 1200 mm, the value of amplitude and first-order wavelength of the guide rail are approximately 4 μm and 1250 mm, respectively. It means the straightness error of the guide rails should be smaller than 8 μm. It can met the accuracy requirement under any circumstances when considering the amplitude, wavelength and phase difference parameters together.

5. Experiment verification and discussion

5.1. Experiment verification

The structure of the experimental setup is shown in Fig. 7. Y-axis is composed of open hydrostatic guideways, which have four pads in the vertical direction and two pairs of opposed pads in the horizontal direction. The Y guide rails are made of granite. Parameters for the experimental setup, which contain the guide rail, oil supply system and fixed restrictor, are listed in Table 1.

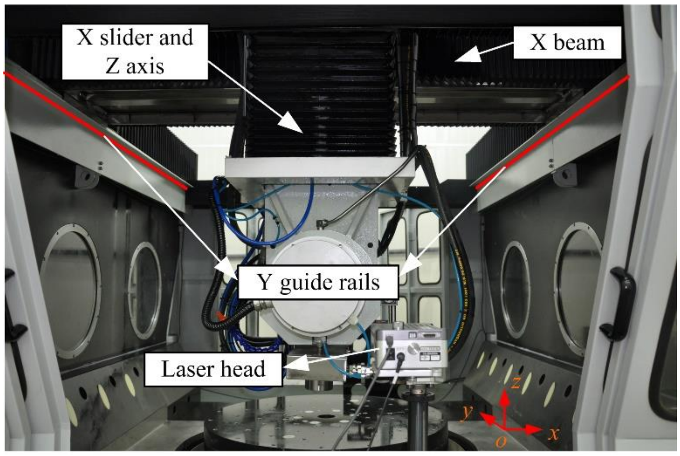


Fig. 7. Experimental setup for motion accuracy measurement

Table 1. Experimental setup parameters

Parameter	Value	Parameter	Value
Dead load of Y slider/N	40000	l_u/mm	50
Dead load of X slider and Z axis/N	14960	l_v/mm	27.5
Pads centers spacing along X axis/m	2.55	Nominal oil film thickness h_0/μm	20
Pads centers spacing along Y axis/m	0.94	Oil supply pressure P_s/Mpa	1.4
Y slider stroke/mm	1200	Oil dynamic viscosity η/Pa.s	0.0615
Pad length l_a/mm	400	Restrictor throttle length/mm	8.9
Pad width l_b/mm	80	Restrictor throttle gap/μm	40

5.2. Motion error measurement and results

Our previous research shown that the measured motion error values were different due to the measured position of the X slider changed. In the open hydrostatic guideways of the grinding machine, the *Y* slider motion error presents a minimum value, when the working position is located in the middle of *X* beam. Keeping the working position away from the center of the *X* beam will make the *Y* slider have bigger motion error value [13]. So, the X slider will located at the middle of the X beam during the motion error measurement in the experimental research. The Y slider moves with a stroke of 1200 *mm* and runs at a speed of 1 *m/min*. The measuring environment has the following properties: controlled room temperature within 21 ± 0.1 °C, humidity of 45.4%, and the experimental setup stood on a 3000 *mm* thick concrete floor with isolation trench. The motion error was measured three times.

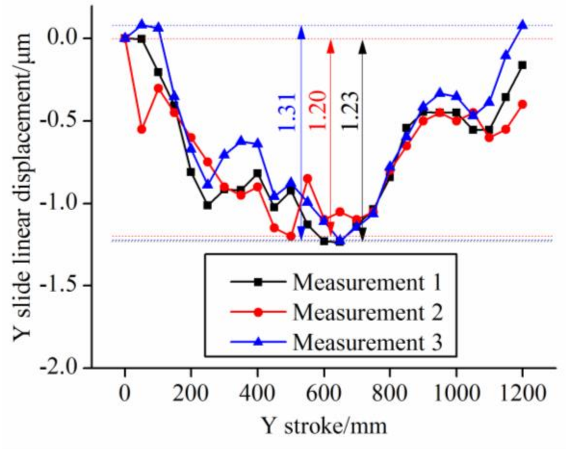


Fig. 8. Y slider vertical motion accuracy measurement and results

For ease of comparison between the measured results for different measurements, the least square line of the measured data was rotated to be coaxial with the horizontal axis. Spacing between the envelope lines through the highest point and lowest point is the Y slider motion error. The corresponding Y slider motion errors of measurement 1, measurement 2 and measurement 3 are 1.23 *μm*/1200 *mm*, 1.20 *μm*/1200 *mm* and 1.31 *μm*/1200 *mm*, respectively. The average value is about 1.25 *μm*/1200 *mm*. The manufacturing of guide rails with amplitude value 4 *μm* (straightness error 8 *μm*) can be realized easily by grinding machining and manual lapping.

6. **Discussions**

It can be found that the error averaging coefficient $\boldsymbol{e_{ac}}$ has smaller value when $\boldsymbol{l_a/\lambda}$ was greater than 1, as shown in Fig. 4. In open hydrostatic guideways, the slider has two pads at least at each side, and every pad can cover one period wave of the guide rails. When means it always keep the slider running smoothly, and the motion error has smaller values. However, it is very difficult to machining the guide rails wavelength with smaller value, especially in the long guide rails. Therefore, the value of $\boldsymbol{l_a/\lambda}$ located at the interval [0, 1] is the main consideration. However, there are two sub-intervals sensitive to the error averaging coefficient $\boldsymbol{e_{ac}}$. So, it can be concluded that the parameters matching should be considered firstly in the tolerance design process of the open hydrostatic guideways.

In Fig. 5, the motion error increased as the guide rails amplitude value increased, but no proportional relation. The amplitude should be designed with smaller value considering the mechanical processing level. Then, the range of the wavelength value can be easily determined, but it is hard to control in the manufacturing process. It can be found that motion error can always met the design requirement even the sensitive value of the wavelength was selected when guide rails had 4 μm amplitude value. Which means the motion accuracy can be met in the whole motion stroke as long as the straightness error of the guide rails was smaller than 8 μm. Considering different motion stroke, in other words, like the main work area, where the local amplitude and wavelength parameters should be reevaluated, and hence the tolerance value of guide rails.

The two guide rails of open hydrostatic guideways were machined together on the same grinding machine. And we can assume that the phase difference $\Delta\varphi$ is near to zero. It can also be found that the motion error will not exceed 3 μm as the phase difference equal π which may be induced by manual lapping after the assemble processes completed, as the Fig. 6 shown. Hence, the phase difference is not a major concern for the tolerance design of guide rails.

The approach could be also be used for tolerance design for journal bearing in hydrostatic rotation table [21], like the roundness error of rotation shaft and bearing bush, based on the Reynolds equation, pressure boundary conditions, flux continuity equation of the land and kinetic equation of shaft. Also, the flatness error of thrust bearing bushing surface and perpendicularity error can be designed in hydrostatic thrust bearing. The results reveal that the rotation shaft should has tighter tolerance for improving the rotation accuracy of hydrostatic journal bearing in hydrostatic rotation table.

7. Conclusions

In this research, a tolerance design method for hydrostatic guideways motion accuracy based on error averaging effect was proposed. The conclusions are as follows:

(1) The motion error analysis model of open hydrostatic guideways for tolerance design was established based on error averaging effect.

(2) Effect of amplitude, wavelength and phase difference of guide rails on motion error were researched. The amplitude value should be designed with smaller value, and the parameters matching between wavelength and pad length is the main consideration. But the phase difference is not a major concern for the tolerance design. The research results can provide the important supports for the active design of tolerance design in the open hydrostatic guideways.

(3) The proposed method was applied to the tolerance design of open hydrostatic guideways in a grinding machine. As the 4 μm amplitude value and 1200 mm wavelength value were selected, the 1.25 μm/1200 mm slider motion error could be obtained that can satisfy the design requirement.

Acknowledgements

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