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Experimental Verification on a Motion Error Analysis Method of Hydrostatic Bearing Tables Using a Transfer Function

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ABSTRACT

A new method using a transfer function was proposed in the previous paper for analyzing motion errors of hydrostatic tables. The calculated motion errors by the new method, named as the transfer function method (TFM), were compared with the results by the conventional multi pad method, and the validity of the proposed method was theoretically verified. In this paper, the relationship between rail form error and motion errors of a hydrostatic table is examined theoretically in order to comprehand so-called 'the averaging effect of an oil film', and the characteristics of the motion errors in a hydrostatic table is tested. The tested hydrostatic table has three single-side pads in the vertical direction and three pairs of double-sides pads in the horizontal direction. The motion errors are tested for three rails which have different form errors. The experimental results are compared with the theoretical results calculated by the TFM, and both results show good agreement. From the results, it is shown that the TFM is very effective to analyze the motion errors of hydrostatic tables.

Keywords : Hydrostatic table, Motion error, Transfer function method, Transfer function of motion error, Limit of motion error, Averaging effect of oil film

1. Introduction

A new method utilizing a transfer function for effectively analyzing motion errors of hydrostatic tables was proposed in the previous paper[1]. The method was named as the TFM (Transfer Function Method). The transfer function is obtained from the relationship between film reaction force and rail form error in the method. As it is independent of variables such as clearance, number of pad and rail form error, motion errors on under different conditions could be simply analyzed. Also, the calculated motion errors by the TFM were compared with the results by the MPM (Multi Pad Method) in which the entire table is considered[2, 3], and the validity of the proposed method was theoretically verified.

In this paper, the relationship between rail form error and motion errors of a hydrostatic table is examined theoretically in order to comprehand so-called 'the averaging effect of an oil film', and the characteristics of motion errors in a hydrostatic table is investigated. The tested hydrostatic table has three single-side pads in the vertical direction and three pairs of double-sides pads in the horizontal direction. The motion errors are tested for three rails which have different form errors.

The experimental results are compared with the theoretical results calculated by the TFM, and as the reference, the results obtained by the MPM are also compared together.

2. Relation between Rail Form Error and Motion Errors of Table

When the table has only one pad, the relationship between rail form error and displacement of the pad is easily comprehensible using the transfer function. But it is not so easy in the case of multi pad, bacause motion errors depend not only on the transfer function but also geometric relation between the pads. For clear comprehension of the relationship, linear and angular transfer functions of the motion error, $Z(\omega)$ and $\Theta(\omega)$, are introduced. They represent mathematically the ratio of linear motion error $z(\omega)$ and angular motion error $\theta(\omega)$ to rail form error $e(\omega)$ as shown in Eq. (1), and represent physically the averaging effect of a table to each spacial frequency component of the rail. A large value of the transfer functions of the motion error means the reduction of the averaging effect.

$$Z(\omega)=\left|\frac{z(\omega)}{e(\omega)}\right|,\quad \Theta(\omega)=\left|\frac{\theta(\omega)}{e(\omega)}\right| \tag{1}$$

Also, in order to compare with the averaging effect of the oil film in a pad, the limit of motion errors, $Z'(\omega)$ and $\Theta'(\omega)$, are introduced as shown in Eq. (2). In those equations, $K(\omega)$ is the transfer function, K_0 is the film stiffness, m is the number of pads and l is the length of the rail.

$$Z'(\omega)=\left|\frac{K(\omega)}{K_0}\right|,\quad \Theta'(\omega)=\frac{2|K(\omega)|}{K_0(m-1)l} \tag{2}$$

$Z'(\omega)$ and $\Theta'(\omega)$ are proportional to the transfer function, and represent the maximum linear and angular motion errors with respect to a unit change in the magnitude of spatial frequency.

Fig. 1(a), (b), (c) show the calculated transfer functions of the motion error, when the same table has 2, 3 and 4 pads, respectively. The limit of the motion errors are represented by dot lines in the figures, and ω_R represents the spatial frequency based on the rail length. The ratio of the table length to the length of rail is 1/2. Film stiffnesses are the same in all cases.

The transfer functions of the motion error, in the case of m=2, are shown in Fig. 1(a). One of motion errors approaches to 0 at the frequencies of even numbers. Illustrating more accurately, the angular motion error approaches to 0 at the frequencies of even multiples of 2, and the linear motion error approaches to 0 at the frequencies of odd multiples of 2. At that time, the other motion error approaches to the limit of the motion error.

The transfer functions of the motion error, in the case of m=3, are shown in Fig. 1(b). The linear motion error approaches to 0 at the frequencies of multiples of 2. But, the angular motion error approaches to 0 and the linear motion error approaches to the limit of the motion error in the case of multiples of 6.

From above, it is confirmed that if frequencies of integer number are positioned within a table, the linear motion error approaches to 0 and the angular motion error approaches to the limit of the motion error, but, especially in the case of multiples of 6 at the frequencies of multiples of m, the aspects of motion errors are reversed. The same relation can be seen in Fig. 1(c). The reason is as belows;

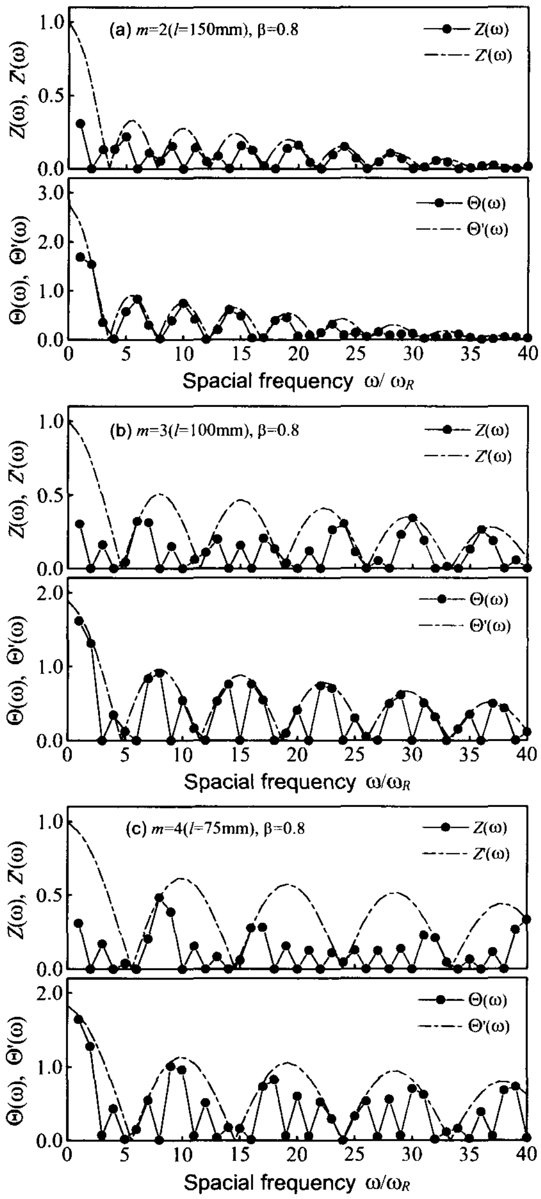

Fig. 1 Relationship between transfer function and motion error

As the integral of rail form error inside the table always be constant for the integer frequencies, the table has no linear displacement, but only has angular displacement.

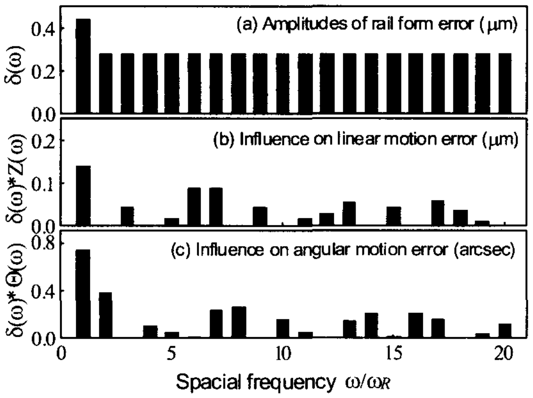

Fig. 2 Influence of spatial frequencies of the rail on the motion error

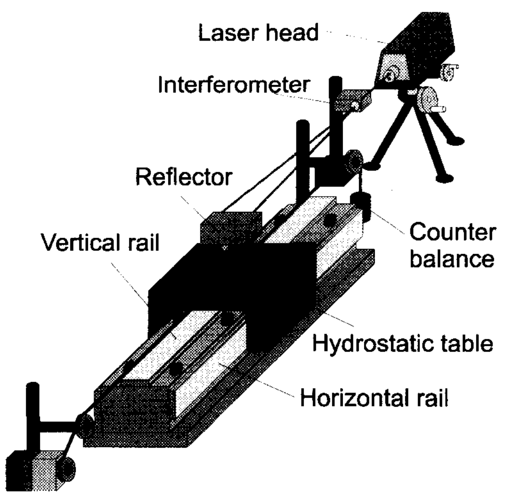

Fig. 3 Experimental setup for verification of the motion error analysis method

Table 1 Specifications of the hydrostatic table and the rail

Rail length, width	L, B	250, 30 mm
Table length, width	l_0, l_t	105, 105 mm
Pad length, width	l_x, l_y	30, 20 mm
Number of pad	n	3
Pocket ratio	β	0.70
Feeding parameter	ξ	1.0
Designed film clearance	h_0	45 μm
Supply pressure	p_s	1 Mpa

Utilizing the above characteristics, it is possible to build up a method effective to improve the motion accuracy. The relationship between spatial frequencies of rail and motion errors can be analyzed quantitatively by multipling the magnitude of frequency to the transfer function of the motion errors.

Fig. 2(b) and (c) show the influence of frequency components on the motion errors, for example, when the length ratio between the table and the rail is 0.5 and the pocket ratio is 0.8. Frequency components $\omega / \omega_R = 1$, 6 and 7 mainly affect the linear motion error, and $\omega / \omega_R = 1$, 2, 7 and 8 mainly affect the angular motion error. Therefore, by adjusting these frequency components of the rail, the motion errors can be improved effectively.

3. Experimental Setup and Method

An experimental setup is shown in Fig. 3. A tested

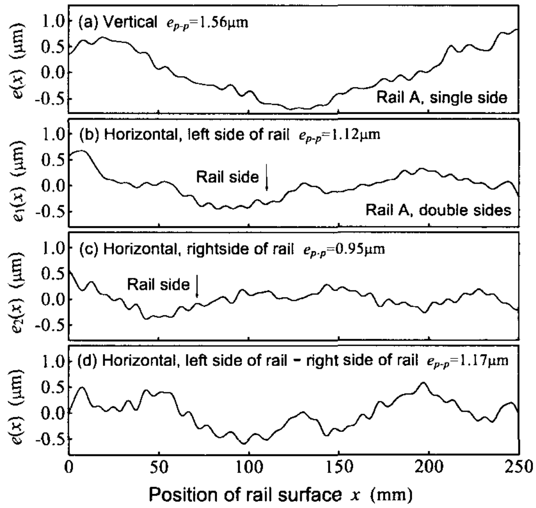

Fig. 4 Vertical and horizontal profiles of rail A

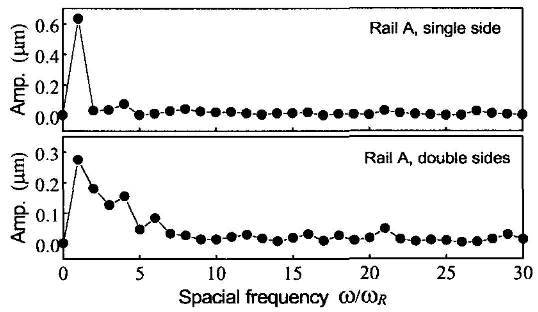

Fig. 5 Frequency components of rail A in the vertical and horizontal directions

hydrostatic table has three single-side pads in the vertical direction and three pairs of double-sides pads in the horizontal direction. The stroke of table motion is 145 mm. A wire rope and a stepping motor are used for driving the table. The specifications of the tested hydrostatic table are shown in Table 1.

For removing the influence of hydrodynamic effect, the feed rate of the table is controlled to 1 mm/s, and the motion errors are measured using a laser interferometer.

Rail A, B and C, which have different form errors respectively, are used in the experiment. Rail form errors are measured using a straightness measuring unit, which has been developed by authors and has the measuring accuracy of 0.04 μm[4].

The form errors of rail A in the vertical (single-side) and horizontal (double-sides) directions are shown in Fig. 4, and their frequency components are shown in Fig. 5. In the vertical direction, $\omega / \omega_R = 1$ is the dominant frequency component, and a few low frequencies are distributed with small magnitudes. In the horizontal direction, $\omega / \omega_R = 1\sim4$ are the dominant frequency components.

The form errors of rail B are shown in Fig. 6, and their frequency components are shown in Fig. 7. In the vertical direction, $\omega / \omega_R = 1$, 2 are the dominant frequency components, and especially the magnitude of $\omega / \omega_R = 2$ is larger than that of rail A. In the horizontal direction, $\omega / \omega_R = 1$, 2 are the dominant frequency components, and $\omega / \omega_R = 3\sim6$ are smaller than those of rail A.

The form errors of rail C are shown in Fig. 8, and their frequency components are shown in Fig. 9. In the vertical direction, $\omega / \omega_R = 3\sim5$ are the dominant frequency components, and larger than that of rails A and B. In the horizontal direction, $\omega / \omega_R = 3\sim5$ are the

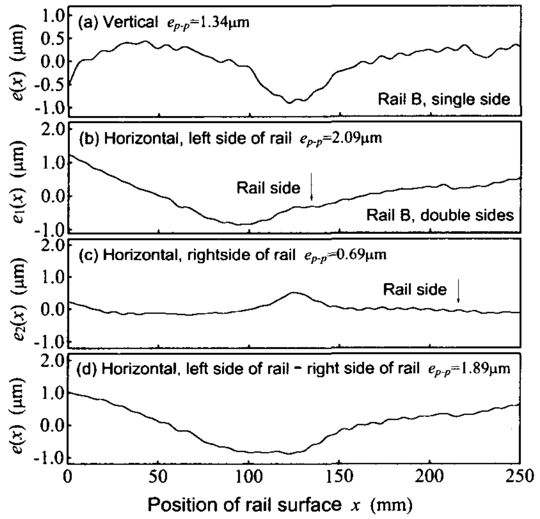

Fig. 6 Vertical and horizontal profiles of rail B

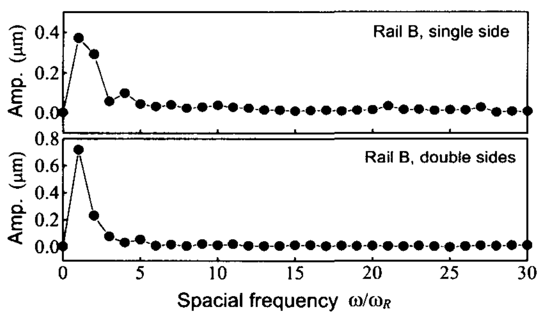

Fig. 7 Frequency components in the vertical and horizontal profiles of rail B

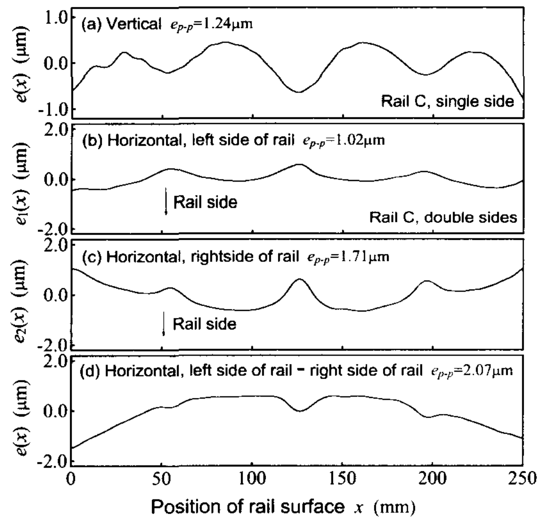

Fig. 8 Vertical and horizontal profiles of rail C

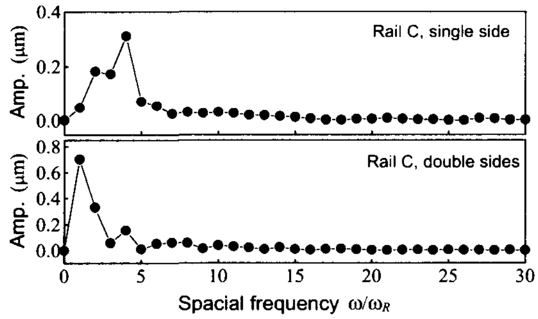

Fig. 9 Frequency components in the vertical and horizontal profiles of rail C

dominant in the upper and lower rails. But as both rails are symetric and the difference between both rails works as a practical form error, ω / ω_R =1, 2 become dominant frequency components as shown in Fig. 8(d) and Fig. 9.

The calculated transfer functions of motion error and the limits of the motion error in the vertical direction are shown in Fig. 10. Frequency ω / ω_T , which is based on the table length, is also shown. Low frequencies mainly affect the motion error as shown in the figure. Examining more precisely, frequency components ω / ω_R =1, 2, 3, 4 and 6 largely affect the linear motion error. In the case of frequency components smaller than 2, as the stroke of table motion is shorter than 1 period of the form error, the influence on the motion error is practically smaller than the transfer function of the motion errors. For example, the transfer function of the motion error on ω / ω_R =1 is 0.75, but the practical motion error is 0.45. On the other hand, comparing Z(ω) with $Z'(\omega)$, it is confirmed that the averaging effect in the table is larger than in the pad. It is due to the interaction between the three pads.

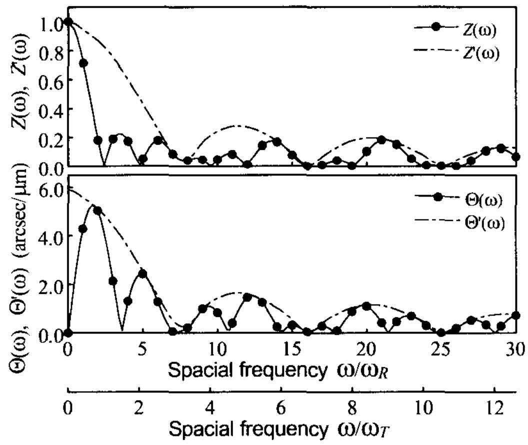

Fig. 10 Transfer function of the table and the limit of motion error on the vertical table

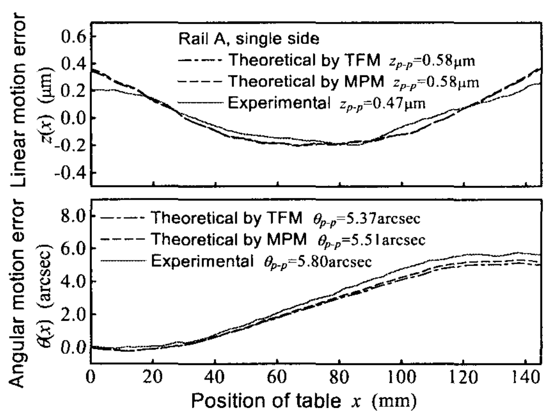

Fig. 11 Motion error in the vertical direction with rail A

As the table dimensions in both directions are the same, transfer characteristics between rail form error and motion errors of the table in the horizontal direction is also shown in as Fig. 10.

4. Results and Discussions

4.1 Case of single -side table

The measured motion errors of the table with rail A, B and C are compared with the theoretical results as shown in Fig. 11~Fig. 13, and the theoretical results by the MPM are presented together in the figures. The

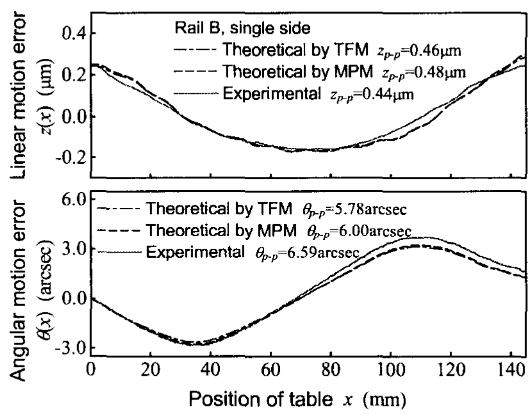

Fig. 12 Motion error in the vertical direction with rail B

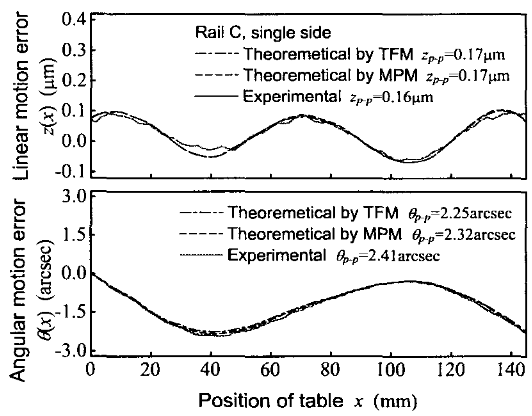

Fig. 13 Motion error in the vertical direction with rail C

experimental and theoretical results show good agreement in all the cases. It is estimated that small differences in both results mainly come from the setup error of the wire rope for driving the table, and from the position error of the optic for measurement.

On the other hand, comparing the measured profiles of the motion errors in rail A and rail B (Fig. 11 and Fig. 12), the linear motion errors are similar to each other, but the angular motion errors are not. The ratio of the form error of rail B to rail A is 0.85, but the measured linear motion error is almost the same and the angular motion error is larger. The reason is that $\omega / \omega_R = 2$ is a dominant frequency component in the case of rail B and it largely affect the angular motion error as shown in Fig. 5, 7 and 10.

In the case of rail C, the motion errors are more improved, compared with the form errors of rails A and B. The reason is that the frequency component $\omega / \omega_R = 1$, most dominant in the linear and angular motion errors, is relatively small.

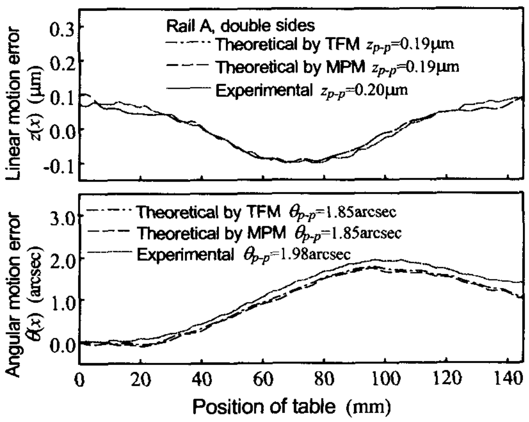

Fig. 14 Motion error in the horizontal direction with rail A

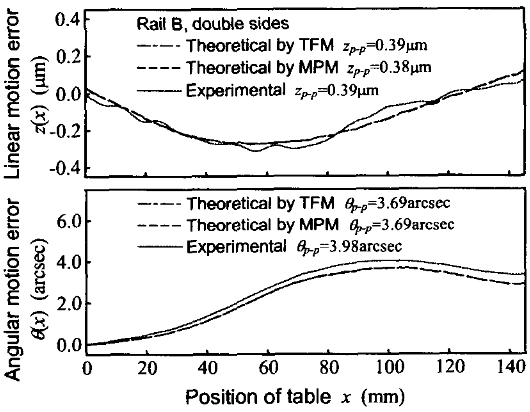

Fig. 15 Motion error in the horizontal direction with rail B

4.2 Case of a double-sides table

The measured motion errors of a double-sides table with rail A, B and C are compared with theoretical results, as shown in Fig. 14~Fig. 16

The experimental and theoretical results show good agreement in all the cases. There is also small difference in the anglur motion error, and the reason is similar to that for the case of the single-side tables.

On the other hand, comparing the ratio of the motion errors with the ratio of form errors like as the case of single-side table, rail B has the largest motion errors because of its dominant frequencies $\omega / \omega_R = 1, 2$.

From above, it is confirmed that the TFM is very effective to analyze the motion error of single-side and double-sides hydrostatic tables.

5. Conclusions

In this paper, the averaging effect of an oil film in hydrostatic tables is calculated and discussed quantitatively, and an attempt to verify the effectiveness of the transfer function method is performed experimentally. From the theoretical and experimental results, it is confirmed that the averaging effect of an oil film in a table can be obtained quantitatively, by calculating the transfer function of motion errors with respect to unit magnitude change in spatial frequencies.

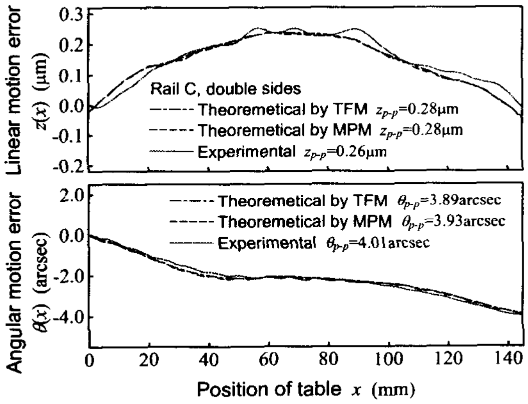

Fig. 16 Motion error in the horizontal direction with rail C

Also, as the experimental and theoretical results of the motion errors show good agreement in both directions, it is shown that the motion errors of hydrostatic tables can be precisely analyzed by using the proposed tansfer function method.

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