International Journal of Precision Engineering and Manufacturing Vol.5, No.3, July 2004.

Experimental Verification on the Corrective Machining Algorithm for Improving the Motion Accuracy of Hydrostatic Bearing Tables

Chun Hong Park[1,#], Chan Hong Lee[1] and Husang Lee[1]

[1] Machine tools group, Korea Institute of Machinery & Materials, Daejeon, South Korea

ABSTRACT

Effectiveness of a corrective machining algorithm, which can construct the proper machining information to improve motion errors utilizing measured motion errors, is verified experimentally in this paper. Corrective machining process is practically applied to single and double side hydrostatic bearing tables. Lapping process is applied as a machining method. The machining information is obtained from the measured motion errors by applying the algorithm, without any information on the rail profile. In the case of the single-side table, after 3 times of corrective remachining, linear and angular motion errors are improved up to 0.13 μm and 1.40 arcsec from initial error of 1.04 μm and 22.71 arcsec, respectively. In the case of the double-side table, linear and angular motion error are improved up to 0.07 μm and 1.42 arcsec from the initial error of 0.32 μm and 4.14 arcsec. The practical machining process is performed by an unskilled person after he received a preliminary training in machining. Experimental results show that the corrective machining algorithm is very effective and easy to use to improve the accuracy of hydrostatic tables.

Key words : Hydrostatic table, Corrective machining algorithm, Transfer function, Motion error, Rail form error, Experimental verification

1. Introduction

Generally, each pad of multi-pad type hydrostatic bearing tables has the same shape and size, and they pass over the same position in the rail sequentially with a spatial phase shift. Therefore, using the geometric relationship between the pads and the transfer function which represents the relationship between the spatial frequency components of the rail profile and the variation of film force in the pad, the motion errors of a multi-pad type table can easily be calculated[1, 2]. Also, reversely, the rail form error can be estimated from the measured motion errors. The authors have proposed a corrective machining algorithm which can construct the corrective machining information (position and amount of machining) without any information on the rail profile, and the effectiveness of the algorithm has been verified theoretically[3].

In this paper, experimental verification on the algorithm was performed. A hydrostatic table which has a single-side table in the vertical direction and a double-side table in the horizontal direction, was prepared and practically machined in experiment. Lapping process was applied as a machining method. In order to confirm the practicality of the algorithm, the machining process was performed by an unskilled person after he had received a preliminary training in machining.

☞ Manuscript received: February 2, 2003 ;
Accepted: May 24, 2003
Corresponding Author:
Email: pch657@kimm.re.kr
Tel: +82-42-868-7117, Fax: +82-42-868-7180

2. Experimental Set up and Method

2.1 Experimental set up

The schematic diagram of the experimental set up is shown in Fig. 1. The hydrostatic table has a single-side table in the vertical direction and a double-side table in the horizontal direction. The table has three vertical and three horizontal pairs of pads in each direction. The specifications of the hydrostatic table is shown in Table 1.

The table was driven by a stepping motor and a wire-rope, and had a stroke of 145 mm. Weights were connected to the opposite side of the motor for the counter balance. Feed rate of the table was 1 mm/s, and the motion errors were measured by a laser interferometer (HP5528A) and a GPIB board. The rail form error in the vertical direction is shown in Fig. 2(a). Left and right side of rail profiles in the horizontal direction are also shown in Fig. 2(b) and (c). In the case of experiment in the horizontal direction, the difference between the left and right side profiles, as shown in Fig. 2(d), was assumed as the rail form error of the equivalent single-side table. The length of rail is 250 mm. The rail form error was measured for the comparison and verification of experimental data using the previously developed unit with a measuring accuracy of 0.04 μm[4].

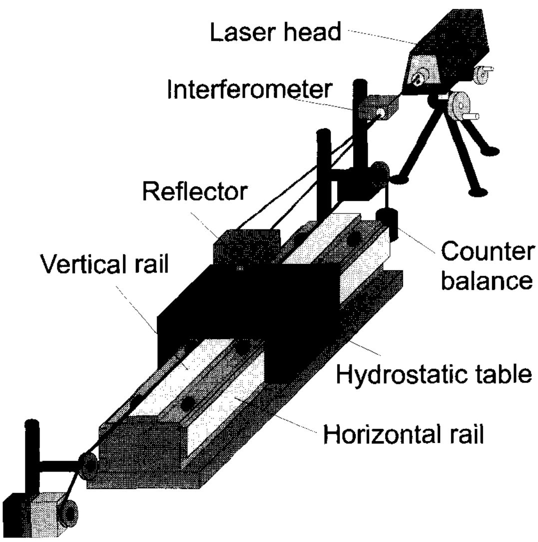


Fig. 1 Experimental setup for corrective machining

Table 1 Specifications of hydrostatic table and rail

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

2.2 Experimental method

The corrective machining information is obtained by applying the algorithm to the measured linear and angular motion errors. It is given initially in the form of amounts to be cut according to the rail position. Then it is converted to the form of the necessary number of times of lapping using the preliminarily decided lapping gain(the number of lapping per unit amounts).

As the rail had been heat-treated with a hardness of HRC 50~55, a rectangular type lapping stone(10×2×150 mm, #800, Bellstone VH-800, Yonjisa) was used with the water for machining. The lapping gain was about 100 times/μm. However, there exist some deviations from the lapping factors such as lapping pressure, contacted area, wear of lapping stone, and so on. In order to maintain the amount of lapping as constant as possible, the stroke of lapping was limited to 30 mm in the direction of rail width. As the width of lapping stone was 10 mm, the number of lapping was computed on every 10 mm along

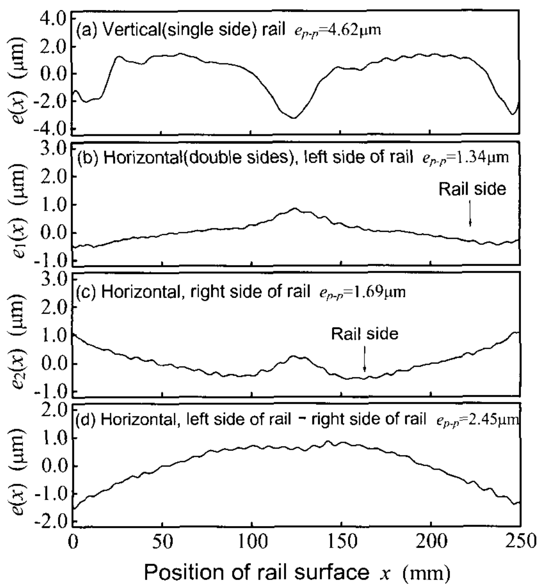


Fig. 2 Profiles of rails used in experiment

the rail. Also, the spatial frequency components, the length of which was shorter than 10 mm, were ignored in the calculation.

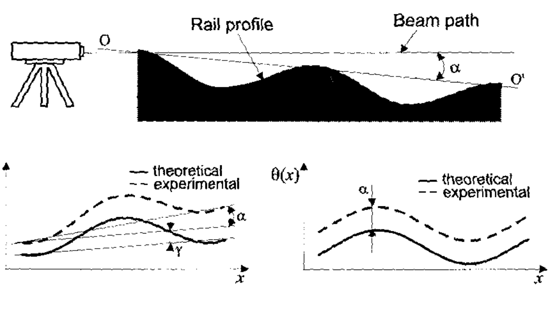
As it was unavoidable that a deviation occurs between the calculated information and practically lapped results, the corrective machining was successively iterated until the target accuracy was acquired in the experiment.

On the other hand, as the whole experimental process was performed based on the estimated rail profile from the algorithm, there always existed two data set: one was from the 'true' rail, and the other from the 'estimated' rail. Therefore, the effect of the remachining could be analyzed and examined by comparing the two data sets in each step. The true linear and angular motion errors $z_c(x)$ and $\theta_c(x)$ measured after the remachining was compared with the estimated linear and angular motion errors $z_t(x)$ and $\theta_t(x)$ expected from the algorithm. Also, the true rail form error $e_c(x)$ measured after the remachining was compared with the estimated form error $e_t(x)$ expected by the algorithm.

2.3 Compensation for the periodic function

Every profile dealt in the algorithm is assumed as a periodic function. But, in practice, two discontinuity problems occur during the process.

One is the fact that it is impossible to obtain the initial values of the true motion errors, because they are removed together with the setup errors of the laser interferometer in the process for removing the setup errors, as shown in Fig. 3. Linear motion errors has a changed slope and angular motion error has a shifted initial value. The calculated film force using these two



(a) linear motion error (b) angular motion error

Fig. 3 Relationship between theoretical and experimental data

measured motion errors has a discontinuous profile. This problem can be recovered by iterative calculation and comparison of the linear motion error calculated according to the varied initial value of angular motion error with measured one.

The other is that the film force profile must be a periodic function over the effective rail length L_f in the algorithm. But the calculated film force is not, because the measured motion errors are not a periodic function over the effective rail length. This problem also can be recovered by the iterative calculation as explained below; Firstly, angular motion error profile is parallelly shifted with a distance of α, and the corresponding slope of linear motion error is changed. Then the film force corresponding to the changed motion error profiles is calculated. This procedure is iterated until both ends of the calculated film force profile have the same height.

3. Experimental verification of the algorithm

3.1 Case of the single-side table

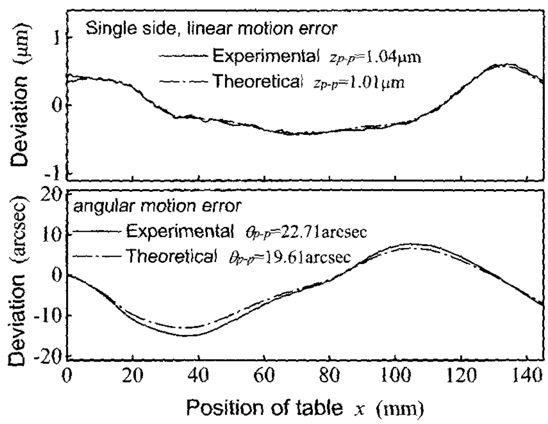


Fig. 4 Motion errors of single side table

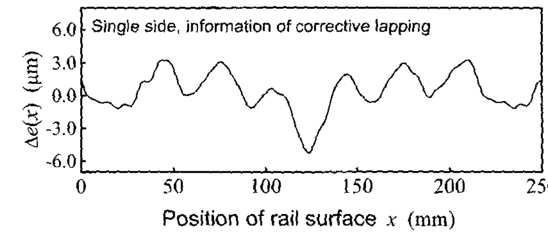


Fig. 5 Information of corrective lapping calculated from the estimated rail

The measured motion errors in the single-side table are shown in Fig. 4. Angular motion error is mainly affected by the influence of a periodic component of ω / ω_R =2. The estimated rail form error using the measured motion errors is shown in Fig. 5. The profile is similar to that of the true rail in Fig. 2(a). But a periodic component of ω / ω_R =8 is overestimated in the calculation. The obtained corrective machining information from the estimated rail and the lapping gain is shown in Fig. 6.

The measured motion errors after the first corrective lapping are shown in Fig. 7. They are compared with the estimated motion errors from the estimated rail in Fig. 5. The motion errors was largely improved comparing with those before the corrective lapping in Fig. 4, but they are not reduced as much as expected. The measured rail form error after the first corrective lapping is shown in Fig. 8. The estimated rail form error using the algorithm is shown together. The periodic component of ω / ω_R =8, which was dominant in the estimated rail, was not shown

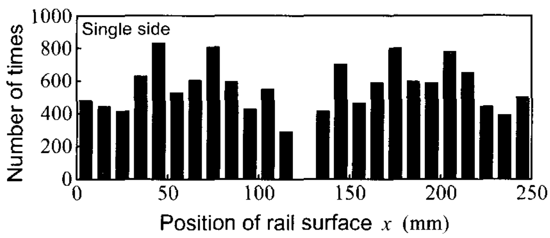


Fig. 6 Calculated amount to be machined for the first corrective lapping

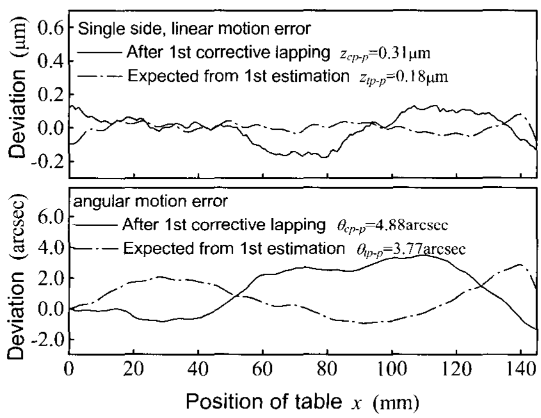


Fig. 7 Motion errors after the first corrective lapping

in the machined true rail. On the whole, the practically machined amount was less than that from the constructed machining information. The amount of lapping might be reduced by the wear and surface loading effect of the lapping stone.

The motion errors and the rail form error measured after the second corrective lapping are shown and compared with the estimated ones in Figs. 9 and 10. Although the rail form error was largely changed from 2.48 μm to 1.27 μm as shown in Fig. 10, the motion

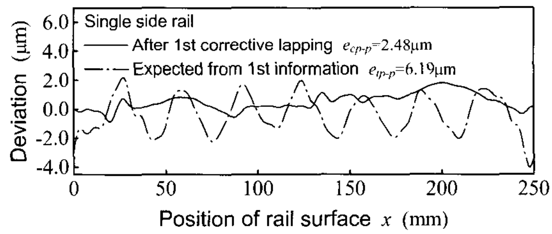


Fig. 8 Rail form errors after the first corrective lapping

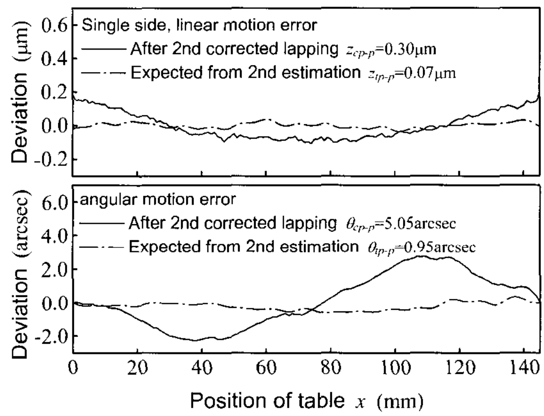


Fig. 9 Motion errors after the second corrective lapping

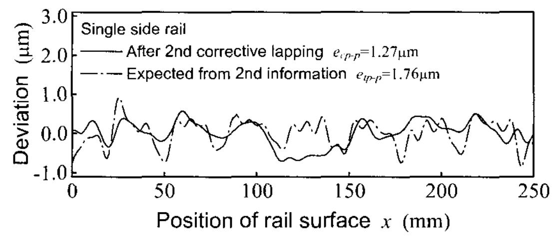


Fig. 10 Rail form errors after the second corrective lapping

errors shown in Fig. 9 was not largely improved. Comparing the rail form errors, both profiles was similar with each other. But, the amount of lapping at the central part of the rail (x=110 ~ 140 mm) largely exceeded the target amount from the machining information, and it might be the main reason why the motion errors had not been improved.

The corrective machining information was newly constructed by using the measured motion errors in Fig.

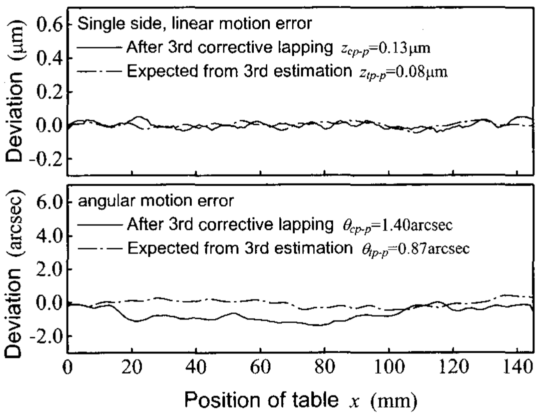


Fig. 11 Motion errors after the third corrective lapping

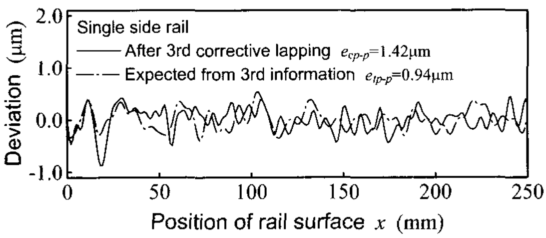


Fig. 12 Rail form errors after the third corrective lapping

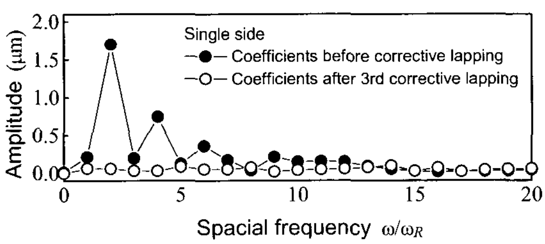


Fig. 13 Frequency components of rail form errors before and after lapping

9, and the third corrective lapping was performed on the basis of the imformation. The motion errors and the rail form error measured after the third corrective lapping are shown and compared with the estimated ones in Figs. 11 and 12. The linear and angular motion errors after the machining were reduced to 1/10 of those before machining and 0.13 μm and 1.40 arcsec.

On the other hand, it was confirmed that the relatively high spatial frequency components were increased when the number of corrective machining was increased, as shown in Figs. 8, 10 and 12. It means that the profile becomes difficult to follow in the next corrective machining. Therefore, it is necessary to reduce the number of times of the corrective machining, in order to obtain more improved motion errors.

Frequency analysis results on the measured rail form error before and after the corrective machining are shown in Fig. 13. It was confirmed that most of the low frequency components had been removed during three

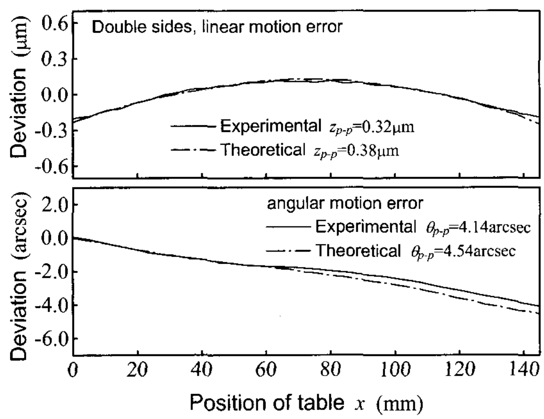


Fig. 14 Motion errors of double sides table

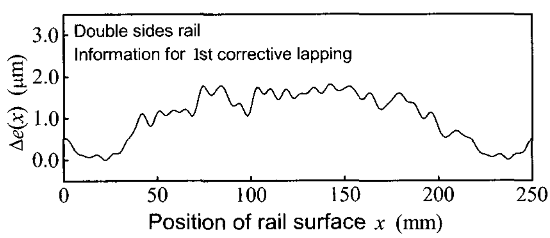


Fig. 15 Information of corrective lapping calculated from estimated rail

corrective machining processes.

From the above experimental results, we could see that the motion errors of the single-side table could be largely improved by the application of the corrective machining, even if there was no information on the rail form error.

3.2 Case of the double-side table

In the case of double-side table, as there existed two rail form errors, the algorithm was applied to the virtual rail having a profile which corresponded to the difference between the two rail profiles, as shown in Fig. 2(d). Practical machining was performed to an arbitrary one of the two rails. The more symmetric the two rail profiles were, the smaller motion errors could be obtained. To maintain the amount of each lapping at a certain level, the surface of the lapping stone was continuously monitored and changed in this case.

The measured motion errors of the double-side table are shown in Fig. 14, and the corrective machining information constructed from them is shown in Fig. 15. The measured motion errors after the first corrective machining were well agreed with the estimated ones as shown in Fig. 16. Compared with the motion errors before machining, They were improved to 0.07 μm from 0.32 μm in linear and also to 1.42 arcsec from 4.14 arcsec in angular, respectively. The target accuracy, which was the same with the estimated motion errors, became satisfactory after one time of corrective machining.

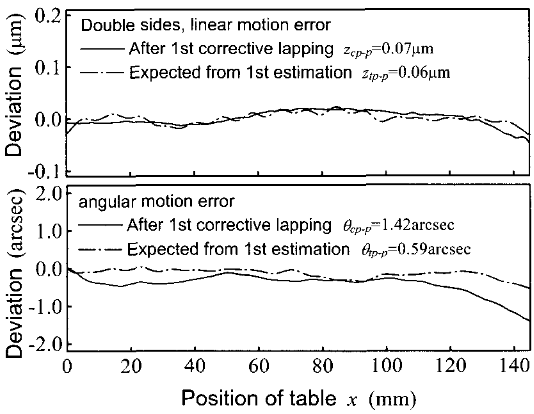


Fig. 16 Motion errors after the first corrective lapping

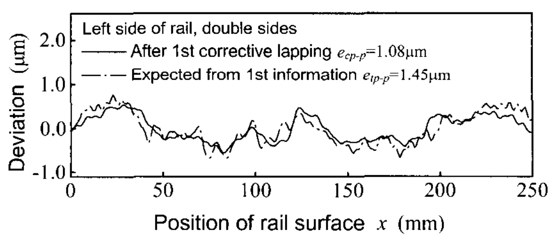


Fig. 17 Rail form errors after first corrective lapping

If we compare the measured and the estimated rail form errors after the machining, we can see that they show good agreement except for a little difference at high frequencies, as shown in Fig. 17. On the other hand, comparing the rail form errors before(Fig. 2) and after(Fig. 17) the machining, the profile of the left side of the rail itself was not largely improved, but became symmetric with that of the right side of the rail as shown in Fig. 2(c). Therefore, it was confirmed that the motion errors of the double-side table were improved, as the shape of the machined rail became identical with that of the other rail.

From above results, we could see that the motion errors of the double-side table could also be effectively improved by applying the corrective machining.

4. Conclusions

Effectiveness of the corrective machining algorithm in the single and double side table was verified experimentally in this paper. In the case of the single-side table, after 3 iterations of the corrective machining, linear and angular motion errors were improved up to 0.13 μm and 1.40 arcsec from the initial errors of 1.04 μm and 22.71 arcsec, respectively. In the case of the double-side table, linear and angular motion errors were improved up to 0.07 μm and 1.42 arcsec from the initial errors of 0.32 μm and 4.14 arcsec. The practical machining process was performed by an unskilled person after he had recieved a introductory training in machining. Experimental results showed that the corrective machining algorithm was very effective, and easy to use to improve the accuracy of hydrostatic tables.

Acknowledgement

The authors gratefully acknowledge the support of the Ministry of Science and Technology under the National Research Laboratory project.

References

1. Park, C. H., Oh, Y. J., Lee, C. H. and Hong, J. H., "Theoretical Verification on the Motion Error Analysis Method of Hydrostatic Bearing Tables Using a Transfer Function," Int. J. of KSPE, Vol. 4, No. 2, pp. 64-70, 2003.
2. Park, C. H., Oh, Y. J., Lee, C. H. and Hong, J. H., "Experimental Verification on the Motion Error Analysis Method of Hydrostatic Bearing Tables Using a Transfer Function," Int. J. of KSPE, Vol. 4, No. 2, pp. 57-63, 2003.
3. Park, C. H., Lee, C. H. and Lee, H., "Corrective Machining Algorithm for Improving the Motion Accuracy of the Hydrostatic Tables," J. of KSPE, Vol. 19, No. 6, pp. 62-70, 2002.
4. Park, C. H., Chung, J. H., Lee, H. and Kim, S. T., "Development of a Submicron Order Straightness Measuring Device," J. of KSPE, Vol. 17, No. 5, pp. 124-130, 2000.