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Development of a web-based simulator for estimating motion errors in linear motion stages

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Abstract. This paper presents a web-based simulator for estimating 5-DOF motion errors in the linear motion stages. The main calculation modules of the simulator are stored on the server computer. The clients use the client software to send the input parameters to the server and receive the computed results from the server. By using the simulator, we can predict performances such as 5-DOF motion errors, bearing and table stiffness by entering the design parameters in a design step before fabricating the stages. Motion errors are calculated using the transfer function method from the rail form errors which is the most dominant factor on the motion errors. To verify the simulator, the predicted motion errors are compared to the actually measured motion errors in the linear motion stage.

Keywords: Motion errors, Linear motion stages, Transfer function method, Simulator

1. Introduction

Motion errors such as straightness (vertical and horizontal) and angular errors (pitch, yaw and roll) are one of the important performances when designing a linear motion stage. However, it is generally not possible to estimate the stage before it is built and tested. If the motion errors do not meet the final goal, the design of stage should be repeatedly modified with other design parameters and tested until the target is met [1]. This is a quite time-consuming and uneconomical process. To overcome this problem, we developed a motion accuracy simulator for the linear motion stages. From the simulator, we can estimate performances such as motion errors, and stiffness of bearing and stage by entering the design parameters in a design step before fabricating the stage. The main calculation modules of the simulator are stored on the server computer. The clients use the client software to send the design parameters to the server and receive the calculated results from the server.

The 5-DOF motion errors are mainly affected by the rail form errors of the linear motion stage. The motion errors can be calculated from the transfer function method, together with the equilibrium equations of force and moment of the stage [2-3]. The transfer function is the relationship between amplitude of the sinusoidal rail form error and the reaction force of a bearing generated when it is straightly moved on the rail without any motion errors. Then, the reaction forces are calculated from the arbitrary rail form errors consisting of the Fourier series in the form of sinusoidal rail, and superimposed for all the bearings on the stage. Therefore, this transfer function method can be applied to various types of bearings; aerostatic, hydrostatic and linear motion bearings. By predicting the motion errors of the stages in a design step, we can evaluate the required machining tolerance of the guide rail before production. Therefore the motion errors can be satisfied with the target value by adjusting the machining...
tolerance of the guide rail. To verify the developed algorithm and simulator, the predicted motion errors are compared to the actually measured motion errors in the linear motion bearing stage.

2. Algorithm for estimating motion errors

Motion errors such as straightness and angular errors are mostly affected by rail form errors. In general, the table is assumed to be rigid, and only the bearings are deformed by forces and moments caused by rail form errors. Conventionally, the motion errors of a linear stage are calculated by fully taking the equilibrium equations of forces and moments into consideration. This method is quite accurate, but, requires a separate analytical model that can be applied to the other types of bearings.

Linear motion stages usually consist of the same bearings. If we know the force characteristics of a bearing when moving on a rail, we can calculate the forces and moments of the entire stage using the geometric relationship between the bearings, as shown in Figure 1 (b). To do this, we introduced the transfer function method [2-3]. The transfer function is the relationship between the amplitude of the sinusoidal rail form error and reaction force of a bearing generated when it is straightly moved on the rail without any motion errors. The reaction forces are then calculated from arbitrary rail form errors consisting of a Fourier series of sinusoidal rail forms, and superimposed for all bearings in the entire stage. Therefore, this transfer function method can be applied to various bearings; aerostatic, hydrostatic and linear motion bearings. This is a great advantage of using the transfer function method when analyzing motion errors.

![Figure 1. Concept of developed analytical method](image)

Figure 2 shows an analytical model for estimating motion errors in a linear motion stage. $K_{y}$, $K_{z}$ are the bearing stiffness in the $y$ and $z$ directions. $e_{y1}(x)$ and $e_{y2}(x)$ are the rail form errors in the $y$ direction, and $e_{z1}(x)$ and $e_{z2}(x)$ are the rail form errors in the $z$ direction. $f_{y}$ and $f_{z}$ are the reaction forces of the bearings in the $y$ and $z$ directions.

![Figure 2. Analytical model for predicting motion errors](image)

The vertical and horizontal displacements ($z_{ij}$ and $y_{ij}$) at each bearing position are expressed using the 5-DOF motion errors, which is shown in equation (1). $\delta_{z}$ and $\delta_{y}$ are vertical straightness and horizontal straightness errors, and $\theta_{x}$, $\theta_{y}$, and $\theta_{z}$ are roll, pitch, and yaw errors, respectively. $i$ is the bearing number,


\[ j \] is the rail number. \( X_i \) is the distance between the table center and the \( i \)-th bearing, and \( Y_j \) is the distance between the table center and the \( j \)-th rail.

\[
\begin{align*}
    z_i &= \delta_i - \theta_i X_i + Y_j \theta_j \\
    y_i &= \delta_j + X_i \theta_i + z_i \theta_i
\end{align*}
\]  

Finally, the equilibrium equation of forces and moments for 5-DOF directions are given in equation (2). By solving these equations, the 5-DOF motion errors can be calculated.

\[
\begin{align*}
    &\sum_j \sum_i (f_{x,0} - K_{x,0} z_i) = 0 \\
    &\sum_j \sum_i (f_{y,0} X_i - K_{y,0} z_i X_i) = 0 \\
    &\sum_j \sum_i (f_{z,0} Y_j - K_{z,0} z_i Y_j) + \sum_j \sum_i (f_{y,0} - K_{y,0} y_j) = 0 \\
    &\sum_j \sum_i (f_{x,0} + K_{x,0} y_j) = 0 \\
    &\sum_j \sum_i (f_{z,0} - K_{z,0} z_i) = 0
\end{align*}
\]  

(2)

### 3. Development of a web-based simulator

Figure 3 shows the structure of a web-based simulator. The simulator consists of four sub-modules [4]: motion error analysis module for linear and rotary motion units, control analysis module, and structural analysis module. In the motion error analysis module, 6-DOF motion errors (including positioning error) for linear and rotary stages can be calculated from rail form errors. And volumetric errors for machine tools can be estimated using the results obtained from these two modules. In the control analysis module, frequency response function (FRF) and step response can be predicted from the developed analysis model and MATLAB software. The structural analysis module performs static/dynamic/thermal analysis based on ANSYS and Inventor with simplification automation service developed in the module. The main modules of this simulator are stored on the server computer. The clients use the client software to send the design parameters to the server and receive the calculated results from the server. This paper focuses on simulator of linear motion unit. The analytical models described in Chapter 2 are coded in Visual Basic and C++.

![Figure 3. Structure of a web-based simulator.](image-url)
Figure 4 shows a web-based simulator. The simulator is very simple and has a hierarchical structure.

![Web-based simulator](image)

**Figure 4.** Web-based simulator.

Figure 5 shows the procedure for estimating motion errors in linear motion units. First, user inputs the axis configuration such as bearing type, feed unit, encoder type, number of bearings and rails, and external force. Second, the design parameters for aerostatic and hydrostatic bearings are provided. For linear motion bearings, the model must be selected from the database (DB) stored in the DB server. In order to analyze the 6-DOF motion errors, rail form errors should be given. In assembly process of stages, user can predict the motion errors by directly measuring the rail form errors. At this time, the rail form errors can be adjusted to satisfy the target. However, the rail form errors are usually not known in a design step. In this case, the rail form errors are assumed based on actual experience. In fact, it is generally a periodic sinusoidal form. Then, feeding unit such as a ballscrew or a linear motor is selected in the database. The positioning error is predicted using the Abbe offset due to the angular motion errors of the table. To more accurately estimate positioning error, scale error of a linear scale should be provided. The 6-DOF motion errors are calculated after all these operations.

4. Experimental verification

Linear motion bearing stage is built to validate simulation results. The stage consists of four linear motion bearings (THK SHS30R), a coreless linear motor (Trilogy 310-4N) and a linear scale (Renishaw RGH24). The UMAC controller is used to feed the stage. For linear motion bearings, the algorithm has been modified since it is not possible to directly measure rail form errors. The modified algorithm uses the straightness errors of the bearing block instead of the rail form errors. The straightness errors of the bearing block can be easily measured using a laser interferometer or other equipment.

The left figure in Figure 6 shows the experimental setup for the linear motion bearing stage. The figure on the right is the result of simulation and experiment. Overall, vertical and horizontal straightness errors, pitch, yaw and roll errors are very well matched with between them.
Figure 5. Process for estimating 6-DOF motion errors in a linear motion stage.

Figure 6. Comparison between predicted and experimental motion errors.
5. Conclusion & Future work

In this paper, we have developed a simulator to estimate the motion errors in linear motion stages. By using the simulator, we can predict performances such as motion errors and stiffness of the stage by entering design parameters in the design step. The simulator works through the server system where all the calculation modules are stored. The developed algorithm for predicting the motion errors has been verified by comparing with experimental data for a linear motion bearing stage.

The developed simulator is unidirectional, so the performance can be evaluated with only given design parameters. Therefore several calculations with different parameters are required to obtain final design results. Recently, we have developed a design optimization module to overcome the shortcomings of the previous one-way simulator. Design optimization systems make it easy to determine design parameters that can meet the target performance.

6. References

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