Force Measurement Acting on the Moving Part of a Linear Air Bearing

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The compressed air supplied from outside is firstly introduced into the guideway rather than directly into the moving part. The reason for this is to avoid pressure piping on the moving part.

In the design, airflow between the guideway and the moving part is always bilaterally symmetric except in the air passage channels.

- **Stroke**: 100 mm
- **Maximum weight**: 30 kg
- **Thickness of the air film**: 8 µm
- **Stiffness of the air film**: 80 N/µm
- **Straightness of the guideway**: 0.1 µm/100mm
Experimental setup for measuring the force acting inside the bearing

- He-Ne laser
- Counter Advantest R5363
- PBS
- CC
- Polarizing plate
- Moving part
- Sig. beam
- Ref. beam
- LD
- Base isolated from other parts
- Computer
- GPIB
- Counter HP 53131A
- Trig. Sig.
- Guideway
- Damper
- Free Reciprocating Motion
- Free Reciprocating Motion
- Sig. beam
- Guideway
Angle measurement system

Silicon oil
used as the horizontal plane

Autocollimator-2

Mirror
put on the guideway

Cube corner prism
attached to the moving part

Moving part

Optical Interferometer

Autocollimator-1

Mirror
attached to the tilting stage

Tilting stage

$\theta$

$x, v$
Data processing procedure

Data processing: from frequency to velocity, position, acceleration and force.

Tilt angle of the guide way $\theta = 0.0$ mrad,

Mass of the moving part $M = 4.119$ kg

$(Mg = 40$ N)
Inertial force acting on the moving part of the bearing

1 measurement for about 15 seconds

All obtained data

Selected data for the analysis
(First 3 sets of reciprocating motion, -38mm < X < 38 mm)
Distributions of the measured force against the time, the position, the velocity and the tilt angle.

Mutual relationships of the force against the position, the velocity and the tilt angle of the stage are sufficiently estimated from the figure.

15 measurements, 7063 sets of data.

Regression analysis
Regression analysis

Under the assumption that the force acting on the moving part is the sum of the components in proportion to the position, the velocity and the tilt angle, the following is derived.

\[ F = A_1 x + A_2 v + A_3 \theta + A_4, \]

Using the 7063 sets of data, the four coefficients of the equation, \( A_1, A_2, A_3, A_4 \), are determined by means of the least squares method.
Theoretical estimate: \( F = A_1 x + A_2 \, v + A_3 \, \theta + A_4, \)

**As for the theoretical estimate of \( A_1: \)**

The coefficient, \( A_1, \) corresponds to the force component being proportional to the position of the moving part, which was measured to be \(-1.5 \times 10^{-1} \) (N/m) in the static condition ([Other paper]). This is thought to come from the pressure difference between the two sides of the air passage channels. Under the assumption that this static force acts as it is even when the moving part is in motion, the value of the theoretical estimate is \(-1.5 \times 10^{-1} \) (N/m).

**As for the theoretical estimate of \( A_2: \)**

The coefficient \( A_2 \) is thought to correspond to the dynamic frictional force acting on the moving part, \( F_D. \) Under the assumption that the dynamic frictional force is equal to the frictional drag of Couette flow in the air film, it is expressed as

\[
F_D = - \mu_{\text{air}} S/h \, v = A_2 \, v,
\]

The coefficient \( A_2 \) is calculated to be \(-5.9 \times 10^{-2} \) (N/ms\(^{-1}\)) using the nominal value of the thickness, \( h \), of approximately 8 \( \mu \)m.

**As for the theoretical estimate of \( A_3: \)**

The coefficient \( A_3 \) is thought to correspond to the component of the force of gravitation in the direction of the guideway, and it is expressed as

\[
F = M g \sin \theta = M g \theta = A_3 \, \theta,
\]

Therefore, the coefficient \( A_3 \) is calculated to be \(4.0 \times 10^1\) (N/rad).

**As for the theoretical estimate of \( A_4: \)**

The coefficient \( A_4 \) is zero in the ideal conditions.
The coefficients obtained experimentally and theoretically

<table>
<thead>
<tr>
<th></th>
<th>Experimental results (Results of Regression)</th>
<th>Theoretical estimates</th>
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<tbody>
<tr>
<td>$A_1$ (N/m)</td>
<td>-1.8 $\times$ 10^{-1}</td>
<td>-1.5 $\times$ 10^{-1}</td>
</tr>
<tr>
<td>$A_2$ (N/ms)</td>
<td>-6.8 $\times$ 10^{-2}</td>
<td>-5.9 $\times$ 10^{-2}</td>
</tr>
<tr>
<td>$A_3$ (N/rad)</td>
<td>4.1 $\times$ 10^{1}</td>
<td>4.0 $\times$ 10^{1}</td>
</tr>
<tr>
<td>$A_4$ (N)</td>
<td>5.3 $\times$ 10^{-3}</td>
<td>0</td>
</tr>
</tbody>
</table>
Relationship between the measured force and the calculated value using the regression equation

The root mean square value (RMS value) of the difference between $F_{\text{meas}}$ and $F_{\text{cal}}$ is 0.0016 N (1.6 mN).

This also indicates both of the accuracy of the force measurement and the validity of the supposed form of regression equation.
Concluding Remarks

A method for evaluating forces acting on the moving parts of pneumatic linear bearings is proposed.

The total force acting on the moving part is accurately measured as the inertial force using an optical interferometer.

Then the components of the force, such as the force component depending on position, the force component depending on velocity, and the force component depending on tilt angle, are evaluated using the least squares method.

In the experiment, the total force acting on the moving part of approximately 4 kg, whose absolute value is up to approximately 0.04 N, is measured with the standard uncertainty of approximately 0.001 N.

The experimentally evaluated values of these force components, such as the dynamic frictional force and the component of the gravitational force in the direction of the guideway, well coincide with the theoretically expected values.

Using this method, the force acting on the moving part of a linear bearing can be accurately measured, and the validity of arbitrary regression equations can be determined.

This method will be effective to elucidate the generation mechanism of the force acting inside the linear bearing. This method will also be useful for inspecting the profile quality of bearings in manufacturing process.