Measurement of Spindle Rigidity by using a Magnet Loader

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Abstract

The static rigidity of a rotating spindle in the radial direction is investigated in this research. A magnetic loading device (magnet loader) has been developed for the measurement. The magnet loader, which has coils and iron cores, generates the electromagnetic force and attracts a dummy tool attached to the spindle. However, the eddy current is generated in the dummy tool with the spindle rotation and reduces the attractive force at high spindle speed. In order to understand the magnetic flux and eddy current in the dummy tool, the electromagnetic field analysis by FEM was carried out. Grooves on the attraction surface of the dummy tool were designed to cut the eddy current flow. The dimension of the groove were decided based on the FEM analysis, and the designed tool were manufactured and tested. The test result shows that the designed tool successfully reduces the eddy current and recovers the attractive force. By using the magnet loader and the grooved tool, the spindle rigidity can be measured when the spindle rotates with a speed up to 10,000 min⁻¹.

Key words: Machine Tool, Spindle, Rigidity, Electromagnetic Attractive Force, Spindle Displacement, Magnet Loader, Noncontact Measurement

1. Introduction

In recent years, it is essential for machine tools industry to develop high speed spindles to enhance the productivity. In order to obtain efficient rough cutting and fine finishing capabilities, not only the high speed but also high rigidity are required for such spindles. Thus the \(d/N\) number of a high speed spindle has been approaching to 2 - 3 millions. Such a spindle often requires the preload control according to spindle rotation speed to prevent a bearing from burning and to ensure sufficient rigidity for machining. In this literature, some researchers presented the measurement of spindle's radial displacement by sensors built into the spindle for monitoring of cutting force\(^{(1)}\).\(^{(2)}\). The important parameter for converting spindle displacement to cutting force is the rigidity of rotating spindle. However, it is difficult to model and predict the spindle rigidity, as it changes due to various factors. Therefore, the rigidity measurement of rotating spindle is essential. Tsuneyoshi\(^{(3)}\) developed...
a measurement system of the rotating spindle’s rigidity in the axial direction. He indicated that it is difficult to measure the static rigidity of the spindle under the non-rotating condition due to the nonlinear characteristics, which is influenced by the preload setting of the bearing system. Matsubara et al. (4) developed the contact type loading device to provide a force to the spindle in its radial direction to model the spindle rigidity. This device can arbitrarily control the force and its duration to measure spindle rigidity. However, it was difficult to measure the spindle rigidity when the spindle rotates at more than 5,000 min⁻¹ because of heat generation at the contact face of the bearings to connect the loading device and the spindle. Furthermore, the dynamics of loading device may affect the measured spindle displacement, which must be eliminated to accurately measure spindle rigidity. On the other hand, Rantatalo et al. (5) developed the noncontact measurement system using the magnetic loading device to load in the radial direction and measured the vibration characteristic including the rotor dynamics of the spindle. Similarly, Kim et al. (6) exploited the similar equipment and reported the relationship between the load and the signal from the displacement sensor installed in the spindle. However, both papers reported mainly dynamic characteristics of the spindles.

In this research, we develop a non-contact magnetic loading device to measure the static rigidity of the rotating spindle in the radial direction. The general outline of spindle rigidity measurement and the developed loading device are described in §2. Then, the electric field analysis of the developed loading device and the grooved tool to prevent eddy currents are described in §3. In §4, the result of the spindle rigidity measurement experiments by using the developed loading device are described. The conclusion is given in §5.

2. Spindle Rigidity Measurement and Loading Device

2.1 Spindle Rigidity Measurement

A spindle in machine tools consists of a rotating body with a motor rotor, bearings, motor our research, the load is applied to a dummy tool that is attached to the spindle with a holder unit and the measurement point of the displacement is at the nose of the spindle.

2.2 Summary of Non-contact Type Loading Device

The non-contact type loading device (magnet loader) generates magnetic field on the inner wall of a cylinder surrounding a tool, and applies load to a tool by magnetic field. The loading device is composed of iron core, coils and housing. The iron core wound by four coils is set in metallic housing, as shown in Fig. 1. The signals (A), (A'), (B) and (B') which are indicated in Fig. 1 are from each coil. The iron core is a laminate structure of piles of steel plates in z-axis.

Figure 2 shows the layout of the loading device and the spindle. The tool is placed between each pair of the iron cores. A dummy tool of sufficiently large diameter is used for measurement.

A magnetic field is generated by an electric current in the direction shown by the dotted line on two coils (A) and (A') shown in Fig. 1. The magnetic attractive force to the dummy tool in +y direction is generated by this magnetic field.

As shown in Fig. 3, the distance between the outer circumference of the dummy tool and the iron core is called the air gap. The air gap is 0.8 mm when the dummy tool is placed at the center of the cylindrical hole. Table 1 shows main specifications of the magnet loader.
3. Electromagnetic Field Analysis of Magnet Loader

3.1 Introduction

The attraction force by a magnet loader drops down by the effect of eddy current generated on the dummy tool's surface when a spindle rotates in higher speed. This section will present a electromagnetic field analysis by FEM (finite element method) to quantitatively evaluate this influence, and then to propose a countermeasure for this problem.
<table>
<thead>
<tr>
<th>Dummy tool</th>
<th>Diameter</th>
<th>40mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material</td>
<td>Chromium molybdenum steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electric Conductivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>: $1.031 \times 10^7$ S/m</td>
</tr>
<tr>
<td>Iron core</td>
<td>Inner diameter</td>
<td>41.6 mm</td>
</tr>
<tr>
<td></td>
<td>Outer diameter</td>
<td>460 mm</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>80 mm</td>
</tr>
<tr>
<td></td>
<td>Width of core in coils</td>
<td>15 mm</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>Non-directional magnetic steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lamination direction : z axis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thickness : 0.35 mm</td>
</tr>
</tbody>
</table>

### 3.2 Electromagnetic Field Analysis Software

Generally, FEM analysis for an electromagnetic field is carried out by making a finite element equation about a vector potential by using Maxwell relations and solve the equation by using iterative method called ICCG (Incomplete Cholesky) method. In addition, an electromagnetic force is obtained by the equation which is derived by applying a virtual displacement method to the energy ($B\cdot H / 2$ per unit area, where $B$: density of magnetic flux, $H$: magnetic field).

The electromagnetic field analysis software (JSOL, JMAG-studio ver.9.1) is used in this research. Figure 4 shows the model of the magnet loader and the dummy tool used for the analysis. The half model of the magnet loader's iron core, the coils and the dummy tool in x and z direction is made with considering the symmetrical property of the experimental setup. An electric current is given to only the coil (A). The deformation and displacement of the model are ignored because the analysis purpose is to calculate electromagnetic field.

![Fig. 4 Model of magnet loader and dummy tool for FEM analysis](image)

### 3.3 Electric Current - Force Relationship on Rotating Spindle

The purpose of the analysis is to examine the behavior of an electric eddy current in the dummy tool and to find its influence to attractive force when the spindle is rotating. The analysis assumes that the electric current to the coils stays constant and the dummy tool's rotation speed is $1,000 \text{ min}^{-1}$. The attractive force to the dummy tool is calculated with different electric currents, 0, 0.5, 1.0... 7A. The nominal air gap, 0.8 mm, is assumed.

The relationship between the electric current and the attractive force is obtained by the analysis as shown in Fig. 5. It can be observed that the attractive force to the dummy tool decreases with the spindle rotations at the higher speed. Figure 6 shows the electric current density on the surface of the dummy tool in the vector representation. The direction of rotation is shown in Fig. 6. There is no electric current flow in the dummy tool when the...
spindle is not rotating. When the spindle rotates, the electric current goes to \(-z\) direction under the coil (A) and to \(+z\) direction under the coil (B). At upper end region, the electric current flows in the rotating direction.

The analysis clarified that the attractive force to the dummy tool decreases by the tool's rotation. It is caused by the electric current induced on the tool's surface canceling the magnetic flux between the tool and attractive faces.

The induction of electric current on the tool can be understood as follows: consider a certain area on the dummy tool's surface as shown in Fig. 7. The magnetic flux going through this area outwardly is named \(\phi\). The magnetic flux \(\phi\) increases when this area moves from the region facing coil (B) to coil (A) with the spindle rotation. The electric current, which makes the magnetic field in the inward direction to cancel the change of this magnetic flux, flows by Lenz's law. This is the electric current shown in Fig. 6 (b).

An electromotive force is generated when a magnetic flux which inter-links to a conduction body changes in terms of time by its motion. This electric current by an electromotive force is an eddy current.

![Fig. 5 Calculated relationship between coil current and attractive force on dummy tool](image)

![Fig. 6 Comparison of current density at dummy tool's surface](image)
3.4 Design of Grooved Dummy Tool

To reduce an eddy current, a rotating body of laminated sheet steels is often used. However, a dummy tool made of laminated sheet steels is not favorable by safety and cost reasons. We thus use a dummy tool with grooves on its circumferential surface as shown in Fig. 8, expecting the effect similar to laminated sheet metal. The width of grooves must be as narrow as possible because smaller tool surface may reduce the attractive force.

A magnetic field in a conduction body generally decreases in an exponential manner with the distance from a conduction surface. The depth where the strength of a magnetic field becomes $1/e$ ($e$: base of natural logarithm) of the strength on the surface is called as the depth of penetration or the epidermis depth, denoted by $d$ [m], and is given as follows:

$$d = \frac{2}{\sqrt{\omega \sigma \mu}}$$  \hspace{1cm} (1)

$$\omega = \frac{20000 \times 2\pi}{60}$$  \hspace{1cm} (2)

where $\omega$ [rad/s] is an angular frequency, $\sigma$ [S/m] is an electrical conductivity and $\mu$ is a magnetic permeability ($= 4\pi \times 10^{-7}$ H/m). Assuming stationary current, $\sigma$ is set $1.031 \times 10^7$ S/m, through it is a function of $\omega$ in a precise sense. In addition, Eq. (1) is obtained by solving Maxwell's equations under the condition in a conductor. $\omega$ is set 2100 rad/s by Eq. (2), considering the spindle's maximum rotation speed, 20,000 min$^{-1}$. Substituting this value into Eq. (1), it is clear that the groove depth $d$ needs to be at least 8.6 mm. Consequently, the grooved dummy tool with the axle diameter is 20 mm and the depth of the grooves 10 mm is produced for the experiment.

The effect of grooves in reducing eddy current and then increasing attractive force is analyzed. The analysis is carried out under the condition where the width of the air gap is 0.8 mm as the nominal distance, the electric current value is 5 A and the spindle rotation speed is 1,000 min$^{-1}$. The analysis is performed for each of following dummy tool models:

1. Massive form (As in § 3.3)
2. Structure with grooves of 2 mm width at 10 mm intervals in radial outward direction
3. Structure with grooves of 1 mm width at 5 mm intervals in radial outward direction
Table 2  Calculated attractive force on dummy tool of each structure

<table>
<thead>
<tr>
<th>Attractive force N</th>
<th>Massive 0 min⁻¹</th>
<th>Grooved (a) 183</th>
<th>Grooved (b) 182</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000 min⁻¹</td>
<td>259</td>
<td>205</td>
<td>182</td>
</tr>
<tr>
<td>Percentage of decrease %</td>
<td>35</td>
<td>21</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2 shows the attractive force to each dummy tool after the convergence of a field. As has been previously shown, the attractive force to the massive form dummy tool is reduced by 35% when it rotates at 1,000 min⁻¹. On grooved dummy tools (a) and (b), the attractive force is reduced by 21 and 30%, respectively. The reduction is smaller than the massive dummy tool case.

Figure 9 shows an electric current density on the face of each dummy tool after the convergence of field. The density is expressed by the brightness. The main electric current pass is shown by the dotted line. The same electric current density is expressed by the same color in each tool.

It can be observed that the electric current on the surface of the grooved dummy tool is significantly smaller than that on the massive dummy tool. The current loop observed on the grooved dummy tool in Fig. 9 is generated at each groove. The magnetic field induced by the electric current to z-direction is a main contribution to cancel the magnetic field generated by coil current, since the influence of the current in the XY plane is canceled by each other.
4. Spindle Rigidity Measurement by Non-contact Loading Device

4.1 Experimental Setup

This section presents the experiment of spindle rigidity measurement by using the developed loading device. Two of the three dummy tools, the massive tool (a) and the grooved tool (b) are actually produced and used in experiments. Figure 10 shows the setup of the measurement experiment. The radial displacement at the spindle nose is measured with eddy current sensors installed in the spindle housing. The maximum spindle speed of the experimental machine tool is 20,000 min⁻¹. The reaction force to the loading device is measured by a dynamometer (Kistler: 9257B), which can be seen as the load to the dummy tool. The electric current to the coils is less than 3 A.

![Picture of experimental device](Fig. 10)

4.2 Relationship between Electric Current and Attractive Force

The electric current to the magnet loader is increased from 0 to 3 A in 2 seconds and is then decreased from 3 to 0 A in 2 seconds. The load to each dummy tool is measured when spindle is not rotating and rotating at 10,000 min⁻¹. Each tool is set at the center of the magnet loader's hole. That is to say that the air gap is 0.8 mm which is the nominal distance.

The relationship between the electric current and the attractive force in each rotation speed is shown in Fig. 11. The horizontal axis represents the electric current in A and the vertical axis shows the attractive force in N. As predicted in the analysis, the load to the grooved dummy tool is slightly smaller than that to the massive dummy tool due to the reduction in the surface facing the iron core. The attractive force to the massive dummy tool drops dramatically to 180 N at 3A when the spindle rotates in 10,000 min⁻¹. On the other hand, the attractive force to the grooved dummy tool under 10,000 min⁻¹ is about 300 N at 3A. It shows that the cutting grooves to dummy tool is effective to recover attractive force.

![Comparison of attractive forces](Fig. 11)
4.3 Relationship between Spindle Displacement and Attractive Force

The electric current to the magnet loader was increased from 0 to 3 A in 2 seconds and is then decreased from 3 to 0 A in 2 seconds, the spindle displacement was measured with two dummy tools, under spindle speeds 0, 2,000, 4,000, 8,000 and 10,000 min⁻¹. Figure 12 shows the measured relationships between displacement and attractive force. As can be seen in Figs. 12 (a) and (b), displacement-force relationships obtained under the spindle rotating conditions have a same pattern, whose slope indicates spindle rigidity. In Fig. 12 (b), the rigidity obtained at the different speeds looks slightly different. The balls of the spindle bearing may be slipped, but this reason is not clear at this moment. When the spindle is not rotating, the force-displacement curves have large hysteresis. We consider that this is why the contact angle of bearing balls changes due to the load when the spindle is not rotating.

5. Conclusions

We constructed the spindle rigidity measurement system with a magnetic loading device. The conclusions are as follows.

(1) Based on the electro-magnetic analysis by using FEM, the dummy tool with grooves on its surface to prevent the eddy current is designed. It has been shown the designed tool recovers the attractive force when the spindle rotates at higher speed.

(2) By using the magnetic loading device and the grooved tool, it is possible to measure the spindle rigidity with the rotation speed up to 10,000 min⁻¹.

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References


