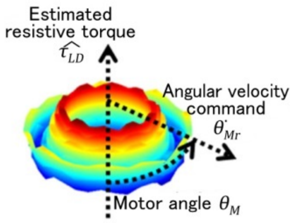
Visualization of Resistive Torque Distribution and Evaluation of Rotational Axis Characteristics for Improvement of Machining Accuracy



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Devices that require high assembly accuracy, such as machine tools, often require performance evaluation through actual machining after assembly is complete in order to evaluate the soundness of the rotational axis.

By accurately estimating the resistive torque at the time when the built-in motor is rotated at a low speed, the magnitude of the rotational axis resistive torque, which depends on the angle and angular velocity, can be evaluated. Furthermore, by displaying the resistive torque distribution in three dimensions, the uniformity of the rotational axis resistive torque can be evaluated at a glance. This inspection test can be conducted immediately after mounting the motor without actual machining.

This report presents a technology that makes it possible to evaluate the state of a rotational axis by visualizing the resistive torque distribution.

1. Introduction

In order to understand the state of the rotational axis of devices that require high assembly accuracy, such as machine tools, performance evaluation through actual machining is required, so a test after completion of assembly is required. In addition, although there are several methods of factor analysis and numerical quantification for performance evaluation, they require a separate measuring instrument to be attached, so such methods may not lead to machining accuracy.

With such a background, Mitsubishi Heavy Industries Machine Tool Co., Ltd. developed a technology to quantify and visualize the resistive torque around the rotational axis based on the driving data of the built-in motor in order to understand the states of the rotational axis and use them to improve equipment performance.

Chapter 2 of this report shows the configuration of the target machines, chapter 3 gives an explanation of the developed algorithm and the verification results using an element test device and chapter 4 presents the results of applying this technology to a gear grinding machine.

2. Target machine configuration and state quantity to be evaluated

Figure 1 shows the element test device that we made to simulate a target machine. The target machine is, like the spindle of a gear grinding machine, composed of a motor that is the drive source of the rotational axis, bearings, a seal and a load that acts as the inertia of the rotational axis.

Figure 2 schematically represents the machine shown in Figure 1. The dynamic characteristics in the low speed region are expressed by the equation of motion (1). In this equation, J_M is motor inertia, J_L is load inertia, θ_M is motor angle, τ_M is motor torque, τ_{MD} is motor internal resistive torque (cogging torque, etc.) and τ_{LD} is load resistive torque.

$$(J_M + J_L)\ddot{\theta}_M = \tau_M - \tau_{MD} - \tau_{LD} \qquad (1)$$

τ_{MD} is cogging torque and Coulomb friction, but the Coulomb friction is small, and the cogging torque is dominant. Therefore, first, two resistive torques are calculated from the right side of the following equation.

$$\tau_{MD} + \tau_{LD} = \tau_M - (J_M + J_L)\ddot{\theta}_M \qquad (2)$$

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By estimating and removing the cogging torque component τ_{MD} from the resistive torque waveform, τ_{LD} is obtained.

The machine characteristics are understood by estimating the load resistive torque τ_{LD} based on the equation (1). In particular, by estimating the resistive torque using the operating data at the time when the axis is rotated at a low speed, it is possible to accurately understand the characteristics of the machine.

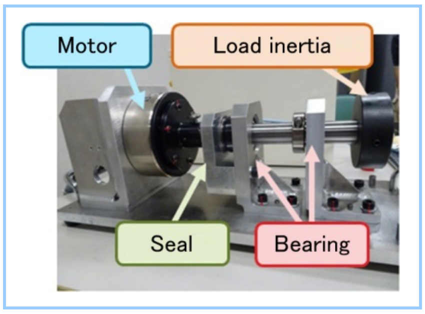

Figure 1 Construction of target machine (element test device)

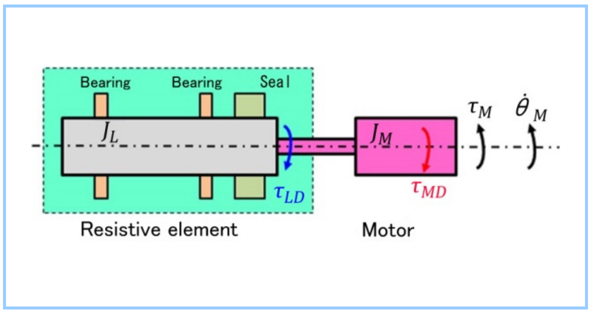

Figure 2 Schematic diagram of machine element

3. Visualization and analysis technology of distribution of rotational axis resistive torque

Figure 3 illustrates the visualization flow of resistive torque distribution for understanding the state of the rotational axis. The resistive torque distribution is obtained by performing processes [1] to [4] based on the test data acquired at multiple rotation speeds. Sections 3.1 to 3.4 give the details of each process.

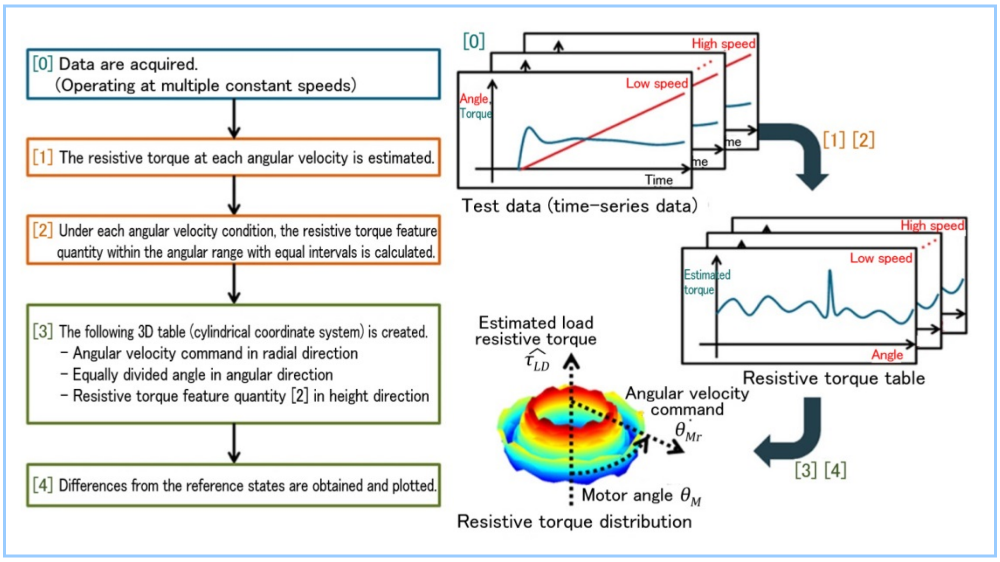

Figure 3 Visualization flow of resistive torque distribution

3.1 Estimation of resistive torque

Based on the equation of motion (1), the load resistive torque τ_{LD} generated at a resistive element of the machine is estimated as the estimated load resistive torque $\widehat{\tau_{LD}}$.

For inertias J_M and J_L in the equation (1), use the design information, and for the motor torque τ_M, the command value. By properly estimating the remaining motor internal resistive torque τ_{MD} and motor angular acceleration $\ddot{\theta}_M$, the estimated load resistive torque $\widehat{\tau_{LD}}$ can be accurately obtained.

First, the motor internal resistive torque τ_{MD} is removed by one of the following methods.

(1) Substitute the motor torque at the time when the load element is removed, and the motor is driven alone.

(2) Extract the measurement noise and cogging torque, which are obtained in advance, using FFT (Fast Fourier Transform) analysis and remove them from the motor torque.

(3) Create the 3D table described later in section 3.3 for the motor alone and obtain the difference in the 3D table between the motor alone and the combination of the motor and the resistive element as shown in Section 3.4.

The motor angular acceleration $\ddot{\theta}_M$ is derived by numerically differentiating the measured motor angle θ_M without phase lag while removing noise using offline processing. The case presented in this report uses the Savizky-golay filter[1] based on the function fitting by the method of least squares method.

The estimated load resistive torque $\widehat{\tau_{LD}}$ was estimated by the equation (1) using the state quantities derived as described above.

3.2 Calculation of resistive torque feature quantity

Using the estimated load resistive torque $\widehat{\tau_{LD}}$ estimated in the previous section and the measured motor angle θ_M and angular velocity command value $\dot{\theta}_{Mr}$, the resistive torque feature quantities for the angle and angular velocity are calculated by the following process.

(1) Estimate the estimated load resistive torque $\widehat{\tau_{LD}}$ for each angular velocity operation prepared in advance.

(2) For each angular velocity operation, calculate the feature quantity from the estimated load resistive torque $\widehat{\tau_{LD}}$ in the angular range with equal intervals. Calculate feature quantities using the maximum value, the p-p value, the variance, the average value, etc., according to the purpose. **Figure 4** is the calculation method using the maximum value as an example.

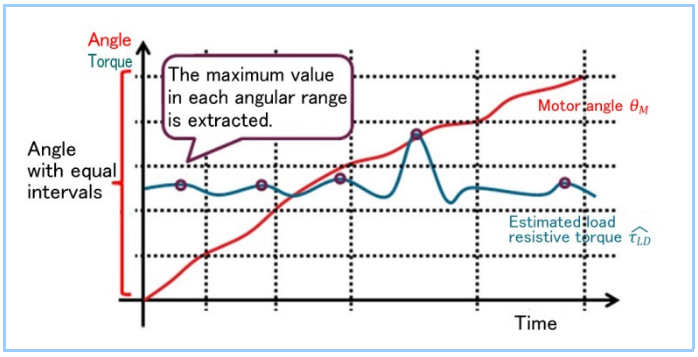

Figure 4 Calculation of resistive torque feature quantity

3.3 Creation of 3D table

Based on the feature quantities calculated in the previous section, the resistive torque distribution is shown as a 3D table in order to express the machine characteristics.

In this report, as an example of using the maximum value for the feature quantity, a table of the estimated load resistive torque maximum values with respective to the motor absolute angle and the angular command is created. The table is expressed in a cylindrical coordinate system where the logarithmic value of the angular velocity command value $\dot{\theta}_{Mr}$ is plotted in the radial direction, the equally divided motor absolute angle is plotted in the angular direction and the maximum value of the estimated load resistive torque calculated in the previous section is plotted in the height direction. **Figure 5** is an example of the 3D table.

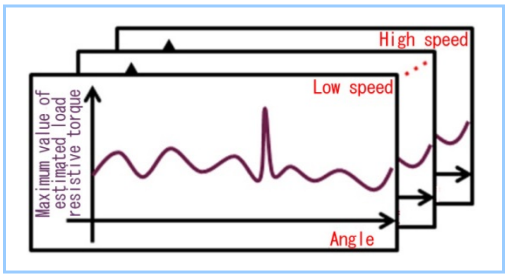

Figure 5 Creation of 3D table

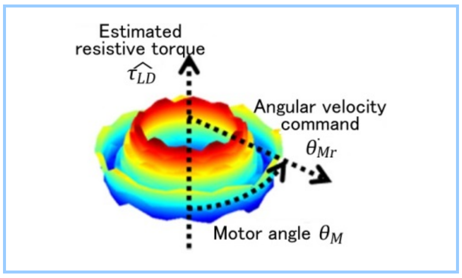

Figure 6 Example of resistive torque distribution

3.4 Obtainment of difference between estimation and reference state

By plotting the 3D table created in the previous section in three dimensions, the resistive torque distribution of the machine is obtained. **Figure 6** gives an example of resistive torque distribution at the time when the maximum value is used for the feature quantity. This distribution enables collective evaluation of the frictional characteristics depending on the angular velocity for each angle.

Obtaining the difference from the reference state using the created resistive torque distribution allows for understanding the state of the machine. By using the resistive torque distribution of a normal machine or the resistive torque distribution immediately after delivery as the reference state, it is possible to evaluate the deviation from the normal state and the degree of device deterioration.

To make it easier to obtain the difference from the reference state, the variation during one rotation can be evaluated by obtaining the difference from the average value for each set rotation speed. **Figure 7** is the distribution obtained by obtaining the difference between the resistive torque distribution acquired on a certain day and the resistive torque distribution acquired on another day, and then obtaining the difference from the average value at each angular velocity. This indicates the day difference of the device.

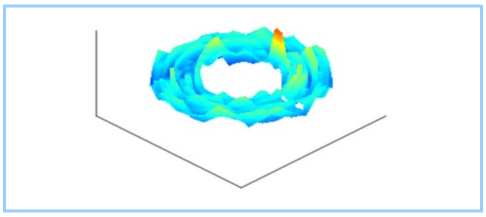

Figure 7 Variation during one rotation

3.5 Verification of effectiveness using element test device

In order to verify the effectiveness of this method, a resistive torque distribution at the time when an abnormality was intentionally generated in the element test device shown in Figure 1 is created. Abnormality examples generated were (1) foreign matter in the bearing, (2) gradient on the seal sliding surface, (3) scratch on the seal sliding surface and (4) shaft eccentricity. **Figure 8** presents the resistive torque distribution of these examples.

Each abnormality generated has a distinct distribution shape, so it is possible to narrow down the cause of the abnormality to some extent.

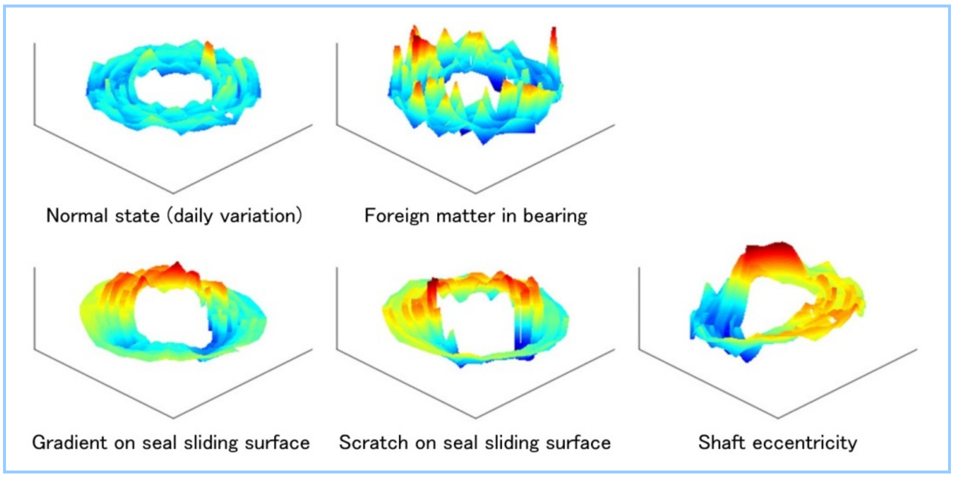

Figure 8 Resistive torque distribution at time of various abnormalities

4. Application to gear grinding machine

The developed technology was applied to the spindle of a gear grinding machine to confirm the effect of visualization of the resistive torque distribution.

The spindle of the gear grinding machine uses a built-in motor. In order to eliminate the characteristics peculiar to the motor, it is necessary to remove the cogging torque and switching noise using FFT analysis as described in 3.1 (2). **Figure 9** depicts the flow at the time when this technology is applied to a gear grinding machine and **Figure 10** shows the removal flow of motor internal resistive torque using FFT analysis.

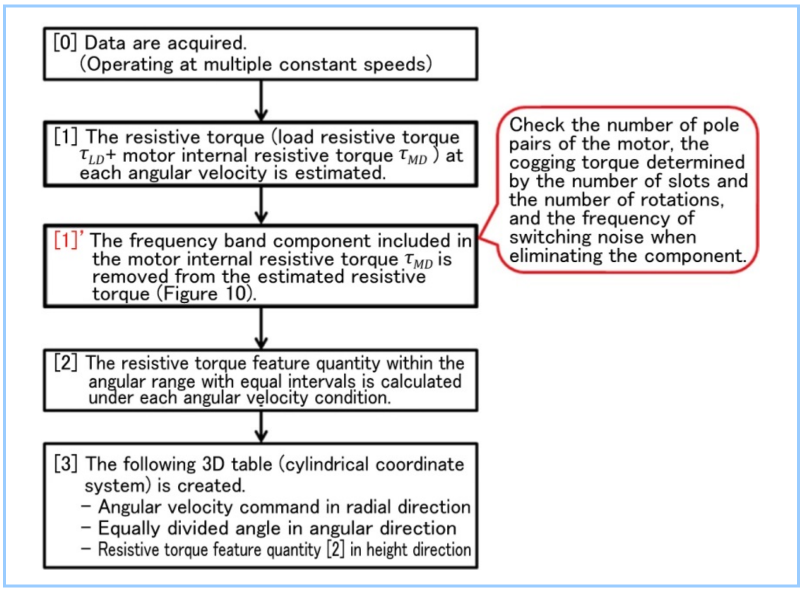

Figure 9　Visualization flow of resistive torque distribution of gear grinding machine

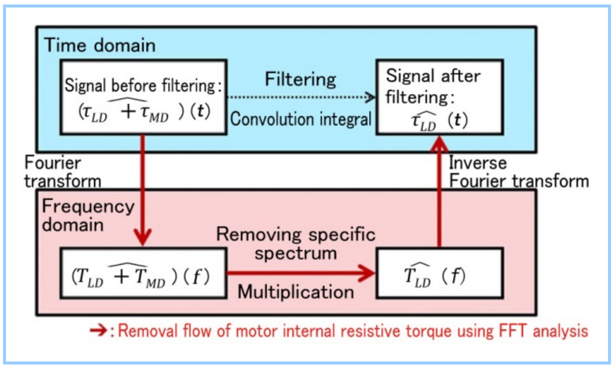

Figure 10　Removal flow of motor internal resistive torque using FFT analysis

Figure 11 compares the resistive torque distributions before and after the removal of motor internal resistive torque based on the test data of the gear grinding machine.

As shown on the right of Figure 11, the torque related to cogging was not removed completely, but can be suppressed to a sufficiently small level, and there was no particularly large bias. By removing the motor internal resistive torque, it is possible to extract the load resistive torque component that occurs in resistive elements such as viscous resistance.

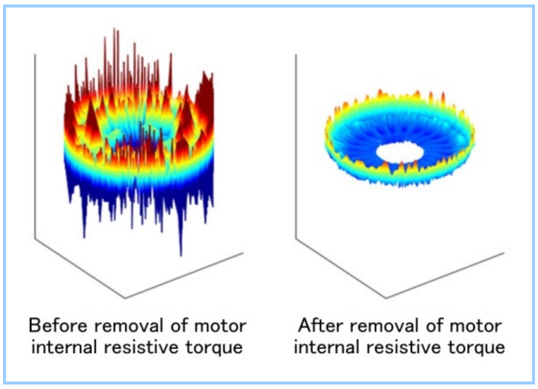

Figure 11　Comparison of resistive torque distributions before and after removal of motor internal resistive torque using FFT analysis

Based on the extracted load resistive torque, the feature quantity was calculated, and the resistive torque distribution was created. **Figure 12** gives an example of listing resistive torque distribution in which the average value, the p-p value and the variance are used as the feature quantities, and the angle division is classified into three levels from dense to rough.

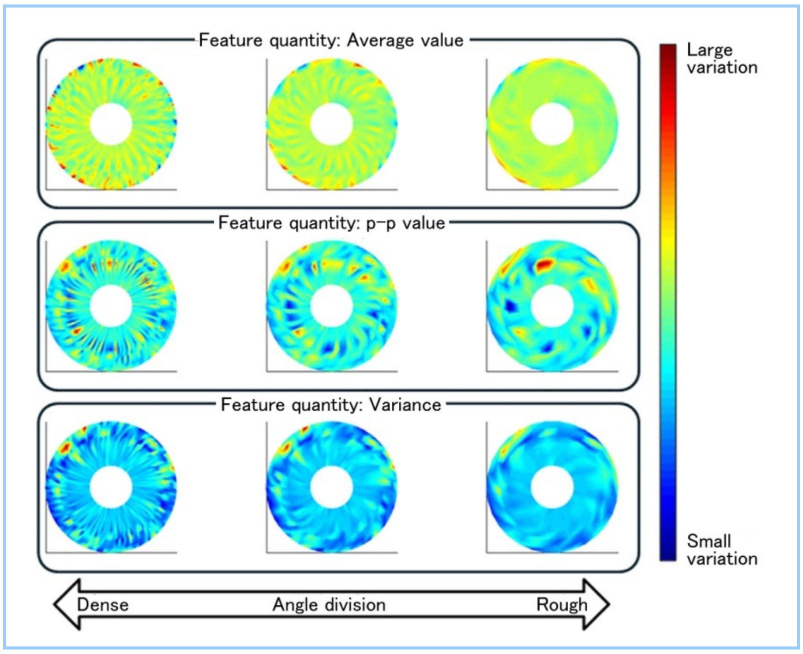

Figure 12 Resistive torque distributions of gear grinding machine

As shown in Figure 12, the resistive torque distribution is expressed from various points of view depending on the feature quantity and the number of angle divisions used. For example, in the resistive torque distribution for which the p-p value is used as the feature quantity and the angle division is rough, there are areas on a medium-speed range concentric circle where a variation increases in a concentrated manner in certain angular ranges. By clarifying the relationship between this variation and the machine state, the soundness of the machine can be evaluated. It is possible to evaluate the machine performance by selecting the feature quantity and angle division width according to the purpose and evaluating the variation.

5. Conclusion

This report presented a technology to quantify and visualize the resistive torque characteristics of the rotational axis of machine tools for which high precision is required and to evaluate the effect of the torque characteristics on machining accuracy. We verified the effectiveness of this technology with an element test device, applied the resistive torque distribution technology to a gear grinding machine and confirmed that the machine characteristics can be expressed from various points of view.

In the future, we will analyze the relationship between this resistive torque distribution and machining accuracy based on the accumulated test data and enhance machining accuracy by improving assembly techniques. Furthermore, we will expand the use of this technology to the field of remote preventive maintenance technology.

References

(1) Savitzky, Abraham et al., Smoothing and differentiation of data by simplified least squares procedures, Analytical chemistry 36.8 (1964): 1627-1639.