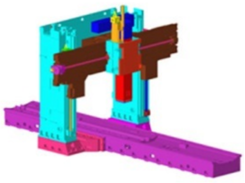
Vibration Suppression Technology of Vertical Precision Milling Machine MVR Using MBD Analysis



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For products comprised of multiple parts such as machine tools, commercial aircraft, new transportation systems and wind turbines, Mitsubishi Heavy Industries, Ltd. (MHI) is striving to improve performance and robustness through the prediction of performance by applying Multibody Dynamics (MBD) analysis to evaluate the vibration characteristics of structural components and the load transfers in machine components. We have developed a high-precision simulation model by combining MBD model and control system model for vertical precision milling machine, the performance of which is affected directly by mechanical vibration. In addition, a vibration suppression method utilizing the MBD model has been developed. This report introduces a summary thereof.

1. Introduction

MHI is advancing the use of multibody dynamics (MBD) analysis that evaluates mechanical characteristics such as the vibration and contact/friction of multibody systems in order to enhance the development efficiency and quality of various products. MBD is, on the basis that a part composed of multiple machine elements and a product (system) composed of multiple parts are defined as “multibody,” a numerical analysis technique to analyze the dynamics of an inter-connecting multibody system structure from the part to system level. When initially introduced, MBD analysis targeted the behavior evaluation and interference problems in kinematics. However, thanks to recent technological advancements, MBD analysis has been able to evaluate, in addition to the elastic characteristics of structural parts and the characteristics of machine components, the performance and damage risk including variations using a virtual test in the digital space, through linking with the same control model as the actual equipment.

We have developed a new technique to derive a vibration compensator using an MBD model of a large vertical precision milling machine that was created so that mechanical vibration during machining can be reproduced. By using the new vibration compensator, improvement of the surface quality of mold machining, in which minute mechanical vibration is generated during the acceleration/deceleration of the feed axis and deteriorates the machining quality, was obtained. This report presents the new technique and the vibration compensator derived thereby.

2. Creation of MBD model that can reproduce vibration during machining

2.1 Issues to be solved

Conventionally, the preliminary evaluation of the target specifications in the design phase of a large vertical precision milling machine was limited to the evaluation of static and dynamic rigidity against the machining reaction force and eigenvalue analysis, and the final machining performance was evaluated by the machining test. However, since actual operation includes various machining paths and acceleration/deceleration patterns, unexpected vibrations may occur and the machining accuracy may not satisfy the evaluation standard depending on the conditions, so it took

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time to make adjustments each time. In addition, reducing the feed rate and the acceleration in order to satisfy the machining accuracy sometimes increased the machining time.

To solve these issues, a low-dimensional control system simulation model that does not consider the vibration characteristics of structural parts and vibration analysis in the linear frequency domain that does not consider the acceleration/deceleration pattern of machining path cannot accurately grasp the factors causing transient vibration, so the examination of measures in consideration of the constant speed pattern was insufficient.

2.2 Accuracy improvement by comparing MBD analysis results and actual equipment behavior

In order to solve the aforementioned issues, we created an MBD model of the actual equipment structure shown in **Figure 1** and combined it with the control model in **Figure 2** to enable vibration evaluation of the actual equipment operation pattern. This model contains information on the vibration characteristics obtained from the structural analysis model in **Figure 3**, as well as the shape, density and Young's modulus of the structural parts that make up the vertical precision milling machine, in addition to the rigidity of mechanical components such as ball screws that connect the parts, etc.

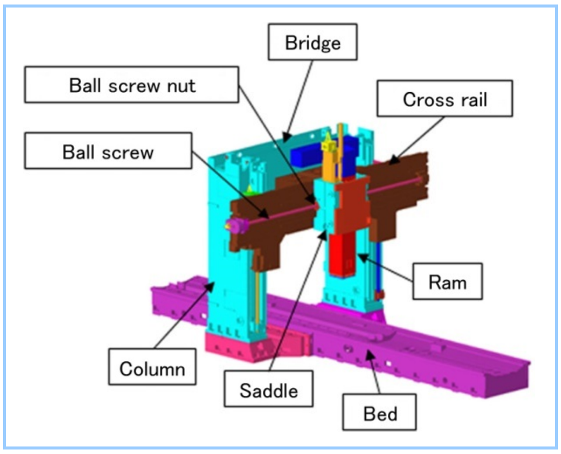

Figure 1 Structure of large vertical precision milling machine MVR

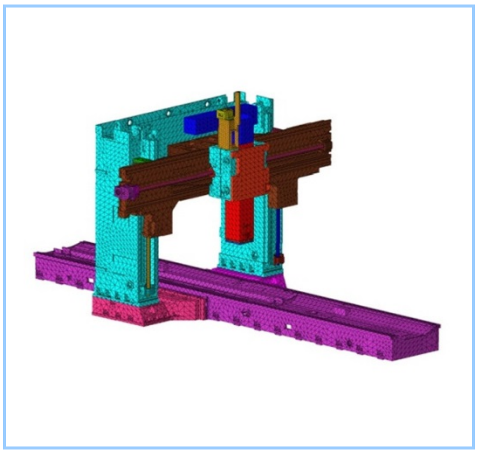

Figure 3 Structural analysis model

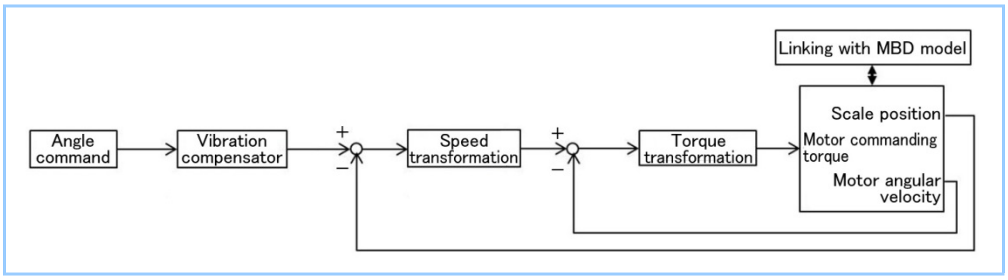

Figure 2 Control model

It was confirmed that the vibration mode, which affects the quality of the machined surface, could be indicated as illustrated in **Figure 4**, and that a transient response with a vibration amplitude in the order of 10 μm to the actual machine operation pattern could be indicated as depicted in **Figure 5**. In this way, MBD analysis can indicate the transient response that occurs during actual equipment operation in addition to the vibration characteristics obtained by conventional FEM analysis. By using simulation results of this model during the design and development of actual equipment, a structure and operation pattern that realizes more accurate machining can be created.

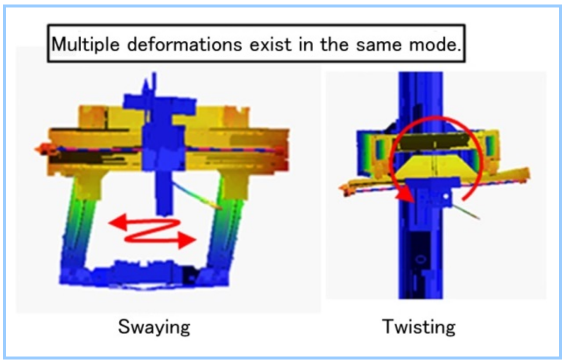

Figure 4 Example of vibration mode prediction results

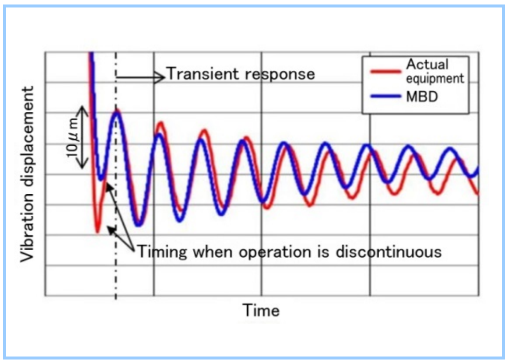

Figure 5 Vibration comparison between actual equipment and MBD

3. Derivation of vibration compensator using MBD model

3.1 Issues with conventional vibration compensators

In an actual machining path of a large vertical precision milling machine, transient vibration that causes the deterioration of the machining quality occurs when the acceleration becomes discontinuous, such as during a change from horizontal movement to vertical movement. To suppress this transient vibration, a compensator is used. Conventional compensator design uses a physical model based on the mass and moment of inertia of the main components and the rigidity of parts as shown in equation (1) to indicate the vibration characteristics of the target structure. However, a design using a physical model cannot take non-linearity into account due to the posture, friction, backlash, etc. As a result, an error occurs during verification with the actual equipment, so a vibration suppression effect cannot be fully incorporated in the design phase.

$$\theta_L = \theta \times \frac{(2\times J_C \times S^2 + C_C \times S + K_C)}{\{(2\times J_G - J_L)\times S^2 + (C_C - D_L)\times S + K_C\}} \quad \text{Equation (1)}$$

θ : Machine tip position
θ_L : Linear scale position
J_L : Load inertia
J_C : Column inertia
D_L : Load viscosity
K_C : Column rigidity
C_C : Column damping

3.2 Proposal of derivation technique of new vibration compensator

The new compensator is derived from the transfer function obtained from the frequency characteristics of the target mechanism structure for which the vibration is to be suppressed, using the MBD model that has been verified to be able to indicate the actual equipment behavior. Specifically, the characteristic points are extracted by fitting the frequency characteristics obtained by MBD simulation result given in **Figure 6**, and applied to the quadratic transfer function in equation (2) is directly derived using them. Then the new compensator is derived using the results.

$$G_m(S) = \frac{\frac{1}{\omega_2{}^2} s^2 + \frac{2\zeta_2}{\omega_2} s + 1}{\frac{1}{\omega_1{}^2} s^2 + \frac{2\zeta_1}{\omega_1} s + 1} \quad \text{Equation (2)}$$

ω_1 : Frequency at gain characteristic point ①
ζ_1 : Attenuation factor at gain characteristic point ①
ω_2 : Frequency at gain characteristic point ②
ζ_2 : Attenuation factor at gain characteristic point ②

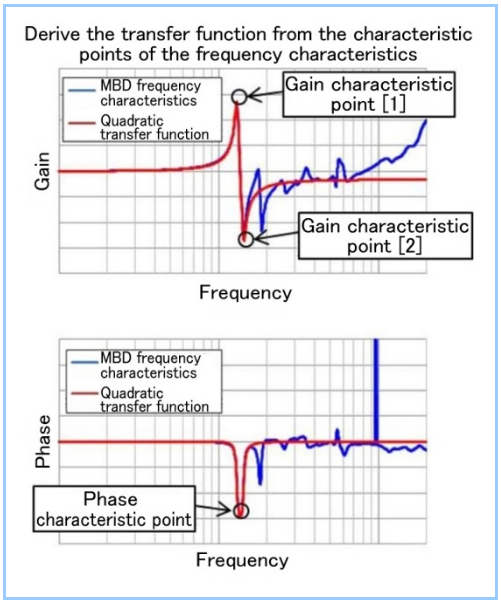

Figure 6 Estimation and derivation of quadratic transfer function

3.3 Effect verification results of developed technique

We conducted effect verification of the aforementioned vibration compensator derived based on the MBD model in actual die milling. As shown in **Figure 7** and **Figure 8**, it was verified that the new vibration compensator had a vibration suppressing effect and that the quality of the machined surface was improved compared with that obtained with a conventional compensator.

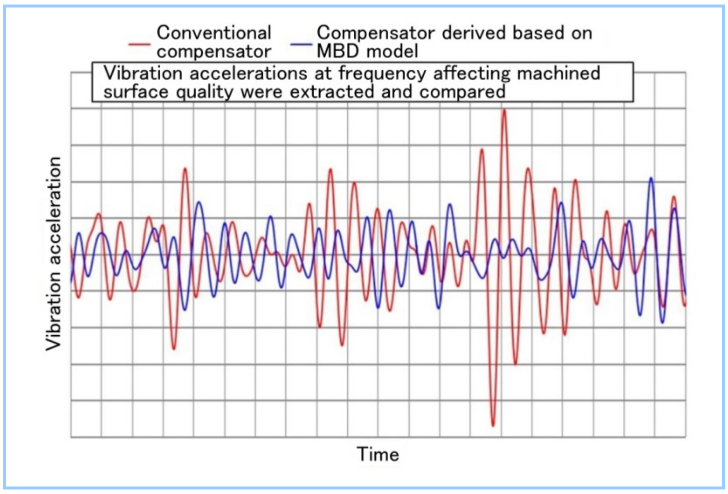

Figure 7 Comparison of vibration accelerations in actual machining

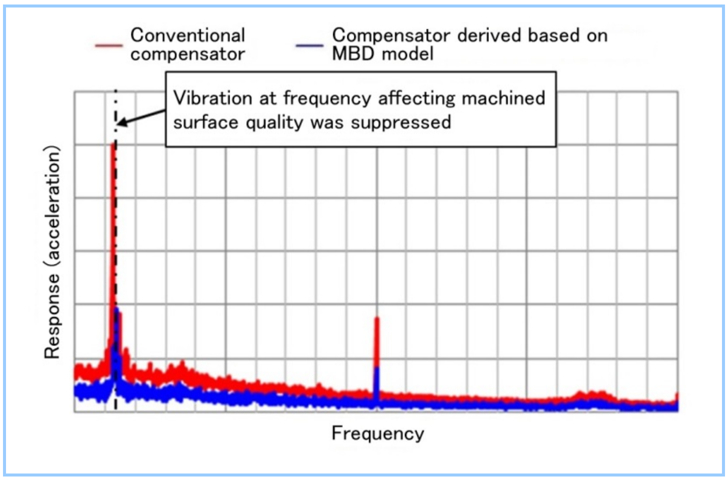

Figure 8 Frequency analysis results of column mechanical vibration acceleration in actual machining

4. Conclusion

This report demonstrated that combining MBD analysis model and the actual equipment control model of a large vertical precision milling machine realizes simulation of the overall system, and that it is possible to derive a vibration compensator that will improve the performance and value of the actual equipment therefrom.

By enabling model-based examinations as shown in this report, improvement studies of machine structure and the optimization of the overall system including control can be carried out quickly and accurately.

We will continue to utilize this technique to shorten the product development period and improve product performance and robustness in the design phase.

References

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