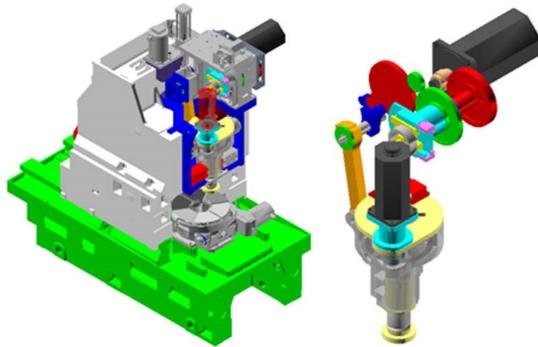


High-accuracy Motion Prediction Using Large-scale Multibody Dynamics (MBD)



HIROYUKI KANAZAWA*¹ TETSUHEI KOBAYASHI*²

TOSHIMASA KIKUCHI*³

For products comprised of multiple parts such as machine tools, new transportation systems and wind turbines, Mitsubishi Heavy Industries, Ltd. (MHI) is striving to improve their performance and robustness through prediction of their performance by applying Multibody Dynamics (MBD)¹ to analyze the vibration characteristics of structural components and the load transfers in the machine components. We have developed a high-precision analytical model for gear-cutting machine, for which the mechanical vibrations directly affects the product's performance with the help of correlation analysis between simulation results and the experimental measurement results of the oscillation. This paper reports a summary thereof.*

Note: Correlation is an approach to decrease the estimated gap in the rigidity, damping, etc., of an analytical model by comparative evaluation of observation results and analysis results.

1. Introduction

MHI is propelling the use of MBD for evaluating machine characteristics such as vibration and contact/friction dynamics of multibody system in order to enhance development efficiency and quality of various products. MBD is a numerical analysis technique to analyze the dynamics of an inter-connecting multibody system structure from part-to-system level. When initially introduced, MBD targeted the behavior evaluation and interference problems in kinematics, but thanks to recent technological advancements, the scope has been extended to dynamics problem taking flexibility and vibration characteristics of machine into account. At present, it is even addressing the coupled problem with hydrodynamic force and thermal deformation to some extent.

Computer Aided Engineering (CAE) has been utilized to design our machine tools including the gear-cutting machines. For example, the machine parts are designed using 3D-CAD system, the static stiffness by machining reaction force is calculated, and the eigenvalues are evaluated by vibration analysis. However, the evaluation of machining performance was still conducted through prototype tests and required adjustments to meet requirement specifications such as machining accuracy and confirmation with testing. For this reason, simple prior assessment for static rigidity and the vibration characteristics of machines alone failed to meet the requirement specifications and required trial and error using prototypes to do so. Therefore, some cases saw prolonged development periods and increased development costs.

We have elevated the precision of an analytical model made possible by adding vibration measurement evaluation technology to MBD targeting gear shapers^{2,3}, for which the machining accuracy (machine accuracy) can be varied by altering the machining condition. Through this effort, the cause of oscillatory excitation can be inferred, and the prior assessment of measurement effects was made possible, as introduced below.

*1 Chief Staff Manager, Machinery Research Department, Research & Innovation Center, Technology & Innovation Headquarters

*2 Machinery Research Department, Research & Innovation Center, Technology & Innovation Headquarters

*3 Mitsubishi Heavy Industries Machine Tool Co., Ltd.

2. Existing modeling method

Since the problem set in question was the undulation of the tooth plane due to tool vibration during gear cutting, we firstly targeted the cutter head as it is directly associated with the process of gear shaping (**Figure 1**). Next we deployed the elastic deformation modeling method for components that are supposed to have low rigidity in their shape (**Figure 2**), but as a result of a comparison between the analysis results and the measurement results of the actual machine motion, the vibration behavior of an actual machine could not be reproduced, as shown in **Figure 3**.

We presumed that this result was involved with issues related to the rigidity/vibration characteristics of an entire gear shaper machine and made efforts to improve the accuracy of analytical modeling through an extension of the analytical model as well as correlation with the measurement results of oscillation.

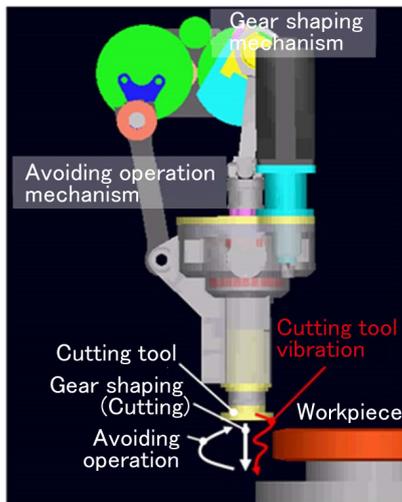


Figure 1 Working by cutter head

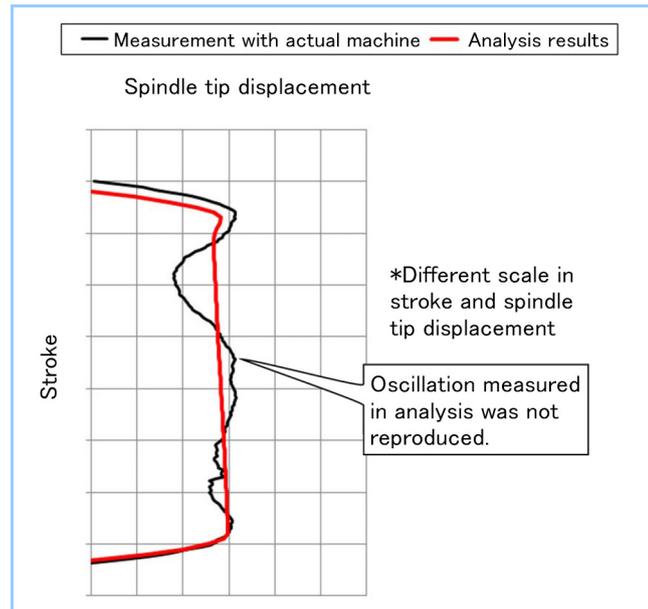


Figure 3 Comparison between analysis results (conventional modeling method) and measurement results of actual machine

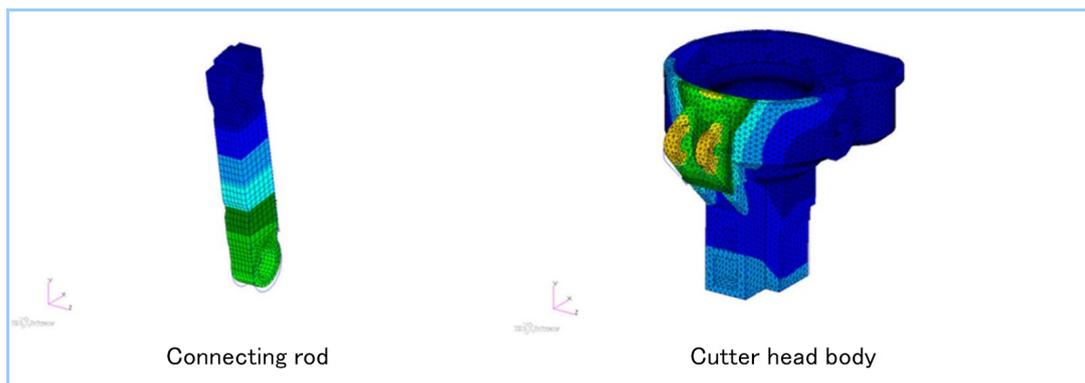


Figure 2 Components for elastic deformation modeling method

3. Composing high-accuracy large-scale MBD model

3.1 Extension of modeling range

As explained in the previous chapter, this issue presumably stemmed from the rigidity/vibration characteristics of a machine in its entirety, and therefore we set a large-scale MBD model for which the modeling range was extended as shown in **Figure 4** for the analytical model, where structures such as the bed, column and saddle are defined by elastic body formulation. Here, for the rigidity of the binding elements between parts including the linear guide, ball joint and oil hydraulic cylinder, we used the nominal values from manufacturers or design data.

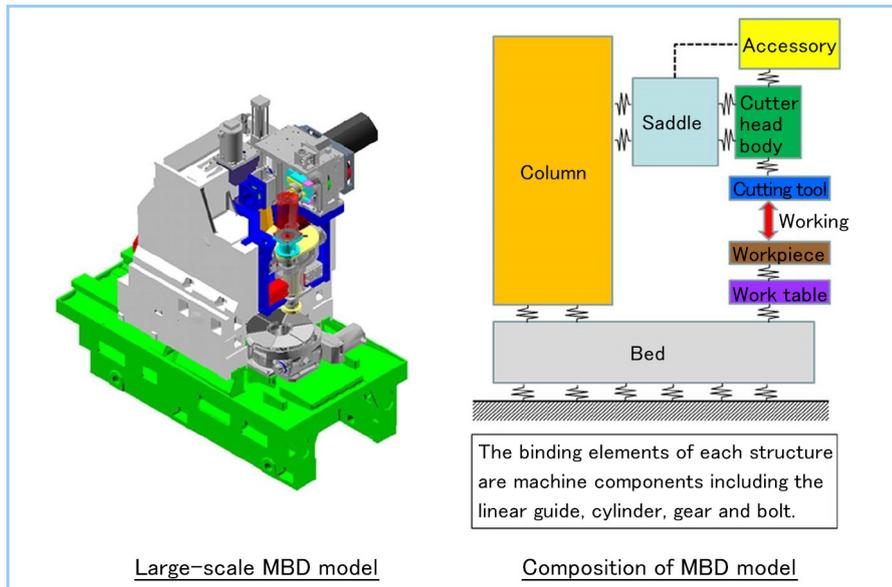


Figure 4 Large-scale MBD model and composition

(1) Modeling method for elastic body components and binding elements

In the full model Figure 4, bed, column and saddle were modeled as elastic body components. For flexibility modeling, Craig-Bampton Method⁴ (component mode synthesis) for extraction of the necessary order of oscillation mode factor, was adopted. For analysis, we first created a FEM model and then the natural frequency and the associated oscillation mode were extracted by eigenvalue analysis. MBD is a large displacement time history response analysis and therefore solving directly by FEM analysis with an elastic body element would entail convergent calculations per time step, which is very inefficient. At the same time, the mode synthesis that we employed in this report is efficient because it can substantially lessen the computation load when dealing with oscillation issues..

(2) Analysis results of large model

Figure 5 demonstrates a comparison between the analysis results of the range-extended large model and the measurement results of an actual machine. Here we have validated the fact that such oscillatory behavior observed in the actual machine can be reproduced. However, as discrepancies were still observed in the amplitude and frequency of vibration, further accuracy improvement was required to apply it to elucidate the occurrence of events in the actual machine and to work out measures for vibration suppression..

3.2 Vibration measurement of actual machine

Thus, we conducted experimental vibration measurement with the purposes of characterization the oscillation of an actual machine and correlating the measurement results of the actual machine's oscillation with that of an analytical model. The measurement signals were obtained from an accelerometer by using hammer for the excitation. The load transfer behavior (acceleration) from the cutter tip was gauged, the band of frequencies was estimated from the time domain measurement results (Figure 5, etc.) of an actual machine, and the natural frequencies of the machine were extracted.

3.3 Modeling accuracy enhancement by correlation

To correlate measurement results with analysis, we set stiffness and damping between bed and column (hydrostatic bearing, ball screw), column and saddle (linear guide, ball screw, hydraulic cylinder) and between saddle and cutter head (bearing) as parameters. Optimization calculation was run with error between actual machine eigenvalues and eigenvalue analysis results from MBD as objective function. Particle Swarm Optimization (PSO) was employed for the optimization calculation. PSO is group intelligence and a heuristic optimization method for multipurpose search based on the behaviors of a group of birds and fish.

The analysis results using the high-accuracy large-scale model agreed with the actual machine's motion as shown in **Figure 6**, and an improvement in prediction accuracy for the actual machine's motion was achieved. By using this model, it could be identified that vibrations during

cutting is due to weight of the Y-axis motor mounted on the cutter head and the eigenvalue of the motor flanges are superimposed.

As a result of the successful identification of the cause of oscillatory excitation (i.e., the reference site) and the frequency, the amount of the undulation of the tooth plane due to tool vibration could be decreased by using a vibration isolating material with effective damping characteristics.

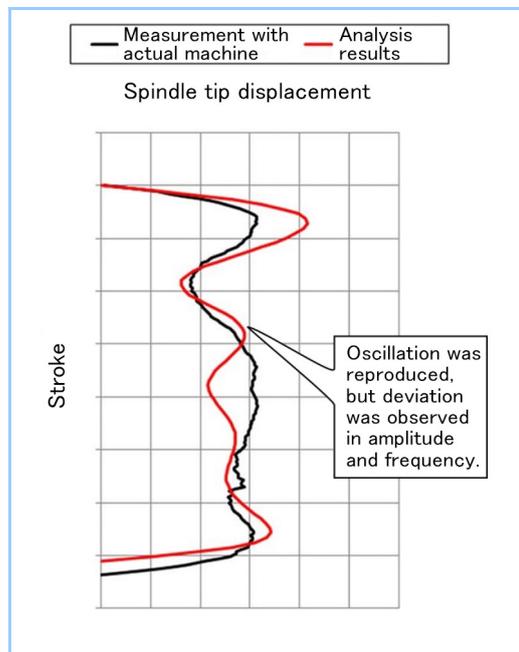


Figure 5 Comparison between analysis results (large-scale model) and measurement results of actual machine

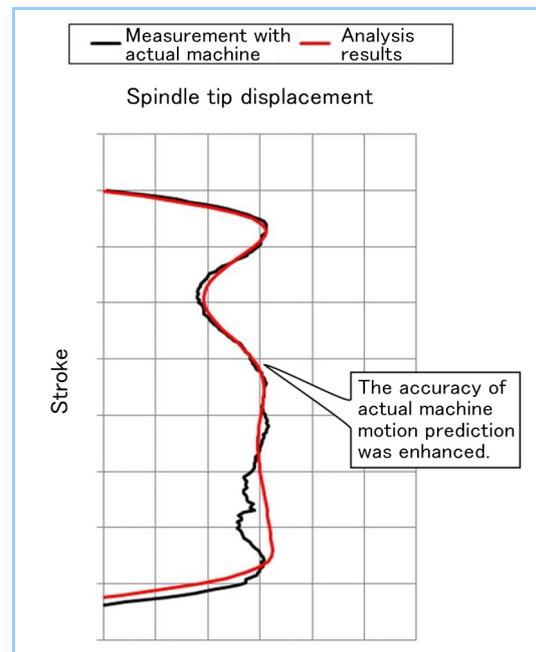


Figure 6 Comparison between analysis results (high-accuracy large-scale model) and measurement results of actual machine

4. Conclusion

This report affirmed that a correlation with the measurement results of vibration enables higher accuracy prediction in composing a large MBD model consisting of a structure involving vibration during cutting and machine components, and that the oscillation phenomenon observed during actual operation resulting from various machining conditions can be reproduced.

As a measure for decreasing deviation from the motion of an actual machine, we opted for correlation with the oscillation measurement results of an actual machine, because it was available. It is possible, however, to continuously improve modeling accuracy without measuring once acquired sets of data from measurements are assembled in a database for reuse, because the parameters after adjustment are general machine components. As such, MBD technology can enable the prior assessment of product performance, which is otherwise only possible after production and actual operation, and can be considered to be an effective tool to substantially streamline optimization processes that called for prototype tests and trial and error for adjustment. We will utilize this technology to shorten product development periods and to enhance product performance and robustness by applying it at the design phase

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