MACHINE TOOL GENOME PROJECT CASE STUDY

Tony Schmitz and Brian Dutterer
Mechanical Engineering and Engineering Science
University of North Carolina at Charlotte
Charlotte, NC, USA

INTRODUCTION

Milling process models may be implemented to enable pre-process parameter selection for optimized performance. To enable accurate process performance prediction using these models, the tool-holder-spindle-machine structural dynamics must be known [1]. The required tool point frequency response function (FRF) can be obtained by modal testing. However, for the large number of tool-holder combinations in typical production facilities, the measurements can be prohibitively time-consuming and costly.

In the Machine Tool Genome Project (MTGP)[1], Receptance Coupling Substructure Analysis (RCSA) is applied as an alternative to modal testing [2-4]. In the RCSA approach, the tool-holder-spindle-machine assembly is considered as three separate components: the tool, holder, and spindle-machine and the individual FRFs of these components are coupled analytically. The archived measurement of the spindle-machine FRF (or receptance) is coupled to the free-free boundary condition receptances of the tool and the holder derived from beam models. In the MTGP paradigm, the tool, holder, and spindle-machine are considered as "genes". RCSA provides the "mapping" step to predict the "body characteristic" (assembly FRF). This paper presents a case study to demonstrate the utility of the MTGP to pre-process milling parameter selection. FRF and stability predictions are compared to experiments.

SETUP DESCRIPTION

Three nominally identical Haas TM-1 CNC machining centers were tested; see Fig. 1. The spindle-machine FRF was measured for all three using a simple geometry "standard holder"; see Fig. 2. The portion of the holder beyond the flange was removed in simulation to isolate the spindle-machine dynamics and this result was archived. A Schunk Sino-R tool holder and M.A. Ford TuffCut GP two flute 12.7 mm x 25.4 mm (flute length) x 76.2 mm (overall length) endmill were modeled and coupled to the spindle-machine receptances. The tool overhang length was 50.9 mm. The connection stiffness between the tool and holder was identified in a separate setup using a 12.7 mm diameter carbide blank. This value is generic to all 12.7 mm diameter tools in this holder and was also archived.

FIGURE 1. Haas TM-1 CNC machining centers.

FIGURE 2. Standard holder used to measure spindle-machine FRF (CAT-40 interface).

FRF PREDICTION AND MEASUREMENTS
Right machine
For the right TM-1 machine in Fig. 1, the spindle-machine receptances were coupled to the tool-holder model and compared to a measurement of the tool point FRF on this machine. The x-direction result is provided in Fig. 3 (prediction: blue, measurement: red).
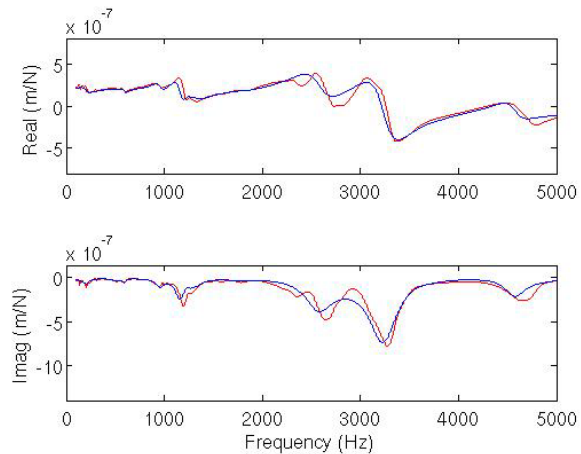

FIGURE 3. Right TM-1 comparison (right spindle-machine receptances).

Middle machine
The spindle-machine receptances for the middle TM-1 were coupled to the tool-holder model and compared to a measurement of the tool point FRF on the same machine. See Fig. 4.
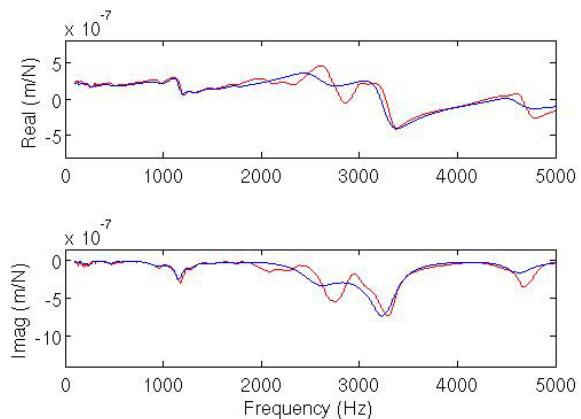

FIGURE 4. Middle TM-1 comparison (middle spindle-machine receptances).

Left machine
The spindle-machine receptances for the left TM-1 were coupled to the tool-holder model and compared to a measurement of the tool point FRF on the same machine. See Fig. 5.
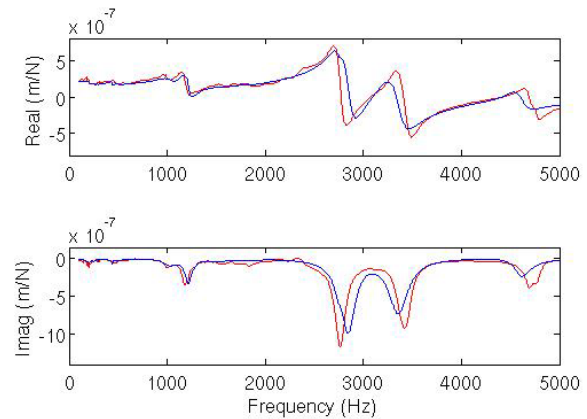

FIGURE 5. Left TM-1 comparison (left spindle-machine receptances).

To extend the analysis, predictions were next completed for the middle and left machines, but using the spindle-machine receptances for the right TM-1.

Middle machine-right machine receptances
The spindle-machine receptances for the right TM-1 were coupled to the tool-holder model and compared to a measurement of the tool point FRF on the middle machine. See Fig. 6. It is observed that the agreement between prediction and measurement is comparable to Fig. 4. This suggests that the spindle dynamics between the right and middle machines are similar.
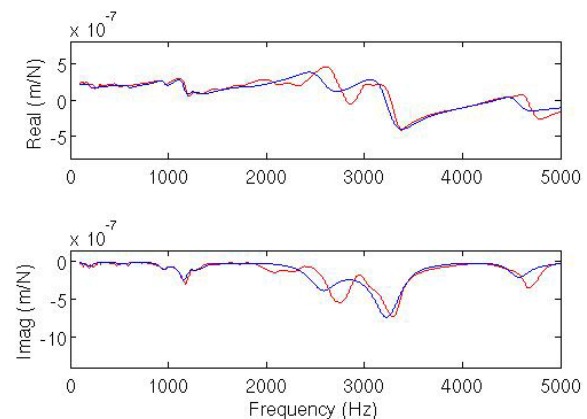

FIGURE 6. Middle TM-1 comparison (right spindle-machine receptances).

Left machine-right machine receptances

The spindle-machine receptances for the right TM-1 were next coupled to the tool-holder model and compared to a measurement of the tool point FRF on the left machine. See Fig. 7. The decreased agreement between prediction and measurement relative to Fig. 5 suggests that the spindle dynamics between the left and middle machines differ.
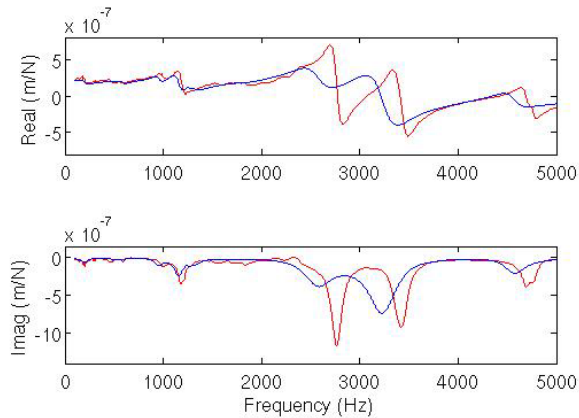

FIGURE 7. Left TM-1 comparison (right spindle-machine receptances).

STABILITY PREDICTION AND TESTS
Right machine

For the right TM-1 machine, the predicted and measured tool point FRFs in the x and y-directions were used to a generate the stability lobe diagram for a 50% radial immersion up-milling cut in 6061-T6 aluminum. Figure 8 shows the limiting axial depth of cut, b_{lim}, for the predicted (blue) and measured (red) FRFs.
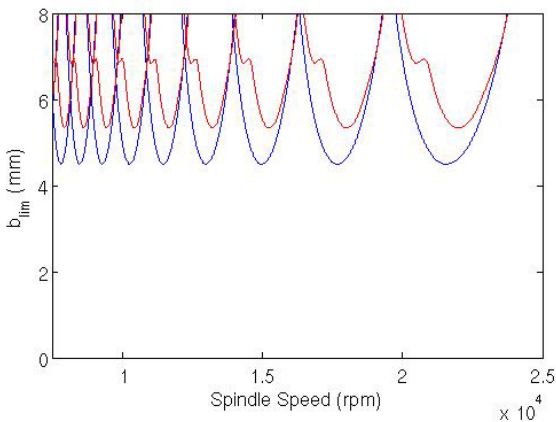

FIGURE 8. Left TM-1 stability comparison (right spindle-machine receptances).

Middle machine-right receptances

Next, the predicted tool point FRFs in the x and y-directions produced using the right machine spindle-machine receptances were used to generate the stability lobe diagram. Figure 9 shows b_{lim} for the predicted and measured (tool-holder in middle TM-1) FRFs. It is again observed that the "best speeds" are accurately identified and the minimum stability limit is conservative for the predicted result.
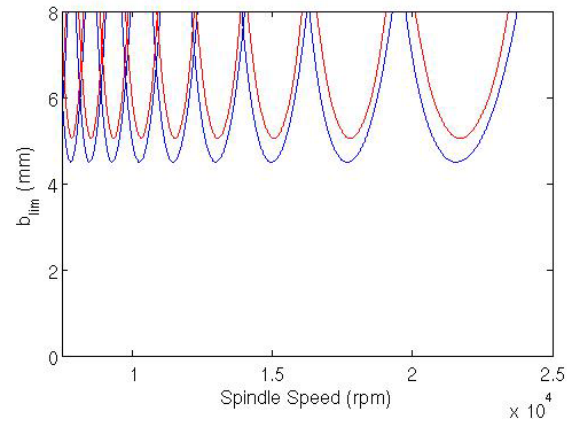

FIGURE 9. Middle TM-1 stability comparison (right spindle-machine receptances).
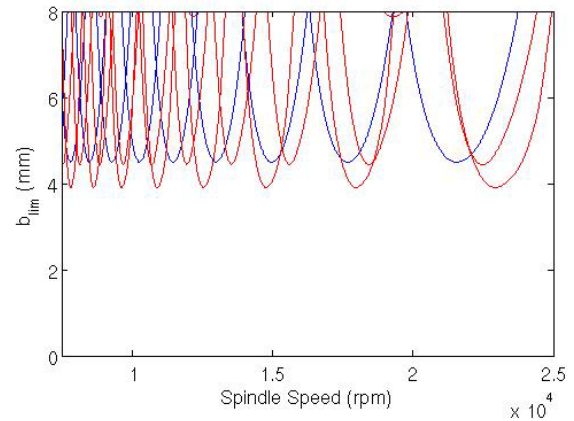

FIGURE 10. Left TM-1 stability comparison (right spindle-machine receptances).

Left machine-right receptances

Finally, the predicted tool point FRFs in the x and y-directions produced using the right machine spindle-machine receptances were used to generate the stability lobe diagram. Figure 10 shows b_{lim} for the predicted and measured (tool-holder in left TM-1) FRFs. The disagreement is a direct result of the FRF mismatch in Fig. 7.

Cutting tests

The middle TM-1 stability limit was predicted using the right machine spindle receptances. This boundary was then evaluated using cutting tests on the middle machine. Figure 11 shows the stability limit and test results: stable (o), unstable (✕), and marginal (□).
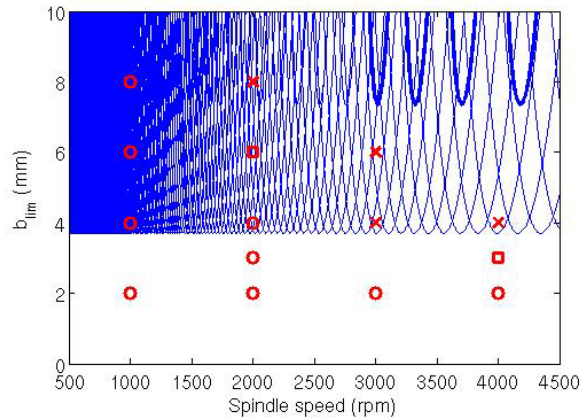

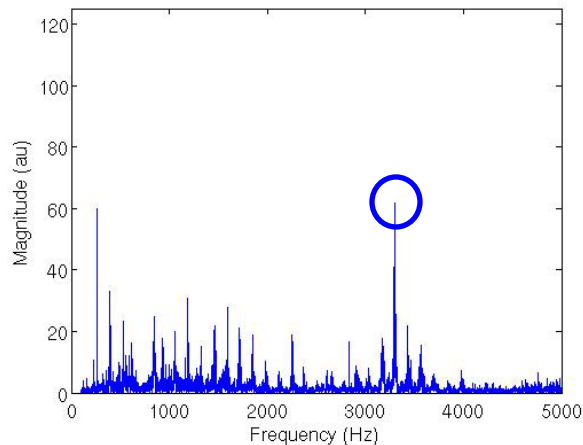*FIGURE 11. Middle TM-1 stability results (right spindle-machine receptances).*

FIGURE 12. Spectral content of sound signal for unstable cut at {4000 rpm, 4 mm}. The chatter frequency near 3400 Hz is identified.

First, it is observed that considerable process damping is present at the 1000 rpm and 2000 rpm spindle speeds. The analytical stability model used here does not include this effect, so the trend of increasing stability with reduced cutting speed is not present in the prediction. At 4000 rpm, however, the experimental results confirm the stability prediction. The spectral content of the sound signal for the {4000 rpm, 4

mm axial depth cut} is provided in Fig. 12. The chatter frequency at approximately 3400 Hz corresponds to the most flexible vibration mode near 3200 Hz in Fig. 6. Conversely, the stable cut at {4000 rpm, 2 mm} does not exhibit content at this frequency; see Fig. 13.
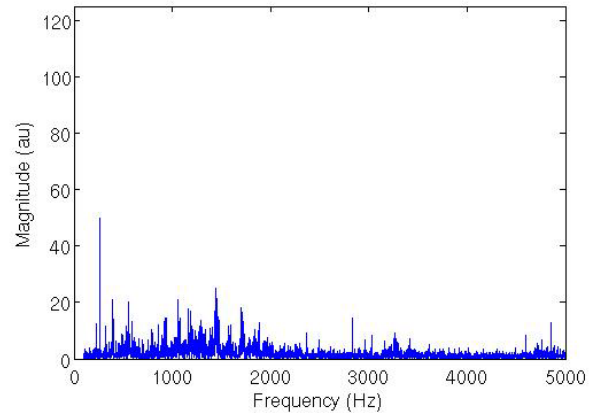

FIGURE 13. Spectral content of sound signal for stable cut at {4000 rpm, 2 mm}.

CONCLUSIONS

The Machine Tool Genome Project was introduced and experiments were used to validate the performance of the Receptance Coupling Substructure Analysis approach to select pre-process milling parameters.

REFERENCES

[1] Schmitz, T. and Smith, K.S., 2009, Machining Dynamics: Frequency Response to Improved Productivity, Springer, New York, NY.

[2] Schmitz, T. and Donaldson, R., 2000, Predicting High-Speed Machining Dynamics by Substructure Analysis, Annals of the CIRP, 49/1: 303-308.

[3] Schmitz, T., Davies, M., and Kennedy, M., 2001, Tool Point Frequency Response Prediction for High-Speed Machining by RCSA, Journal of Manufacturing Science and Engineering, 123: 700-707.

[4] Schmitz, T. and Duncan, G.S., 2005, Three-Component Receptance Coupling Substructure Analysis for Tool Point Dynamics Prediction, Journal of Manufacturing Science and Engineering, 127/4: 781-790.