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REPEATABILITY ANALYSIS ON THE TOOL POINT DYNAMICS FOR INVESTIGATION ON UNCERTAINTY IN MILLING STABILITY

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ABSTRACT

Stability analysis is needed to maximize milling performance while avoiding chatter. However, such an analysis is time-consuming, requiring the use of sophisticated instrumentation, and has significant level of uncertainty, which impedes the widespread use by industry. A main source of uncertainty is believed to be the changes in dynamics of the tool-holder-spindle system during the milling operation. This study investigates the variation in the tool point dynamics reflecting the dynamics of the tool-holder-spindle system and associated machining stability. The investigation focuses on the effects of the conditions generated by typical milling operations, such as tool changes and spindle warm up. The results of analyses demonstrate the necessity of continuous updates of the tool point dynamics during milling process by in-situ measurements to minimize uncertainty in evaluation of machining stability.

1. INTRODUCTION

Research conducted during the past several decades to avoid chatter in milling resulted in improvements in the analysis of milling stability [1- 9]. The stability analysis relies on estimation or measurement of the dynamic behavior at the tool point (tool point dynamics) to generate stability lobes (regions of stable machining in machining parameter space). The tool-holder-spindle assembly provides the most flexible mode within the machine structure. Therefore, the dynamics at the tool point are greatly affected by any changes in the dynamic properties of components or interfaces between these components in the tool-holder-spindle assembly [2, 4-12]. The stability analysis is used either to identify the stable machining parameters for a given tool-holder-spindle-machine assembly or to modify the components (e.g., tool geometry) to achieve more favorable stability lobes depending on the particular milling objective (e.g., maximizing the material removal rate or maximizing the precision of the cut) [8-10]. Nevertheless, both approaches require that pre-process determination of the dynamic behavior at the tool point accurately reflect the behavior during the process. However, it is believed that typical milling operations induce variations in the dynamic behavior at the tool point. Such variations are the sources of uncertainty that impede the reliable employment of any approach relying on pre-process determination of tool point dynamics to evaluate machining stability [13].

In this paper, variations in the tool point dynamics resulting from changes in dynamic properties of the tool-holder-spindle system induced by typical milling operations are investigated as sources of uncertainty in evaluation of machining stability. The potential factors that may influence the dynamics of the tool-holder-spindle system are identified and changes in the tool point dynamics in response to these factors are examined. The variation indices are used to indicate degrees of variability showing the relative importance of these factors in estimating and maintaining machining stability.

2. TOOL POINT DYNAMICS FOR MACHINING STABILITY EVALAUATION

Milling stability is expressed as the stability lobes describing the maximum axial depth of cut without chatter, a_{lim} [mm], as a function of the spindle speed, n [rpm]. These critical machining conditions are evaluated by solving the eigenvalue problem of the characteristic equation derived from the frequency response function (FRF) of the tool point dynamics [3-6, 9, 14]. A solution may be represented by the following equations [6, 9, 14]:

$$a_{\lim} = \frac{2\pi\lambda_R}{NK_t}\left(1+\left(\frac{\lambda_I}{\lambda_R}\right)^2\right) \quad (1)$$

$$n = \frac{60\cdot\omega_c}{N(\varepsilon+2k\pi)}, \; k = 1,2,3,... \quad (2)$$

where λ_I, λ_R = real and imaginary components of eigenvalue from tool point FRF, K_t = tangential cutting coefficient, N = number of cutter flutes, ε = phase shift between previous and present vibration marks, ω_c = chatter frequency, k = integer number of lobes. Any changes of natural frequency and magnitude of response at the natural frequency in the tool point FRF modify the critical spindle speed and the axial depth of cut in the stability lobe according to equations (1) and (2). Hence, the machining stability is subject to the changes in the tool point dynamics.

3. Measurement of Tool Point Dynamics by Impact Tests

The tool point FRF is traditionally measured by the impact tests. Before investigating the effects of milling conditions on the evaluation of the tool point FRF, the measurement repeatability of impact tests itself was analyzed. Behavior of measured tool point dynamics in this paper were examined in terms of changes in natural frequency and dynamic stiffness that is the product of stiffness and damping at the tool point [15].

To examine behaviors of the tool point dynamics, a simulated carbide tool (a cylinder with a diameter of 12.7 mm, and overhang length of 120 mm with flat spots at the tip for applying the impacts) was inserted into a tool holder and assembled to the spindle of a high-speed machining center. The tool point FRFs in x and y directions were measured 10 times by manual impact tests at the tool tip. A sample pair of FRFs in x and y directions of the initial condition of the tool-holder-spindle system are shown in Figure 1. The results of 10 sets of measurements indicated that the maximum ranges of differences between natural frequencies and dynamic stiffness, calculated in x and y directions, are 1.5 Hz (0.17 %) and 850 N/m (6.85 %). Therefore, although stability lobes shown in later part of this paper were evaluated using the tool point dynamics in both x and y directions, since the FRFs in both directions of single bending mode are very similar, this paper illustrates changes in tool point dynamics in only x direction.

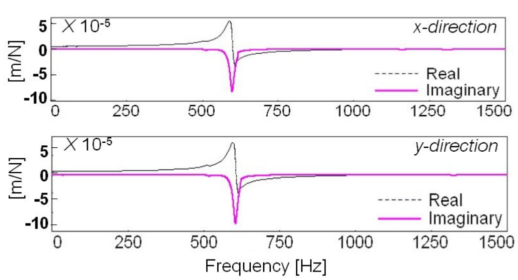


Fig 1: FRFs of initial condition

3.1 Measurement Variations due to Improper Impacts

When the tool point dynamics are measured by manual impact tests, improper impacts are a source of measurement variations in the tool point dynamics. Improper impacts take the form of impacting with multiple impulses, with considerable variations in force level, deviating from x- or y-directions, and away from the target spot. Following the typical practice in such measurement procedures, individual measurements only satisfying a strong coherence function (0.99 to 1.00) were accepted for use in the calculations and others were rejected [15-16]. An average of five consecutive 'acceptable' measurements was used to generate each FRF. Ten sets of FRFs were calculated based on repeated measurements. Figure 2 shows the repeatability of 10-individual tool point dynamics in natural frequency, ω_n, and dynamic stiffness, k_d, from each average of 10-measurement sets of the initial condition. As shown in Figure 2, the variation of calculated natural frequency is about 0.02 % of its average value where as the variation of the dynamic stiffness is about 1.95 % of its average value.

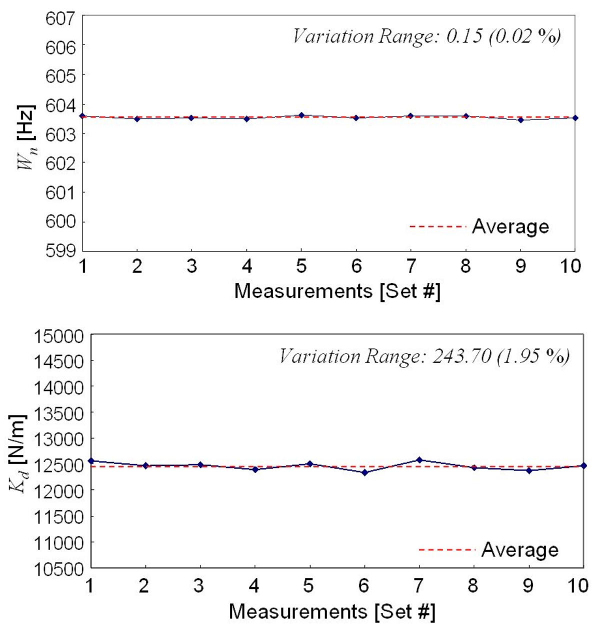


Fig 2: Tool point dynamics of initial condition

3.2 Measurement Variations due to Spindle Orientations

Another source of variation in calculating FRF is the variation of the spindle orientation in each test. For rolling element in bearing spindles, it is expected that when a ball/roller in the spindle bearing is aligned with excitation force, the result reveals higher stiffness. Therefore, typical FRF results may exhibit a periodic behavior closely correlated to ball spacing in the bearing. Figure 3 illustrates such a behavior for a twenty-ball bearing.

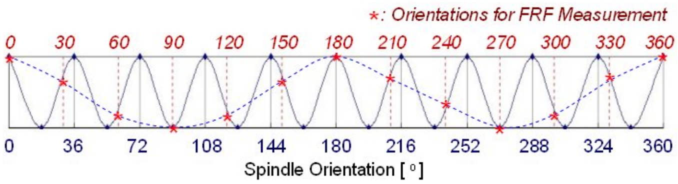


Fig 3: Expected variation in FRF measured at every 30 ° orientation of spindle with twenty-ball bearing

In this study, the tool point dynamics were measured every 30 ° by rotating the spindle. A cylinder with twelve flat surfaces at the tip with 30 ° intervals was used for these tests. The periodic variations in the measured tool point dynamics according to spindle orientations in Figure 4 are explained by the periodic changes in ball positions at every 30 ° corresponding to spindle orientations for FRF measurement shown in Figure 3.

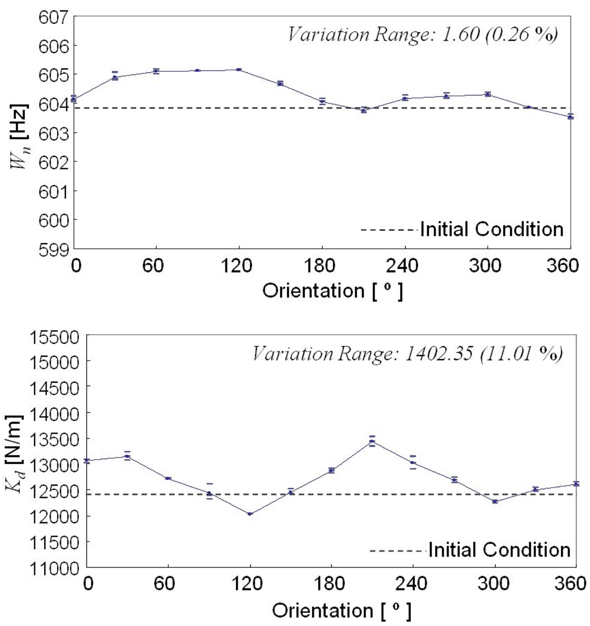


Fig 4: Variations in tool point dynamics according to spindle orientations

If the tool point dynamics are measured in random spindle orientation, uncertainty caused by measurement variations in spindle orientations should be included in each measurement. In the tool point dynamics measurement in this study, variation range of 1.60 Hz (0.26 %) in natural frequency and 1402.35 N/m (11.01 %) in dynamic stiffness as illustrated in Figure 4 must be considered if measurements are performed in random spindle orientation. In the next part of this study, to exclude measurement uncertainty due to random spindle orientation, the constant spindle orientation was achieved by commanding the machining center to lock the spindle at zero orientation and unlock the spindle before taking the measurements.

4. CHANGES IN TOOL POINT DYNAMICS IN MILLING OPERATIONS

This section describes how typical milling operations with multiple tool changes affect the tool point dynamics.

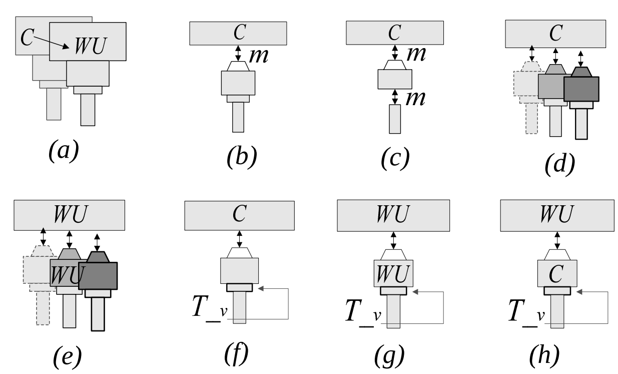
The potential factors that may influence the dynamics of the tool-holder-spindle system in milling operations can be classified as follows.

- Spindle warm up
- Tool and tool-assembly changes in spindle
- Torque variations between tool and holder

Series of impact tests were conducted under various conditions simulating the milling operations and corresponding FRFs were calculated. The conditions under which the tests were conducted are listed below.

(*a*) Starting from the cold condition, spindle was warmed up by about 10 ºC running the spindle 40 min (with the same tool-holder assembly).
(*b*) A single tool-holder assembly inserted into the spindle multiple times
(*c*) A single tool and holder combination were assembled multiple times and inserted into the spindle
(*d*) Using different tool holders of same type and size with one tool
(*e*) Combination of condition (*a*) and (*d*)
(*f*) Varying torque levels for tightening the tool in the holder
(*g*) Combination of condition (*a*) and (*f*)
(*h*) Condition of cold tool-holder assembly inserted into warm spindle while torque levels varied

These test conditions are depicted in Figure 5.



C = cold, *WU* = warmed-up, *m* = multiple mounting or assembling, $T_{\_v}$ = torque variation

Fig 5: Conditions in milling operations for variations in tool point dynamics

4.1 Effects of Spindle Warm Up

Tests conducted under conditions (*a*) described above resulted in the noticeable changes in the tool point dynamics, as shown in Figure 6, 0.37 % per 10 °C for natural frequency and 6.16 % per 10 ºC for dynamic stiffness. Natural frequency decreases as a result of decrease in system stiffness and dynamics stiffness increases as a result of increase in damping because assembly clearances among components in the tool-holder-spindle system increase from thermal expansion of each component in the warmed-up system [17].

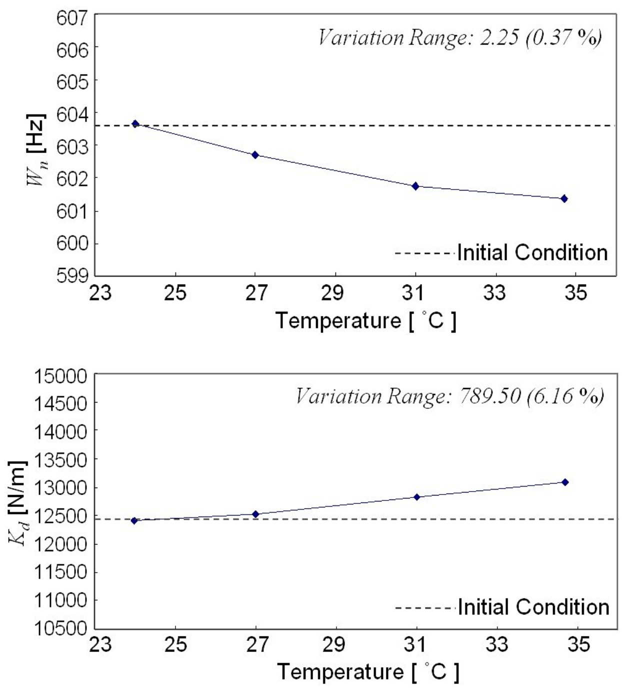


Fig 6: Changes in tool point dynamics in warmed up tool-holder-spindle system

4.2 Effects of Tool and Tool-Assembly Changes in Spindle

To investigate the effects of tool and tool-holder assembly changes, tests were conducted under conditions (*b*), (*c*), (*d*), and (*e*) described above. Figure 7 illustrates changes in the tool point dynamics resulting from those changing conditions. The range of variation observed corresponding to each condition is indicated in the figure.

Changes in condition (*b*) are relatively insignificant compared to changes in other conditions due to constant force (drawbar force) between the holder and the spindle. Condition (*c*) shows slightly bigger changes than condition (*b*) because dynamic properties in the interface between a tool and a holder may change when a tool is re-assembled to a holder by manual operation. More considerable changes are found in condition (*d*) and (*e*) because of non-identical dynamic properties in individual holders. Even greater changes in dynamic stiffness are found in condition (*e*) because the variations in damping due to individual holders in the tool-holder-spindle system are amplified by increases in damping in the warmed up system.

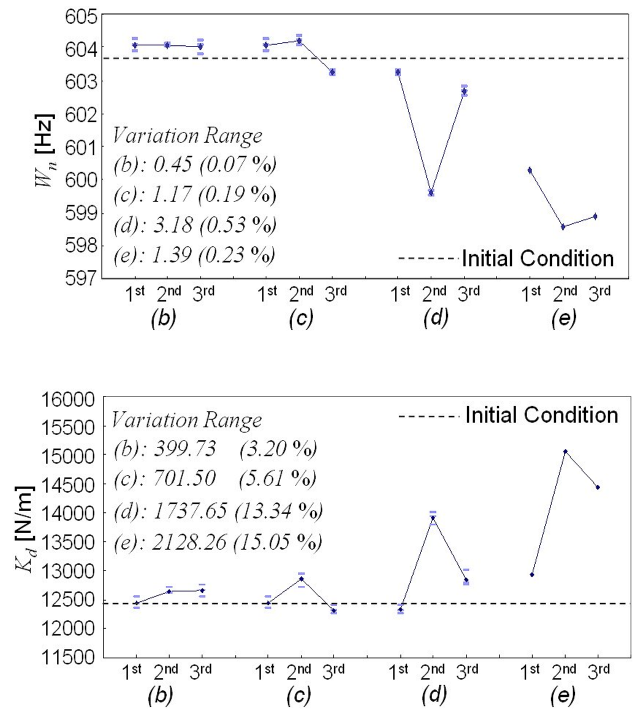


Fig 7: Changes in tool point dynamics by tool and tool assembly changes in spindle

4.3 Effects due to Torque Variations between Tool and Holder

Figure 8 shows changes in the tool point dynamics by tightening torque variations in a collet (torque range of 3.5 kg·m to 5.5 kg·m in this study) that connects a tool to a holder. The torque variations represent the changes that may result from machinist's manual tightening. The changes in the tool point dynamics were examined in the conditions of (*f*), (*g*), and (*h*) described above. The range of variation observed corresponding to each condition is indicated in the figure.

Generally, stiffness increases and dynamic stiffness decreases when components are tightened with higher torque. More definite changes in dynamic stiffness are identified in torque variations when the tool-holder-spindle system is warmed up.

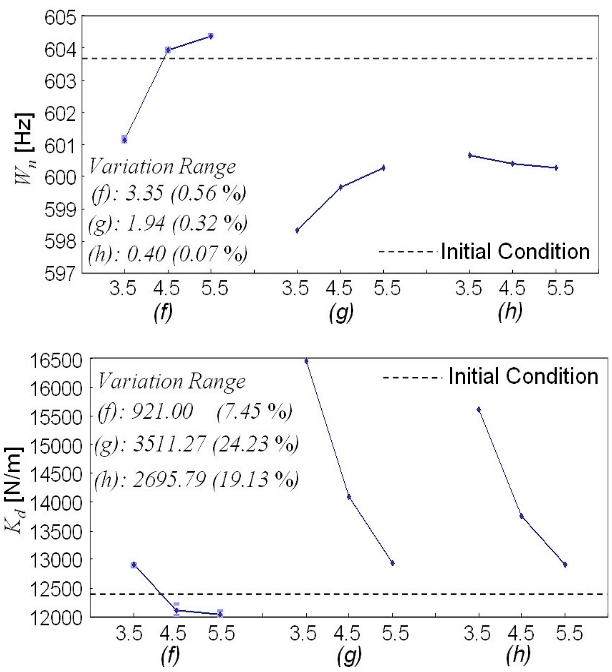


Fig 8: Changes in tool point dynamics by torque variations between tool and holder

Figure 9 summarizes the results of changes in tool point dynamics illustrating the maximum and minimum values of the tool point dynamics according to the conditions in milling operations.

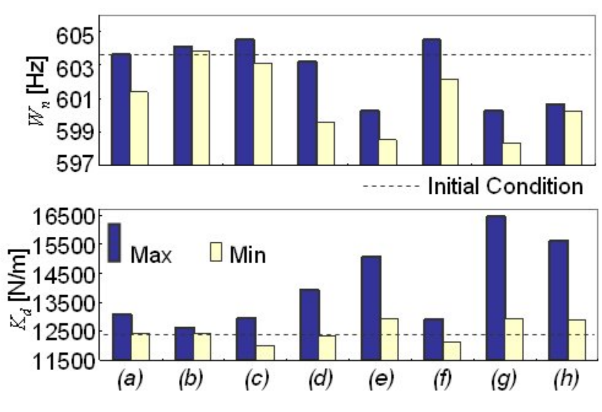


Fig 9: Maximum and minimum values of tool point dynamics according conditions in milling operations

5. REPEATABILITY OF TOOL POINT DYNAMICS AND MACHINING STABILITY

Repeatability of the tool point dynamics and the associated machining stability were analyzed based on the conditions in milling operations.

Main input parameters to evaluate the machining stability in high-speed milling from measured tool point are listed in Table 1.

Machine & Tool	
Max. Spindle Speed	3142 rad/s (30000 rpm)
Cutter Type	Cylindrical End
Cutter Material	Carbide
Numbers of Flutes	2
Workpiece	
Material	Aluminum AL 7075-T6
Cutting Coefficient	Average
Cutting Conditions	
Milling Mode	Down-milling
Radial Depth of Cut	50 % Radial Immersion

Table 1: Main inputs for stability evaluation

For repeatability analysis on the machining stability, changes in the best speed and the best axial depth of cut (best machining conditions) at the peak in stability lobes closest to the maximum spindle speed of the machining center were examined. For the input parameters listed in Table 1, the best speed in the initial condition is 1903 rad/s (± 0.20 rad/s, 0.01%) as seen in Figure 10.

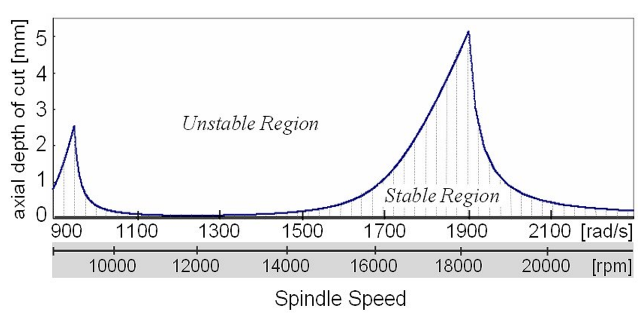


Fig 10: Stability lobes of initial condition

Repeatability of the tool point dynamics and the associated machining stability for various test conditions mentioned was examined by coefficient of variation,

$$CV = \sigma / \mu \quad (3)$$

$$CVP = CV * 100 \quad (4)$$

where μ and σ are mean value and standard deviation of parameters in the tool point dynamics (ω_n, k_d) or machining stability (a_{lim}, n) for each condition. *CVP*s are variation indices that indicate degrees of variability of the tool point dynamics or the associated machining stability in response to conditions in milling operations. *CVP*s are dimensionless numbers that allow comparison of the variations in parameters with significantly different mean values or different units as parameters in the tool point dynamics and the machining stability in this study.

Because the machining stability is dependent on the tool point dynamics as shown in equations 1 and 2, changes of *CVP*s in the best speed and the best axial depth of cut in Figure 12 follow aspects of changes of *CVP*s in natural frequency and dynamic stiffness in Figure 11 respectively.

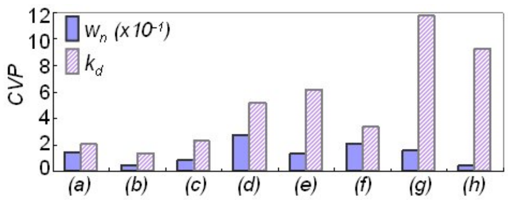


Fig 11: Coefficient of variation (*CVP*) of dynamics

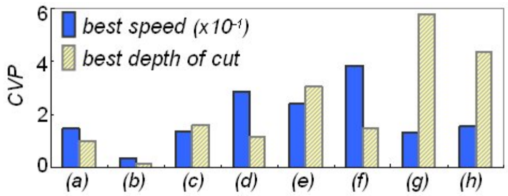


Fig 12: Coefficient of variation (*CVP*) of stability

The *CVP*s in Figure 11 and 12 illustrate relatively significant variability when individual holders are assembled to the spindle or components are tightened with variable torques especially the spindle system is warmed up.

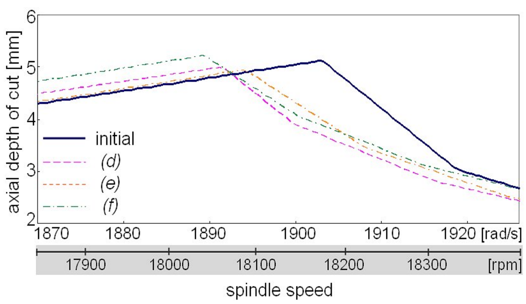


Fig 13: Changes of stability lobes
with significant changes in best speed

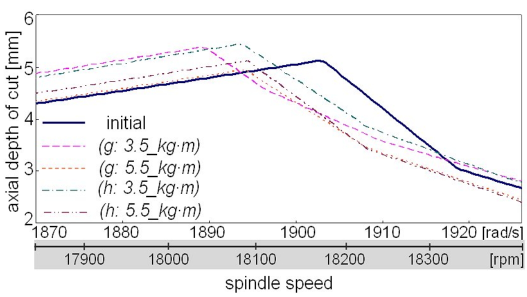


Fig 14: Changes of stability lobes
with significant changes in best axial depth of cut

Some of these conditions, with significant changes in the best speed and the best depth of cut, are demonstrated in Figure 13 and Figure 14 respectively. When the tool point dynamics are re-measured and stability lobes are re-created in different conditions, the stable regions for milling shift. In fact, the best machining conditions selected based on the initial condition (the peak of the solid line in Figure 13 and 14) are outside of the updated stability regions. Relatively smaller *CVP*s were found in the best speed than the best axial depth of cut (for example, n is 0.24 and a_{lim} is 3.06 at condition (*e*)). However, shifts in the best speed are as critical as shifts in the best axial depth of cut since best conditions are selected at the peak of the stability lobes as illustrate in Figure 13.

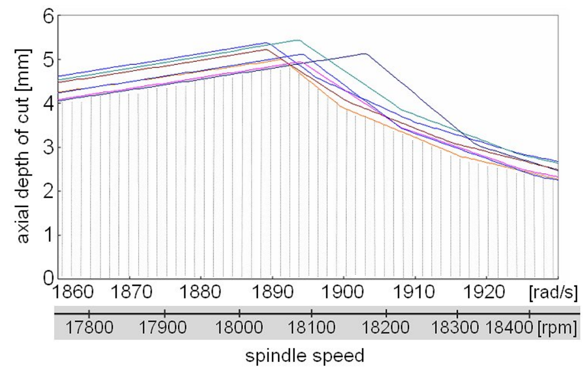


Fig 15: Stable region considering changes
in machining stability

In Figure 15, the shaded region illustrates the stable region common to all conditions of milling operations considered in this research. It can be seen that any best machining condition selected from a single stability lobes (from the tool point dynamics measurement at single condition) will be outside of the shaded region. Therefore, a best machining condition selected from any single condition of the tool point dynamics will eventually fall in an unstable region as changes in the tool point dynamics result in stability lobes changes during milling process. The results of repeatability analyses in this paper demonstrated the necessity to update the tool point dynamics during milling process to minimize uncertainty in milling stability evaluation. The relative degrees of variability by *CVP*s in the tool point dynamics and the associated stability presented which conditions in typical milling operations were most likely to lead to instability during machining process. Therefore, the results presented in this paper can be used as a guide to when the tool point dynamics need to be updated.

While the tool point dynamics were measured in this study, minimization of variation from measuring process of manual impact test was managed with great care. However, it is very difficult and very time-consuming to routinely maintain such care at the shop floor level. Therefore in-situ measurement with an automated impacting unit providing uniform impacts is necessary for efficient and reliable updates of the tool point dynamics.

6 CONCLUSIONS

This study investigated changes in the tool point dynamics and the associated milling stability according to potential factors influencing the tool-holder-spindle system. Significant changes in the dynamics and the stability were observed for most of the possible cases in the milling operation based on conditions tested. In repeatability analyses, importance of each condition for maintaining milling stability was presented by variation indices, *CVP*s that indicate degrees of variability according to these cases. The updates of the tool point dynamics to minimize the uncertainty in stability evaluation can be guided by the repeatability results in this paper. Further research is planned to employ an in-situ measurement system that is designed to update the tool point dynamics continually for machining stability in high-speed milling operation.

7 ACKNOWLEDGEMENTS

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