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Machining Stability of a Milling Machine with Different Preloaded Spindle

Jui-Pin Hung, Qiao-Wen Chang, Kung-Da Wu, Yong-Run Chen

Abstract**—**This study was aimed to investigate the machining stability of a spindle tool with different preloaded amount. To this end, the vibration tests were conducted on the spindle unit with different preload to assess the dynamic characteristics and machining stability of the milling machine. Current results demonstrate that the tool tip frequency response characteristics and the machining stabilities in X and Y direction are affected to change due to the different preload of spindle bearings. As found from the results, a high preloaded spindle tool shows higher limited cutting depth at mid position, while a spindle with low preload shows a higher limited depth. This indicates that the machining stability of a milling machine is affected to vary by the spindle unit when it was assembled with different bearing preload.

Keywords**—**Dynamic compliance, Bearing preload, Machining stability.

I. Introduction

THE spindle tool system is the most important component for a machine tool executing the machining operation. For various application areas, a wide variety of spindles of different designs have been developed [1], [2]. For the machining of large frames in auto industry, spindles were designed with high power and high rigidity, which requires a heavy preload applied to the bearings. In order to increase the rigidity of spindle unit, the bearing groups could be adequately preloaded to increase the rigidity of spindle unit. However, several studies [3]-[6], Gunduz et al. [7] have revealed that the dynamic behavior of a spindle tool system is significantly affected by the preload state of the supporting bearings.

On the other hand, for machining precision in airplane and semiconductor industries, spindles with high speed and high precision are developed. But occurrence of chatter vibration during machining was a fatal problem for a machine tool toward high performance. Studies [8]-[10] reported that chattering is caused by the dynamic interaction between the cutting tool and the work-piece during the chip generation process. Also the machining stability is greatly determined by the dynamic characteristics of the spindle tool system. Therefore, for the design of spindle with high machining performance, the machining stability over a wide operation range should be taken into consideration. Under this condition, the setting amount of preload to the bearings is of importance to ensure the spindle with enough dynamic stiffness and damping capability. As discussed in studies [11]-[13], increasing the bearing preload can increase the bearing stiffness, but also reduces the damping ratio of the bearings. This would be unfavorable for suppression of the chattering in high speed machining.

This study was aimed to identify how the changing of spacer clearance affects the dynamic characteristics of a spindle tool. In particular, we intended to examine the correlations between the spacer clearance and modal parameters by experimental approaches. The results are expected to provide a reference for tuning or examine the variation of the dynamic characteristics of the spindle.

Jui P. Hung, Qiao W. Chang, Yong R. Chen, and Kung D. Wu are with the Graduate Institute of Precision Manufacturing, National Chin-Yi University of Technology, Taichung, Taiwan, R.O.C. (phone: +886-4-23924505; fax: 886-4-23939932, e-mail: hungjp@ncut.edu.tw).

II. Evaluation of Machining Stability

According to the theory of machining stability proposed by [14], the dynamic cutting forces F_x and F_y are related to the displacements Δx and Δy of the cutter by the following relationship:

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = \frac{1}{2} z K_t [A(t)] \begin{Bmatrix} \Delta x \\ \Delta y \end{Bmatrix} \tag{1}$$

In which $[A(t)]$ is the direction coefficients matrix with feeding times [14]. The above equations can be redefined in frequency domain as

$$\{\Delta r(s)\} = \left(1.e^{-sT}\right) G(s) \{F\} e^{st} \tag{2}$$

In above, $G(s)$ is the transfer function between dynamic displacements and cutting forces

$$\Phi_{xy} = G(s) = \begin{bmatrix} G_{xx}(s) & G_{xy}(s) \\ G_{ys}(s) & G_{yy}(s) \end{bmatrix} \tag{3}$$

The characteristic equation of the cutting systems is

$$\det([I] + \Lambda[\Phi_{xy}(iw_c)]) = 0 \tag{4}$$

Solution of the characteristic equation can give the complex eigenvalues defined by

$$\Lambda = \Lambda_R + i\Lambda_I = -\frac{N}{4\pi} z_0 K_t \left(1 - e^{-i\omega T}\right) \tag{5}$$

From (5), the critical axial cutting depth Z_{lim} and spindle speed n for stable machining can be obtained as:

$$Z_{lim} = -\frac{2\pi\Lambda_R}{NK_t}(1+\lambda^2)$$

$$n = \frac{60w_C}{N(2k\pi + \pi - 2tan^{-1}\frac{\Lambda_R}{\Lambda_I})}, \qquad k = lobes(0,1,2...) \tag{6}$$

III. Experimental Measurements

Fig. 1 illustrates the experimental configuration of the milling machine, which has equipped with a high speed spindle (DDS BT-30) with a tool holder-tool unit (BT30). In this study, three different spindles were assembled with different spacer between the front and rear bearing groups, which preloading the spindle at three different amount, namely, slight preload (68P), standard medium preload (69P), and high preload (70P). The different three spindles were respectively installed into the spindle head of the milling machine for subsequent vibration test.

In test, the spindle tool was located at the height of 500, 250 mm from the working table. Two accelerometers were respectively mounted on the tool end in the X and Y directions. The hammer was used to hit the tool end in the opposite side respectively to excite the vibration of spindle tool system. Following this procedure, we obtained the frequency responses functions of the tool tip measured as G_{xx} and G_{yx}, and G_{xy} and G_{yy}. The dynamic responses were then extracted from the recorded FFT spectrum. The modal parameters such as damping ratio and dynamic stiffness associated with the dominant vibration modes were extracted from the measured FRFs for assess the differences of the dynamic characteristics among the spindles with different preloads.

The measured frequency response functions at tool tip were further used to calculate the stability lobe diagram. For the calculation of machining stability, a two-tooth high speed steel cutter was employed to machine the stock material of Al7075. The cutting resistance coefficients were calibrated as K_t=796 N/mm^2 and K_r=0.21 [14].

Fig. 1 Bearing spacers and configuration of vibration test

IV. Results and Discussions

A. Preload Effect on Frequency Response Functions

The measured vibration responses of the milling machine with different preloaded spindles are illustrated in Figs. 3 and 4 for comparison, which are measured for spindle tool at the height of 250 and 500 mm, respectively. The vibration responses are expressed in terms of the compliance at the tool end varying with frequency. It can be found that the spindles tooling system with different bearing preload show similar vibration behaviors. When the spindle is positioned at height of 500 mm, the maximum compliance of the tool occurs at the frequency of 851– 895Hz, slightly varying in X and Y direction, which is about the natural frequency of the spindle unit. Also the resonant frequency slightly changes with the changing of the bearing preload of the spindle. As found, for medium preload, it resonates at 866 Hz. When the spindle is preloaded to a higher amount, the resonant frequency also shifts to a higher value (890 Hz). Besides, the maximum compliance of the tool is about 2.87 –2.93 um/N in X-direction and 2.97– 3.62 in Y-direction, respectively, which are also affected by the preloaded amount of the spindle. According to the study of Hung et al., [15] this apparent vibration mode of the spindle tool is mainly caused by the bending deformation of the spindle shaft. It could be also accompanied and affected by the yawing or pitching vibration of the spindle head on the machine frame. This may also contribute the difference between the resonant frequency in X and Y direction.

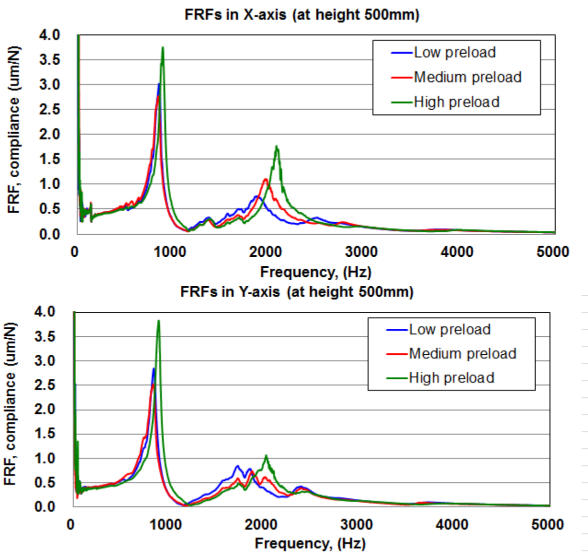

Fig. 2 Tool tip frequency response functions measured for different preloaded spindle. The spindle tool was positioned at height of 500mm from the working table

Similar phenomenon was also found when the spindle was positioned at height of 250 mm, as show in figure the resonant frequency is about 841– 894Hz with maximum compliance of between 2.92– 3.53 um/N. As shown in Table I, the resonant frequency and maximum are affected to change by the preload of the spindle. The spindle with high preload has a high resonant frequency than that with lower preload. But the high preload do not enable the spindle to show a lower dynamic compliance or higher dynamic stiffness as compared to the spindle with lower preload. This can be ascribed to the fact that the dynamic compliance or stiffness is determined by the damping ability of the spindle tool system which is further dependent on the preload state of spindle bearing and the machine frame structure.

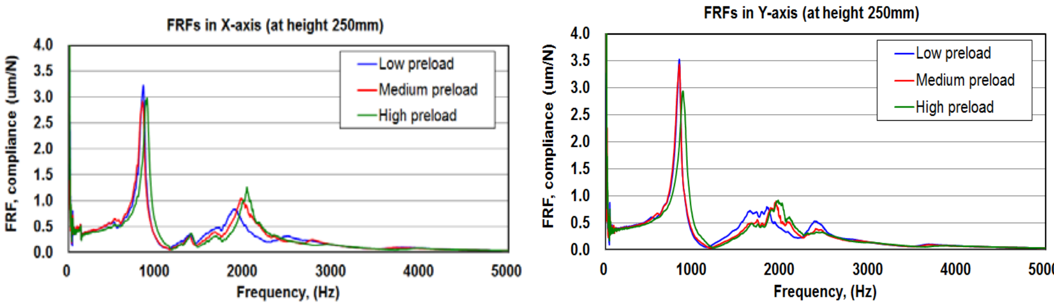

Fig. 3 Tool tip frequency response functions measured for different preloaded spindle: The spindle tool was positioned at height of 250

TABLE I
COMPARISONS OF THE MODAL FREQUENCY AND COMPLIANCE OF SPINDLE TOOL WITH DIFFERENT PRELOADS

Spindle position	Spindle preload	X direction		Y direction	
		Modal frequency (Hz)	Max. compliance (um/N)	Modal frequency (Hz)	Max. compliance (um/N)
500	high	895	2.93	884	2.97
	medium	857	2.94	851	3.62
	low	852	2.87	846	3.08
250	high	894	2.99	881	2.94
	medium	853	3.22	841	3.53
	low	843	2.92	841	3.44

B. Preload Effect on Machining Stability

Figs. 4 and 5 present the stability lobes in the X and Y direction, respectively, which also compares the difference of the stability lobes of the spindle tool system with different preloaded amount. In case that the spindle tool is positioned at height of 500mm, the limited depth for high preloaded spindle tool is 1.97 and 1.94 mm in X and Y direction, respectively. For medium preloaded spindle tool, the limited depth is 2.45 and 2.55 mm in X and Y direction, respectively and the limited depth for spindle tool with low preload is 2.40 and 2.86 mm in X and Y direction, respectively. According to the stability analysis, the spindle tool system used in this study shows a superior machining stability in Y direction than in X direction.

When the spindle tool is positioned at height of 250 mm, the stability lobes in the X and Y directions are shown in Fig. 4. As shown in the figures, the limited depth in X-direction is 2.38, 2.25 and 2.67 mm for spindle preloaded at slight, standard and medium preload, respectively. The Y-direction limited depth corresponding to the three preloaded spindles is 2.07, 2.27 and 2.67 mm, respectively. Also, the machining stability varies with the feeding of the spindle head along Z axis. As noticed, variation of the stability with the spindle position is also different when the spindle is preloaded at different amount.

For milling machine with low preloaded spindle, the limited cutting depths decrease from a higher value (2.86 mm) to a lower value (2.07 mm) when the tool is feed downward from the top to mid position along Z axis, decreased by 28%. To the contrast, the limited cutting depths of a high preloaded spindle tool increases from lower value (1.97 mm) to a higher value (2.67 mm), which shows an increase of 35%. As can be known, the spindle tool with different preloaded amount shows a different variation in the limited cutting depth.

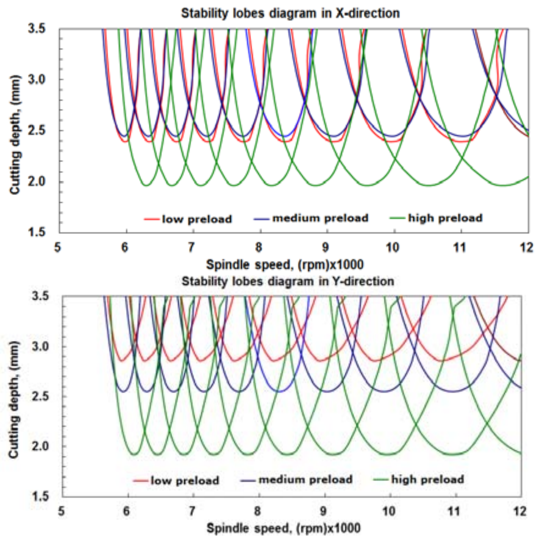

Fig. 4 Stability lobes diagrams of spindle tools with different preloads

Comparison of the results in stability analysis indicate that the machining tooling system has a different limited depth for stable machining in X and Y directions. This implies that the machining stability of spindle tool system is affected to vary not only by the spindle dynamics, but also by the machine frame structure. Moreover, such an effect caused by machine frame is quite different and varied with the preload of the spindle.

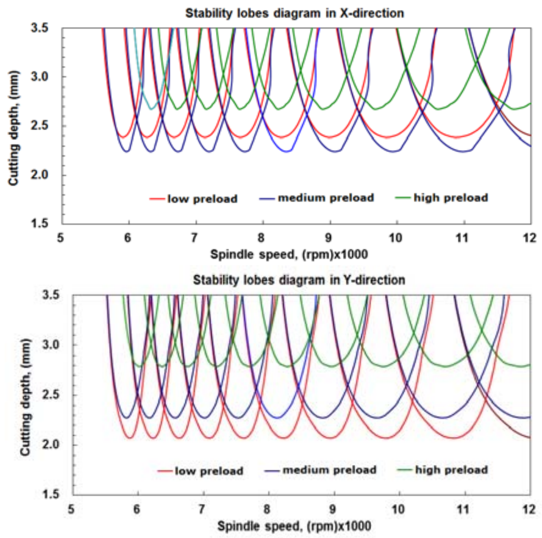

Fig. 5 Stability lobes diagrams of spindle tools with different preloads

V. Conclusion

This study presents an investigation on the variation of dynamic characteristics and machining stability of a spindle under the influence of the bearing preload. Based on the results, the following conclusions are drawn:

1. A variation in spindle preload will affect the dynamic characteristics of the milling machine to vary in different extent. As found in vibration tests, the spindle tool with a lower bearing preload vibrates at lower frequency when compared to the one with medium or high preload. Such influence can be quantified by examining the variation of the modal compliance
2. Besides, the machining stability of the spindle tool is affected to vary with the bearing preload in the spindle. The limited cutting depth is also different when the spindle tool is moved to different position along Z axis. This implies that the dynamic characteristics and the machining performance of the spindle tool system are also affected by the machine frame structure, in addition to the spindle unit. Besides, such an effect is quite different and varies with the preload of the spindle.

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References

[1] E. Abele, Y. Altintas, C. Brecher, “Machine Tool Spindle Units,” CIRP Annals – Manufacturing Technology, vol. 59, no. 4, pp. 781–802, 2010.

[2] M. Weck, A. Koch, “Spindle-bearing systems for high-speed applications in machine tools,” CIRP Annals-Manufacturing Technology, vol. 42, no. 1, pp. 445–448, 1993.

[3] S. P. Harsha, L. Sandeep, R. E. Prakash. “Effects of Preload and Number of Balls on Nonlinear Dynamic Behaviors of Ball Bearing System,” International Journal of Nonlinear Science and Numerical Simulation. vol. 4, no. 3, pp. 265-278, 2003.

[4] Y. Cao, Y. Altintas, “Modeling of Spindle-Bearing and Machine Tool Systems for Virtual Simulation of Milling Operations,” International Journal of Machine Tools and Manufacturing. vol. 47, no. 9 pp. 1342-1350, 2007.

[5] M. A. Alfares, A. A. Elsharkawy. “Effects of Axial Preloading of Angular Contact Ball Bearings on the Dynamics of a Grinding Machine Spindle System,” Journal of Materials Processing Technology. vol. 136, no. 3, pp. 48-59, 2003.

[6] S. A. Spiewak, T. Nickel. Vibration Based Preload Estimation in Machine Tool Spindles, International Journal of Machine Tools & Manufacture. vol. 41, no. 4, pp. 567-588, 2001.

[7] A. Gunduz, J. T. Dreyer, R. Singh. “Effect of Bearing Preloads on the Modal Characteristics of a Shaft-Bearing Assembly: Experiments on Double Row Angular Contact Ball Bearings,” Mechanical Systems and Signal Processing. vol. 31, pp. 176-195, 2012.

[8] J. Tlusty, .M. Polacek. “The Stability of Machine Tools Against Self-Excited Vibrations in Machining,” Trans. ASME, International research in production engineering. Pp. 465-474, 1963.

[9] S. A.Tobias, W. Fishwick. “The Chatter of Lathe Tools under Orthogonal Cutting Conditions", Trans. ASME, Journal of Engineering for Industry, vol. 80, pp. 1079-1088, 1958.

[10] E. Ozturk, U. Kumar, S. Turner, T. Schmitz. “Investigation of Spindle Bearing Preload on Dynamics and Stability Limit in Milling,” CIRP Annals-Manufacturing Technology. vol. 61, no. 1, pp. 343-346, 2012.

[11] C. W. Lin, J. F. Tu. “Model-Based Design of Motorized Spindle Systems to Improve Dynamic Performance at High Speeds,” Journal of Manufacturing Processes. vol. 9, no. 2, pp. 94-108, 2007.

[12] S. Jiang, H. Mao. “Investigation of Variable Optimum Preload for a Machine Tool Spindle,” International Journal of Machine Tools and Manufacture. vol.50, no. 1, pp. 19-28, 2010.

[13] S. Jiang, H. Mao. “Investigation of Variable Optimum Preload for a Machine Tool Spindle,” International Journal of Machine Tools and Manufacture. vol.50, no. 1, pp. 19-28, 2010.

[14] Y. Altintas, E. Budak. “Analytical prediction of stability lobes in milling,” Annals of the CIRP Vol. 44, pp.357–362, 1995.

[15] J. P. Hung, Y. S. Lai, T. L. Luo, K. D. Wu, Y. Z. Zhan, “ Effect of Drawbar Force on the Dynamic Characteristics of a Spindle-Tool Holder System,” World Academy of Science, Engineering and Technology, International Journal of Mechanical, Industrial Science and Engineering vol. 8, no.5, pp. 970-975, 2014