Compensation of Machine Tool Spindle Error Motions in the Radial Direction for Accurate Monitoring of Cutting Forces Utilizing Sensitive Displacement Sensors

Ahmed A. D. Sarhan, M. A. Hassan, Atsushi Matsubara, and M. Hamdi

***Abstract*—This paper deals with the cutting force monitoring for intelligent end milling operations. The authors have employed displacement sensors to monitor the cutting forces, as they are cheap and small enough to be built in the spindle structure. A monitoring method, which utilizes sensitive displacement sensors, is discussed. The sensors are installed in X Y directions near the front bearings of the spindle, to detect the small displacements of a spindle caused by cutting forces. Monitoring tests are carried out under end milling operations and the cutting forces are estimated from the displacement signals by the simple signal processing technique. However, as the displacement sensor measures the variation of the gap size between the sensor head and the target surface, it also records displacements due to error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface. By comparing the cutting force estimated from displacement sensors with the cutting force measured by using a dynamometer, the machine tool spindle error motions is investigated, and its compensation scheme is proposed. The test results show that the monitoring system is reliable for the adaptive control of machining accuracy for end milling process.**

***Index Terms*— CNC Machine Tools, Cutting Force, Displacement Sensor, Monitoring System**

I. INTRODUCTION

THE present global market competition has attracted the manufacturer's attention on automation of manufacturing systems via condition monitoring of machine tools and processes as a method of improving quality of products, eliminating inspection, and enhancing manufacturing productivity [1-6]. The cutting forces are the most important indicator for that as they could tell limits of cutting conditions, accuracy of the workpiece, tool wear, and other process information, which are indispensable for process feedback control [7-14]. Hence, reliable cutting force measurement systems are investigated. The most common method to measure cutting forces in machining operations is through table dynamometers. Although table dynamometers provide accurate and effective force measurement, they are more suitable for laboratory or experimental use rather than for practical application on production machines, due to the limitation of workpiece size, mounting constraints, high sensitivity to overload, and high costs [15-17]. Furthermore, the dynamic characteristics of table dynamometers are strongly dependent on the workpiece mass, which may change during machine operation. To overcome limitations of workpiece mass and size, a force sensor can be integrated to the spindle itself instead of installing it on the machine table, thus converting an ordinary spindle into a so-called monitoring spindle [18-20].

The authors have employed displacement sensors, as they are cheap and small enough to be built in the spindle structure. Displacement signals are translated into cutting force information by the calibration. However, the monitoring quality is a problem, because sensors also detect the displacement caused by machine tool spindle error motions in the radial direction [21-25]. In this research, we develop a spindle with displacement sensors in X and Y-axis directions near the front bearings of the spindle, to monitor the spindle displacement. Cutting forces are estimated from the displacement signals by the simple signal processing technique. Monitoring tests are carried out under end milling operations on cast iron workpieces. By comparing the estimate with the measured cutting force by using a dynamometer, the machine tool spindle error motions in sensor output is investigated, and its compensation scheme is proposed. With its compensation scheme implemented, the experimental result shows that the monitoring system is reliable for the adaptive control of machining accuracy for end milling process.

II. MEASUREMENT OF THE MACHINE TOOL SPINDLE DISPLACEMENT TO INVESTIGATE THE RADIAL ERROR MOTIONS

A. Experimental set-up

In order to measure the machine tool spindle

Manuscript received January 27, 2011; revised February 11, 2011. This research has been supported by the MTTRF (Machine Tool Technologies Research Foundation) via Equipment on Loan Award Program.

Ahmed A. D. Sarhan is with Center of Advanced Manufacturing and Material Processing, Department of Engineering Design and Manufacture, Faculty of Engineering, University of Malaya, Kuala Lumpur, 50603, Malaysia (corresponding author, phone: 0060379674593; fax: 0060379675330; e-mail: ah_sarhan@um.edu.my).

M. A. Hassan is with Center of Advanced Manufacturing and Material Processing, Department of Engineering Design and Manufacture, Faculty of Engineering, University of Malaya, Kuala Lumpur, 50603, Malaysia (e-mail: mohsenegypt@um.edu.my).

Atsushi Matsubara is with Department of Micro Engineering, Graduate School of Engineering, Kyoto University. Yoshida-honmachi Sakyo-ku Kyoto, Japan 606-8317 (e-mail: matsubara@prec.Kyoto-u.ac.jp).

M. Hamdi is with Center of Advanced Manufacturing and Material Processing, Department of Engineering Design and Manufacture, Faculty of Engineering, University of Malaya, Kuala Lumpur, 50603, Malaysia (e-mail: hamdi@um.edu.my).

displacement caused by cutting force during cutting, displacement sensors are installed on the spindle unit of a high precision machining center. The machine used in the study is a vertical-type machining center (GV503 made by Mori Seiki Co., LTD.). The spindle has constant position preloaded bearings with oil-air lubrication, and the maximum rotational speed is 20000 min^{-1}. Four eddy-current displacement sensors are installed on the housing in front of the bearings to detect the radial motion of the rotating spindle. Tables 1 and 2 respectively show the specifications of the machining center and the displacement sensor used in this research. A thin collar with a fine cylindrical surface is attached to the spindle as a sensor target. Figure 1 shows the sensor locations. The two sensors, S_1 and S_3, are aligned opposite in the X direction, and the other two sensors, S_2 and S_4, are aligned opposite in the Y direction.

TABLE 1. SPECIFICATIONS OF THE MACHINING CENTER

Spindle	Spindle speed (min^{-1})	200 - 20000
	Power 15min./cont. (kW)	22 / 18.5
	Tool interface	7/24 taper No.40 with nose face contact
Feed drive	Max. rapid traverse rate (mm/min)	33000
	Max. feed rate (mm/min)	10000
	Max. acceleration rate (G)	X-axis：0.67, Y-axis：0.64, and Z-axis：0.56
	Travel distance (mm)	X-axis： 630, Y-axis： 410, and Z-axis： 460
Machine size	Width×Length×Height (mm)	2320×3780×2760
	Mass (kg)	5500
CNC servo system	64bit CPU (RISC processor) + high gain servo amplifier	

TABLE 2. SPECIFICATIONS OF THE DISPLACEMENT SENSOR

Detection principle	Eddy current
Measurement range (mm)	0～1
Output scale (V)	0～5
Diameter mm	5.4
Length mm	18
Sensitivity (mm/V)	0.2
Linearity (% of full scale)	±1
Dynamic range (kHz)	1.3 (-3dB)

B. Experimental procedure

A slot end-milling test is carried out to investigate the machine tool spindle error motion in radial direction. Table 3 shows the tool and cutting conditions. The cutting time for one operation should be short enough to avoid the thermal disturbances on displacement signals.

First, the spindle is rotated at 1500 min^{-1} without cutting for 30 min for the first warm-up. Then, the 1st cutting test is carried out at the same spindle speed. The spindle is warmed up again at the speed of 3000 min^{-1} for another 30 min without cutting followed by the 2nd cut at the speed of 3000 min^{-1}.

Similarly, the third and forth warm-up and cutting tests at 6000 and 12000 min^{-1} are carried out. The displacement signals are digitized with a 16-bit A/D board, and the dynamometer signals are digitized with a 12-bit A/D board. The sampling frequency is set so that 40 points per one spindle revolution can be obtained.

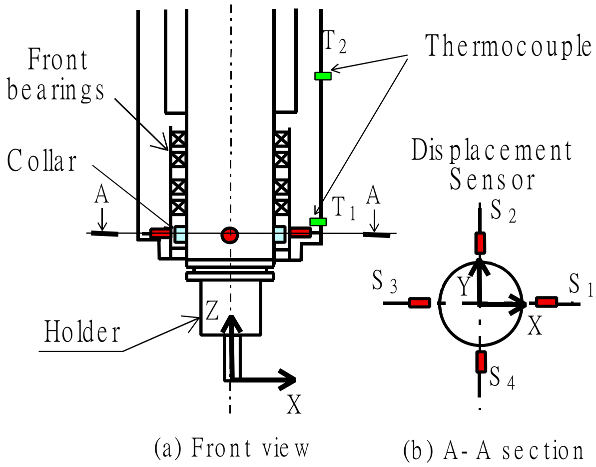


Fig.1 Locations of the sensors

TABLE 3. THE TOOL AND CUTTING CONDITIONS

Spindle Speed (min^{-1})	1500, 3000, 6000, 12000
Axial depth of cut (mm)	10
Feed mm/min	600
Cutting tool	Coated carbide end mill, Diameter: 10 mm,
Holder	BT40-C20 (collet)-20 (extension)
Cutting mode	Down cut
Coolant	No
Workpiece material	Carbon steel (S50C)

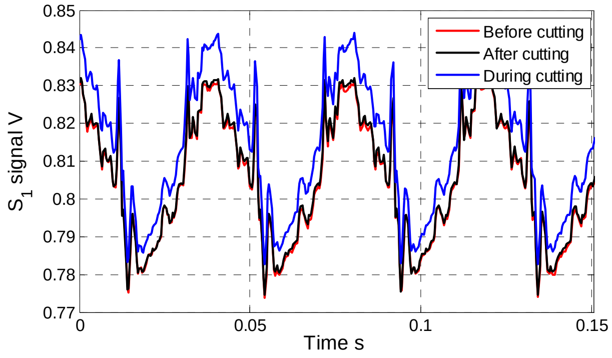
C. Experimental results

Figure 2 shows an example of the output of the displacement sensor signals in X-axis direction before, during, and after cutting at spindle speed of 1500 min^{-1}.

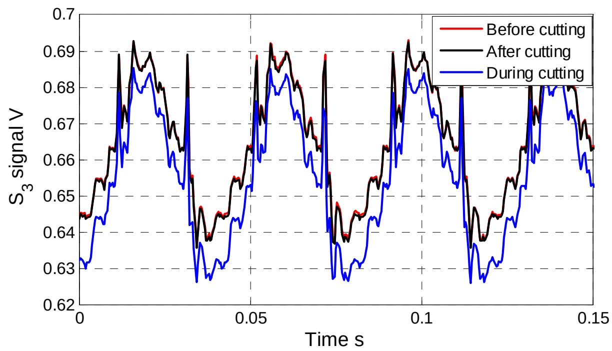
As can be seen in Fig. 2, before cutting, all the displacement profiles involve periodical type of fluctuation. These periodic fluctuations are related to the error motion of

ISBN: 978-988-18210-6-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

a spindle's axis of rotation in radial direction and roundness errors of the target surface. During cutting, it is observed that, the displacement profile shifts but it returns back to its original position after the end of cutting.



(a) The output of the S_1 sensor signals



(b) The output of the S_3 sensor signals

Fig. 2. The output of the displacement sensor signals at 1500 min^{-1}

III. The Compensation of the Machine Tool Spindle Radial Error Motions

As can be seen in Fig.2, the displacement sensor measures not only the variation of the gap size between the sensor head and the target surface but also the displacements due to error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface. These errors are simply compensated by subtracting the displacement signals measured while air cutting from the displacement signals measured while cutting.

A. *The concept of the radial error motion compensation scheme*

Figure 3, shows the concept of the spindle displacement measurement. When the spindle axis shifts by Δx µm in X direction due to the cutting force, the displacement signals from S_1 and S_3 are as follows.

$$S_1(\theta) = G[R_1 - r(\theta) - \Delta x] \tag{1}$$

$$S_3(\theta) = G[R_3 - r(\theta + \pi) + \Delta x] \tag{2}$$

Where G: sensor sensitivity [mV/µm], R_i: the distance between the spindle center and detection surface of the sensor S_i [µm] (i=1,..,4), θ: rotation angle of the spindle [rad], $r(\theta)$: the sum of the radial error motion and surface roughness of the sensor target [µm].

Subtracting the displacement signals and dividing the subtraction by two, we obtain;

$$S_x(\theta) = [\ S_3(\theta) - S_1(\theta)\ ]/2 \tag{3}$$

Letting $S_x(\theta) = S_{xo}(\theta)$ at air cutting such that $\Delta x = 0$, and subtracting $S_{xo}(\theta)$ from $S_x(\theta)$ to compensating the radial error motions.

$$S_x(\theta) - S_{xo}(\theta) = G \cdot \Delta x \tag{4}$$

Then we obtain the axis shift Δx after the compensation as follows.

$$\Delta x = [\ S_x(\theta) - S_{xo}(\theta)\ ]/G \tag{5}$$

Similarly, the axis shift in Y direction, Δy, is calculated from the displacement signals from S_2 and S_4. The axis shift is called the spindle displacement hereafter.

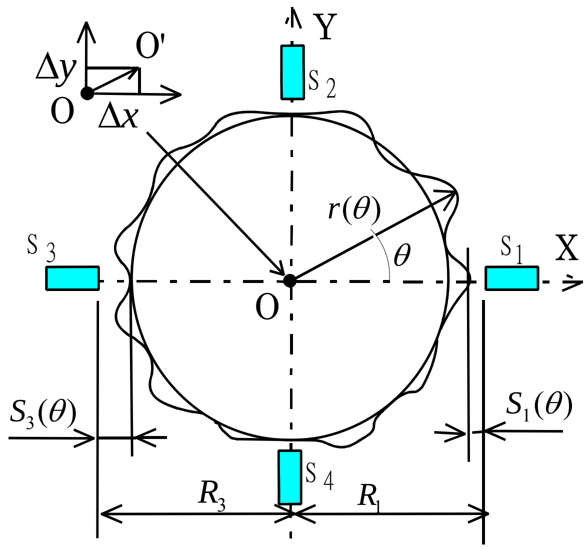


Fig.3. The concept of the spindle displacement measurement

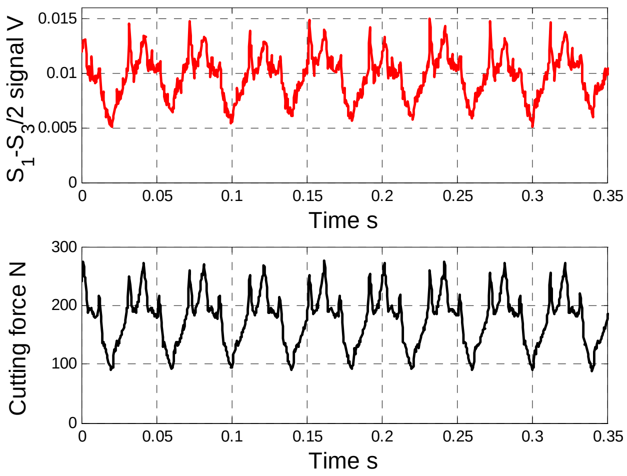
B. *Investigate the accuracy of the compensation*

The accuracy of the compensation is investigated by comparing the compensated spindle displacement with cutting forces measured by using a table type tool dynamometer (Model 9257B made by Kistler). Figure 4 shows the compensated spindle displacement and measured cutting force with the dynamometer at different spindle speeds. As can be seen in Fig. 4, the displacement profiles looks similar to the force profiles.

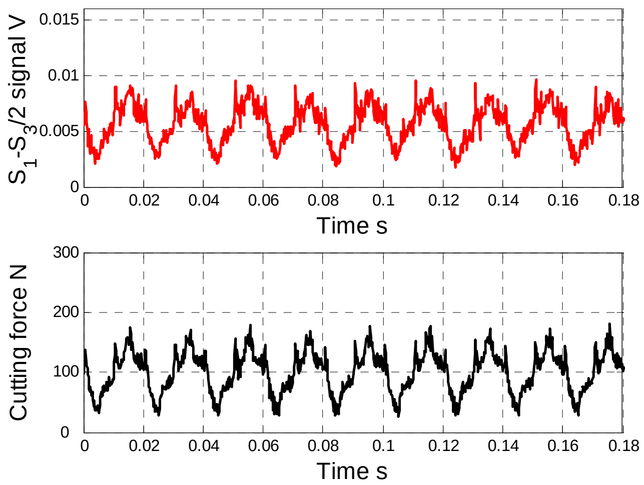
Figure 5 shows the relation between the spindle displacements and cutting forces at different spindle speeds.

ISBN: 978-988-18210-6-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

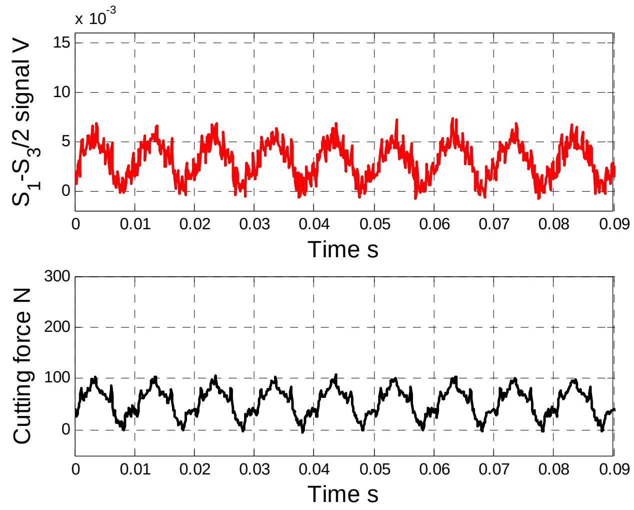
The quantization error in digital measurement system is 0.1526 mV. As can be seen in Fig. 5, the spindle displacement has a linear relationship with the cutting force when the spindle speed is less than 12000 min^{-1}. In the case where the spindle speed is 12000 min^{-1}, the relationship between the spindle displacement and the cutting force shows an unstable characteristic. This characteristic may come from the dynamics limitations of the measurement system.



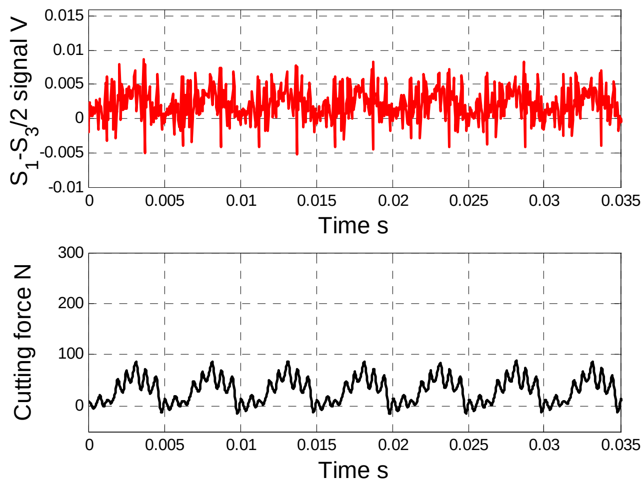
(a) Spindle speed: 1500 min^{-1}



(b) Spindle speed: 3000 min^{-1}



(c) Spindle speed: 6000 min^{-1}



(d) Spindle speed: 12000 min^{-1}

Fig. 4. The compensated spindle displacement and measured cutting force

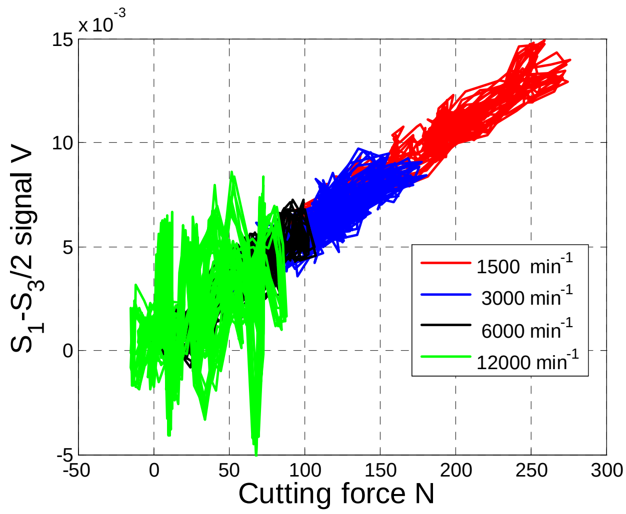


Fig. 5. The relation between the spindle displacements and cutting forces at different spindle speeds.

ISBN: 978-988-18210-6-5
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

IV. Conclusion

Displacement sensors are installed in the spindle structure of a machining center for the monitoring of cutting forces. We present how to monitor the spindle displacement more precisely by using four eddy-current displacement sensors. The displacement sensor measures not only the variation of the gap size between the sensor head and the target surface but also the displacements due to error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface. The error motion of a spindle's axis of rotation in radial direction and roundness errors of the target surface are compensated by subtracting the displacement signals measured while air cutting from the displacement signals measured while cutting. The accuracy of the compensation is investigated by comparing the compensated spindle displacement with cutting forces measured by using a table type tool dynamometer. The test results show that the monitoring system is reliable for the adaptive control of machining accuracy for end milling process. However, in the case where the spindle speed is 12000 min^{-1}, the relationship between the spindle displacement and the cutting force shows an unstable characteristic. This characteristic may come from the dynamics limitations of the measurement system.

Acknowledgment

This research has been supported by the MTTRF (Machine Tool Technologies Research Foundation) via Equipment n Loan Award Program. The authors would like to express our sincere appreciation for the continuing support on our research work.

References

[1] Martin, K.F., "A Review by Discussion of Condition Monitoring and Fault Diagnosis in Machine Tools" Int. j. Mach. Tools Manufact. Vol. 34 No. 4 pp 527 - 551 (1994).
[2] Andrews, G. C., and Tlusty, J., "A critical review of sensors for unmanned machining," Ann. CIRP 32-2, 1983, pp. 563–572.
[3] Byrne, G., Dornfeld, D., Inasaki, I., Ketteler, G., Konig, W., and Teti, R., "Tool Condition Monitoring (TCM)-Status of Research and Industrial Application-," Annals of the CIRP, 44-2, 1995, pp.541-567.
[4] K. N. Strafford, J. Audy, "Indirect monitoring of machinability in carbon steels by measurement of cutting forces" Journal of Materials Processing Technology, Volume 67, Issues 1-3, May 1997, Pages 150-156
[5] D. E. DimlaSr., P. M. Lister, "On-line metal cutting tool condition monitoring.: I: force and vibration analyses" International Journal of Machine Tools and Manufacture, Volume 40, Issue 5, April 2000, Pages 739-768
[6] Dong-Yeul Song, Nobuo Otani, Takayuki Aoki, Yuichiro Kamakoshi, Yasuhiro Ohara, Haruo Tamaki, "A new approach to cutting state monitoring in end-mill machining" International Journal of Machine Tools and Manufacture, Volume 45, Issues 7-8, June 2005, Pages 909-921.
[7] A. Sarhan, R. Sayed, A. A. Nasr, and R. M. El-Zahry, "Interrelation Between Cutting Force Variation and Tool Wear in End-Milling", Journal of Materials Processing Technology, Vol.109, No.3, pp 229-235, 15 February 2001.
[8] Lee P, Altintas Y, "Prediction of ball end milling forces from orthogonal cutting data" Int J Machine Tools Manuf 1996; 36:1059–72.
[9] Feng HS, Menq CH, "The prediction of cutting forces in the ball end milling process-II. Cut geometry analysis and model verification." Int J Machine Tools Manuf, 1994, 34, pp711–9.
[10] Sokolowski, J., and Kosmol, "Intelligent monitoring system designer," Japan/USA Symposium on Flexible Automation, Vol. 2, 1996, ASME, New York.
[11] Feng HS, Menq CH, "The prediction of cutting forces in the ball end milling process model-I. Formulation and model building procedure" Int J Machine Tool Manuf, 1994, 34, pp697–710.
[12] R. Teti, I.S. Jawahir, K. Jemielniak, T. Segreto, S. Chen, J. Kossakowska, "Chip Form Monitoring through Advanced Processing of Cutting Force Sensor Signals" CIRP Annals - Manufacturing Technology, Volume 55, Issue 1, 2006, Pages 75-80
[13] Dimla E. DimlaSnr. "Sensor signals for tool-wear monitoring in metal cutting operations—a review of methods" International Journal of Machine Tools and Manufacture, Volume 40, Issue 8, June 2000, Pages 1073-1098.
[14] S.N. Huang, K.K. Tan, Y.S. Wong, C.W. de Silva, H.L. Goh, W.W. Tan, "Tool wear detection and fault diagnosis based on cutting force monitoring" International Journal of Machine Tools and Manufacture, Volume 47, Issues 3-4, March 2007, Pages 444-451.
[15] Matsubara, A., Kakino, Y., Ogawa, T., Nakagawa, H., and Sato, T., "Monitoring of Cutting Forces in End-Milling for Intelligent Machine Tools," Proc. of the 5th Int'l Conf. on Progress of Machining Technology, 2000, pp. 615.
[16] Y.L. Chung, S.A. Spiewak, "A model of high performance dynamometer", Journal of Eng. for Ind. (ASME), 16, 1994, pp279–288.
[17] M. Santochi, G. Dini, G. Tantussi, M. Beghini, "A Sensor-Integrated Tool for Cutting Force Monitoring." CIRP Annals - Manufacturing Technology, Volume 46, Issue 1, 1997, Pages 49-52
[18] Altintas, Y., " Prediction of Cutting Forces and Tool Breakage in Milling From Feed Drive Current Measurement," ASME Journal of Engineering for Industry, Vol. 114, No.4, pp 386-391, 1992.
[19] Ahmed A. D. Sarhan, Atsushi Matsubara, Motoyuki Sugihara，Hidenori Saraie, Soichi Ibaraki, Yoshiaki Kakino, "Monitoring Method of Cutting Force by Using Additional Spindle Sensors", JSME International Journal, Series C, Vol.49, No.2, pp.307-315, June 2006
[20] Donaldson RR. "A simple method for separating spindle error from test ball roundness" Ann CIRP 1972, 21:125–26.
[21] Jay F. Tu, Bernd Bossmanns, Spring C. C. Hung, "Modeling and error analysis for assessing spindle radial error motions" Precision Engineering, Volume 21, Issues 2-3, September-December 1997, Pages 90-101
[22] H. Shinno, K. Mitsui, Y. Tatsue, N. Tanaka, T. Omino, T. Tabata, K. Nakayama, "A New Method for Evaluating Error Motion of Ultra Precision Spindle" CIRP Annals - Manufacturing Technology, Volume 36, Issue 1, 1987, Pages 381-384
[23] Kengo Fujimaki, Kimiyuki Mitsui, "Radial error measuring device based on auto-collimation for miniature ultra-high-speed spindles" International Journal of Machine Tools and Manufacture, Volume 47, Issue 11, September 2007, Pages 1677-1685
[24] H.F.F. Castro, "A method for evaluating spindle rotation errors of machine tools using a laser interferometer" Measurement, Volume 41, Issue 5, June 2008, Pages 526-537
[25] Shoji Noguchi, Tadao Tsukada, Atsushi Sakamoto, "Evaluation method to determine radial accuracy of high-precision rotating spindle units" Precision Engineering, Volume 17, Issue 4, October 1995, Pages 266-273