The 19th Conference of Mechanical Engineering Network of Thailand
19-21 October 2005, Phuket, Thailand

Development of in-process cutting condition monitoring system for turning operation

Somkiat Tangjitsitcharoen
Department of Industrial Engineering, Chulalongkorn University
Phayathai Road, Pathumwan, Bangkok 10330
Telephone: 0-2218-6814-6, 0-2218-6853, Fax: 0-2251-3969
Email: Somkiat.T@eng.chula.ac.th

Abstract

In order to realize an automated and intelligent manufacturing, a method has been developed to identify the cutting states for CNC turning by utilizing the dynamic cutting forces based on proposed pattern recognition technique. The method proposed introduces three parameters to classify the cutting states of continuous chip formation, broken chip formation, chatter and chatter occurred with broken chips. The three parameters are calculated and obtained by taking the ratio of the average variances of the dynamic cutting forces. The algorithm was developed to calculate the values of three parameters during the process in order to obtain the reference feature spaces and determine the proper threshold values for classification of the cutting states. A new quartz-type high sensitive tool dynamometer is developed, and implemented to the tool turret of a small CNC turning machine to monitor the turning process.

It is proved by series of cutting experiments that the states of cutting are well identified by the method developed and proposed regardless of the cutting conditions.

Keywords: Dynamic Cutting Force, Turning, Broken Chip, Continuous Chip, Chatter

1. Introduction

As the fully automated and intelligent manufacturing is expected to be realized in the near future, it is necessary to develop a methodology to identify the state of manufacturing process automatically. The cutting process is recognized as one of the most important processes, which requires reliable sensing or monitoring, since it plays the key role not only in quality of product but also production rate as well as production cost.

In turning operation, the continuous chips are often produced while turning steel family and aluminum alloys which are most popularly used for mechanical parts. They apt to entangle the work piece or cutting tool, which causes deterioration of the finished surface and sometimes breakage of cutting tools as well as injuring the machine operator. They are also difficult to remove from the machine, and cause the thermal deformation of machine tool. It is therefore desired to make chips broken into small pieces to realize safe and reliable machining by changing the cutting conditions during the in-process cutting [1-5]. Normally, the continuous chips become broken at lower cutting speed. The chip breaking condition is improved as the feed rate and the depth of cut are increased.

The chatter is one of the major limitations on productivity in metal cutting. It always affects surface finish, dimensional accuracy, tool life, and machine life. The surface deterioration is substantially caused by the occurrence of chatter. It is then necessary to avoid the chatter occurred during the cutting process. The chatter is generally avoided by reducing the depth of cut and the feed rate. The cutting stability is greatly increased at low cutting speeds because of the process damping force effect due to an increase in the slope of the surface undulations [6-9,22]. As the tool wear progresses on the tool flank, the stability limit increases due to the process damping effect [6-7, 10]. However, the increase in nose wear causes larger contact length between the cutting tool and the workpiece, and consequently the chatter happens. The chatter is best minimized by designing machine tool, fixture and tooling structures which have high dynamic stiffness, especially in the direction of major cutting forces [11].

Extensive research efforts have been devoted so far to develop sensors and methodologies for detection of chatter [12-15], and identification of chip forms [19-20]. It is already known that sensing cutting force signals from the cutting process is one of the most promising methods, and researches have been carried out from various points of views [16-18]. It is known that the generation of chatter affects mostly the main force component [17, 21], while the feed force component is most sensitive to chip breaking [18]. A simplified method for recognizing the cutting states has been proposed by utilizing the dynamic components of cutting forces [21]. The comparison of the results between the method proposed and the FFT method is almost the same success rate, but the method proposed requires much less data-processing time. As a consequence, the undesirable cutting states can be effectively avoided within the very short time or real time. Hence, the dynamic components of cutting forces were adopted to monitor and identify the chip forms and chatter in this research in order to increase the reliability of automated and intelligent manufacturing.

The aim of this research is to develop an in-process monitoring system for identification of continuous chip, broken chip, chatter, and chatter occurred with broken chip, regardless of the cutting conditions by using a proposed pattern recognition technique. The method proposed introduces three parameters, which are calculated and obtained by taking the ratio of the average variances of the dynamic cutting forces. The pattern recognition method developed will be used in the future work for optimization of cutting conditions in CNC turning.

2. In-process identification of cutting states

2.1 Cutting states and dynamic cutting forces

The dynamic cutting force has its own characteristic pattern in each cutting situation of continuous chip formation, broken chip formation, and the generation of chatter. As the chips are broken during cutting, the dynamic cutting forces vary either due to chips hitting upon the cutting tool or workpiece. The dynamic component of the feed force, among the three force components, is relatively large in amplitude when the chips are broken into pieces [1]. On the other hand, the dynamic cutting forces are small in amplitude when the chips are continuous.

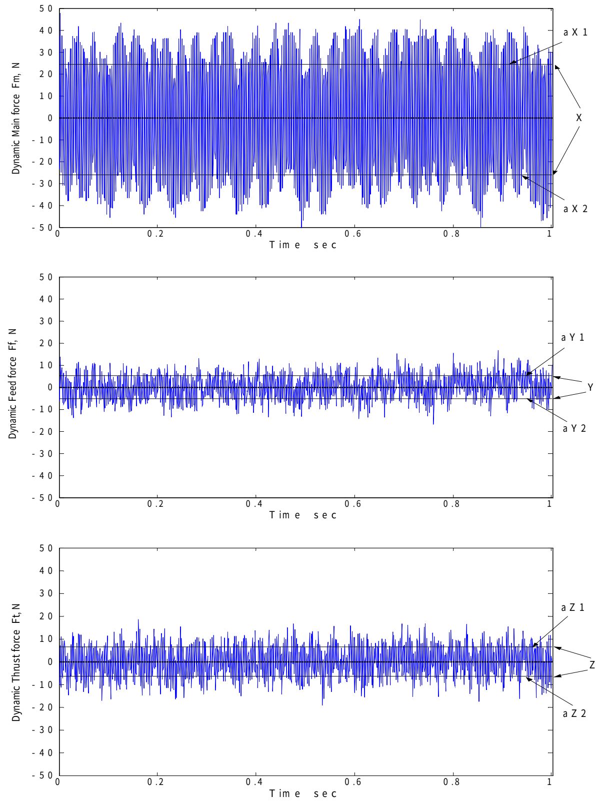
However, the generation of chatter affects mostly the main cutting forces when the chatter appears [17]. It is then expected that the dynamic component of the main force is relatively large in amplitude, among the three force components. And, the amplitude of dynamic main force of the chatter is also expected to be larger than the ones of continuous and broken chip formation.

The chatter might sometimes occur simultaneously with the broken chip formation depending on the cutting conditions, especially at large feed rate. In such a case, the amplitude of dynamic main force and feed force may be mixed and increased due to the mixture of chatter and broken chip formation.

The above mentions suggest that the continuous chip formation, broken chip formation, chatter, and chatter occurred with broken chip can be classified by monitor the dynamic components of three cutting forces (which are main force Fm, feed force Ff, thrust force Ft). In general, the use of the dynamic cutting force as a tool to identify the cutting states, it is then necessary to eliminate noise signals from other sources by using the low-pass filter in the experiments.

2.2 Pattern recognition method

In order to classify the cutting states of continuous chip formation, broken chip formation, chatter, and chatter occurred with broken chip during the in-process cutting, the pattern recognition method is proposed by utilizing the average variances of the dynamic cutting forces (X, Y, Z) as shown in Figure 1. Figure 1 illustrates the example of dynamic components of three cutting forces, and the definition of the average variances of the dynamic cutting forces, which are calculated based on the dynamic components of three cutting forces measured. The average variances of the dynamic cutting forces are normalized by taking the ratio of the corresponding time records of three average variances of the dynamic cutting forces.



$$I1 = \frac{X}{Y};\ I2 = \frac{X}{Z};\ I3 = \frac{Y}{Z}$$

Figure 1. Illustration of the average variances of the dynamic components of three cutting forces (X, Y, Z), and the parameters I1, I2, and I3.

The method introduces three parameters I1, I2, and I3 in order to represent the ratio of the average variance of the dynamic components of three cutting forces as shown in Figure 1. The parameters I1, I2, and I3 are the ratio of the average variance of the main force to feed force, the ratio of the average variance of the main force to thrust force, and the average variance of the feed force to thrust force, respectively. The parameters I1 and I3 are supposed to be significant when the broken chips are formed due to the relatively large in amplitude of dynamic feed force. In case of chatter, the parameters I1 and I2 are expected to be significant since the dynamic main force is mostly affected. On the other hand, the parameters I2 and I3 are expected to be significant when the chatter occurs with broken chip formation.

The dynamic components of cutting forces are relatively small in amplitude when the continuous chips are formed. However, it is possible to classify the state of continuous chip. Since, the dynamic cutting forces of continuous chip formation are relatively small in amplitude as compared to those of the broken chip formation and the chatter. Thus, all parameters I1, I2, and I3 become significant.

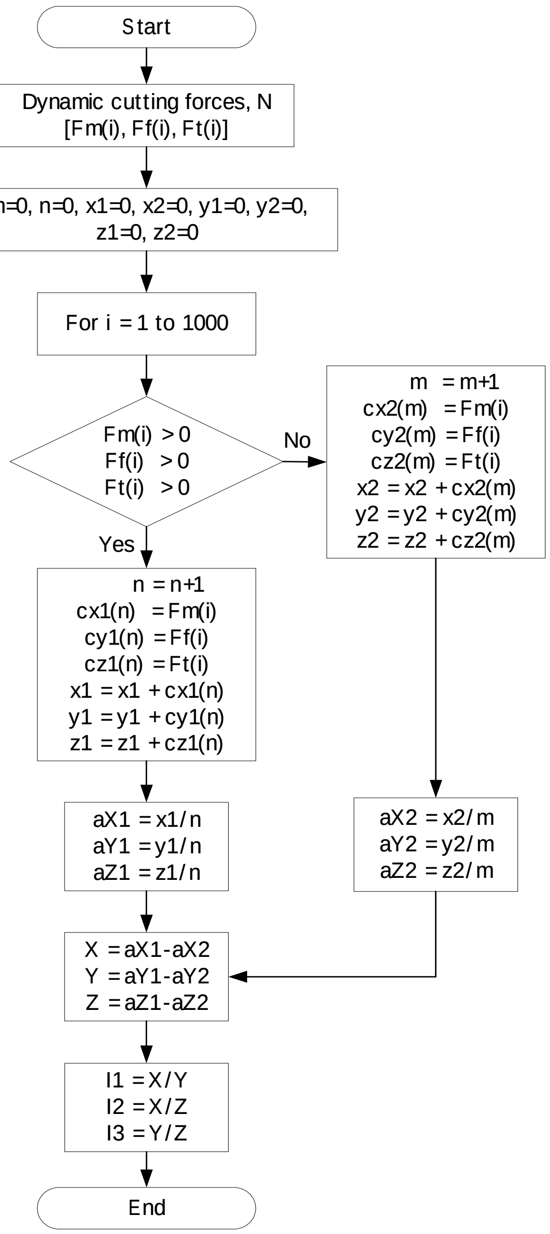


Figure 2. Flow chart of the algorithm to calculate the parameters I1, I2, and I3.

In order to obtain the reference feature spaces and determine the proper threshold values for classification of the cutting states, the following algorithm was developed here to calculate the values of parameters I1, I2, and I3.

(1) Calculate the dynamic cutting forces (Fm, Ff, Ft) during the in-process cutting.
(2) Search for the dynamic cutting forces which are the plus values from 0 to 1 second, and calculate the average plus value lines (aX1, aY1, aZ1).
(3) Search for the dynamic cutting forces which are the minus value from 0 to 1 second, and calculate the average minus value lines (aX2, aY2, aZ2).
(4) Calculate the average variance of the dynamic cutting forces (X=aX1-aX2; Y=aY1-aY2; Z=aZ1-aZ2), and then take the ratio of the average variance of the dynamic component of three cutting forces, I1 = $\frac{X}{Y}$, I2 = $\frac{X}{Z}$ and I3 = $\frac{Y}{Z}$.
(5) Determine the proper threshold values C1, C2, and C3 in the reference feature space for classification of the continuous chip formation, broken chip formation, chatter, and chatter occurred with broken chip. The flow chart of the above algorithm is shown in Figure 2.

3. Experimental equipments and conditions

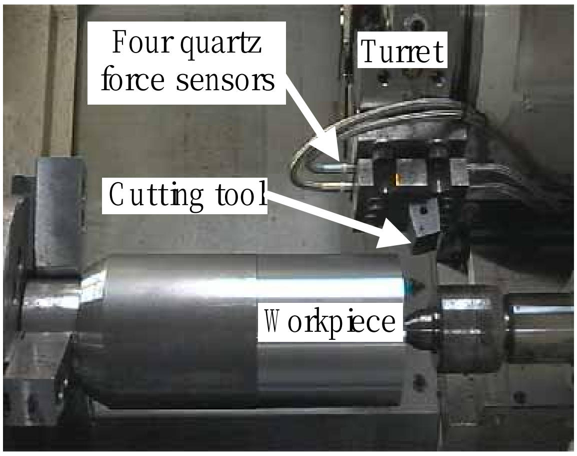
In order to obtain the reference feature spaces and the proper threshold values (C1, C2, C3) for classification of the cutting states, series of cutting tests were carried out. The cutting tests are conducted on a commercially available small CNC turning machine. A new tool dynamometer, with four quartz force sensors, has been developed and installed onto the tool turret of the machine as shown in Figure 3. The major cutting conditions are summarized in Table 1. The tool life is set at the flank wear 0.4 mm.

The dynamic cutting force components detected by the tool dynamometer are amplified and low-pass filtered with the cut-off frequency of 500Hz prior to digitization and calculation within PC. The sampling rate is 1 kHz. It is proven that the resonant frequency of the tool dynamometer is about 2.7kHz, and hence the dynamic cutting force components are well detected with the tool dynamometer developed [1].

Table 1. Major cutting conditions

Workpiece	Plain carbon steel (JIS:S45C)
Cutting tool	Coated carbide tool
Tool geometry	-5°, -6°,5°,6°,15°,15°,0.8 mm
Cutting speed, m/min	100, 150, 200, 250
Depth of cut, mm	0.5, 1, 1.5
Feed, mm/rev	0.05, 0.1, 0.15, 0.20, 0.25

(a) Open architecture CNC turning machine employed for experiments.



(b) New tool dynamometer installed onto tool turret of CNC turning machine.

Figure 3. Illustration of experimental setup.

4. Experimental results and discussions

4.1 Cutting states and the average variances of the dynamic cutting forces

Series of cutting tests were carried out under the major cutting conditions mentioned above, and the dynamic cutting force signals were measured. Figure 4 shows the typical examples of experimentally obtained dynamic components of three cutting forces at different cutting states. When the chips are continuous, the dynamic components of three cutting forces are small in amplitude. On the other hand, the dynamic components of three cutting forces become larger when the chips are broken due to chips hitting upon the cutting tool or workpiece, especially at the dynamic feed force component. Hence, the values of X, Y, and Z of broken chip formation are larger than those of the continuous chip formation.

When the chatter occurs, the dynamic main force is relatively large in amplitude, among the three force components. The chatter usually occurs in the radial and feed directions, which lead to irregular distribution of chip thickness along the cutting edge in turning operation. The dynamic thrust force and dynamic feed force of the chatter are then larger than those of the continuous chip formation. While the chatter occurs with broken chip formation, the dynamic components of three cutting forces are mixed and increased in amplitude due to the mixture of chatter and broken chip formation, especially in main force and feed force. In case of the chatter occurred with the broken chip, the main force and feed force are increased due to the mixture of chatter and broken chip formation. The average variances of the dynamic cutting forces are then mixed between the variances of the dynamic cutting forces of the chatter and broken chip formation.

4.2 Classification of the cutting states

Figures 5 to 7 show the experimentally obtained reference feature spaces of I1 and I2, I1 and I3, and I2 and I3, respectively. The values of parameters I1 and I2 are relatively large when the chatters appear as shown in Figsures 5 and 7. It is understood that the average variance of the dynamic component of main force is larger than those of feed force and thrust force. However, when the chatters occur with the broken chips, the values of parameters I2 and I3 are relatively large due to the increase in main force and feed force, which are mixed between the chatter and the broken chip formation. The value of parameter I1 then becomes small.

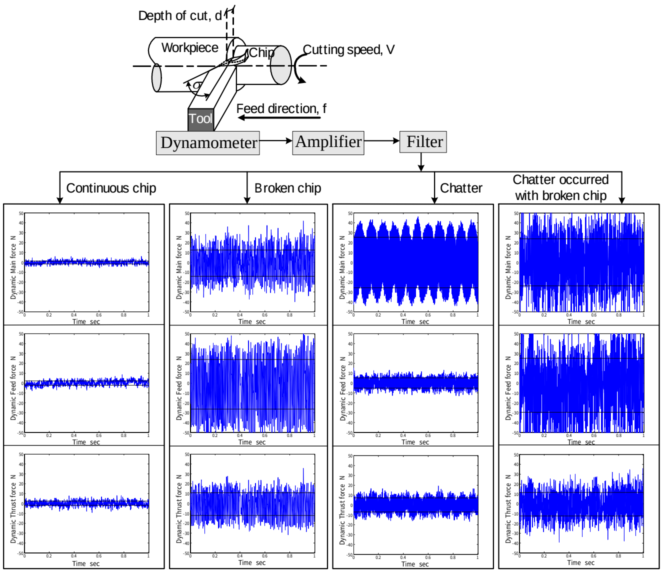


Figure 4. Illustration of typical examples of experimentally obtained dynamic cutting forces occurred at different cutting states.

While the chips are broken, the values of parameter I3 are relatively large and the values of parameter I1 are relatively small as shown in Figures 6 and 7. Since the feed force component is most sensitive to the chip breaking among the three force components. However, the values of parameter I1, I2 and I3 are relatively small when the chips are continuous as compared to others as shown in Figures 5 to 7. It is understood that the amplitudes of the dynamic cutting force components are less difference.

According to the Figures 5 to 7, the threshold values of each cutting state can be determined in the reference feature spaces. The proper threshold values of C1, C2, and C3 are defined as 3, 1.5, and 1.3 respectively. The three-dimensional reference feature space of the parameters I1, I2, and I3 is then obtained as shown in Figure 8. It is then concluded that 1) the chips are identified to be broken when the values of parameters I1 and I2 are less than the threshold values C1 and C2 respectively, while the value of parameter I3 exceeds the threshold value C3; 2) the chatter is identified when the values of parameters I1 and I2 exceed the threshold values C1 and C2, respectively; 3) the chatter occurred with broken chip is identified when the values of parameters I2 and I3 exceed the threshold values C2 and C3, respectively; 4) finally, the chips are identified to be continuous when the values of parameters I1, I2, and I3 are less than the threshold values C1, C2, and C3, respectively.

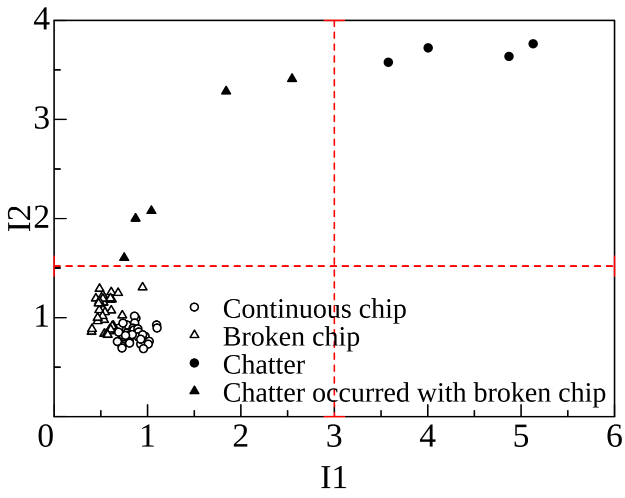


Figure 5. Illustration of the experimentally obtained reference feature space between I1 and I2.

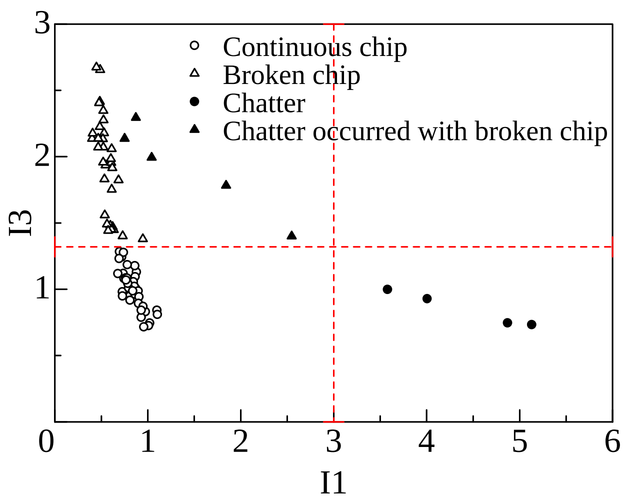


Figure 6. Illustration of the experimentally obtained reference feature space between I1 and I3.

Above mentions suggest that the cutting states can be simply identified during the in-process cutting regardless of the cutting conditions by mapping the experimentally obtained values of parameters I1, I2, and I3 into the reference feature spaces of Figures 5 to 8, regarding to the threshold values C1, C2, and C3. Hence, the algorithm to identify the cutting states are developed referring to the threshold values C1, C2, and C3 in the reference feature spaces as shown in Figure 9. Figure 9 also illustrates the algorithm to avoid the chatter and make the continuous chips broken into small pieces by changing the cutting conditions during the in-process cutting.

The new cutting tests were employed to identify the cutting states in order to check and verify the threshold values in the reference feature spaces. The experimentally obtained values of parameters I1, I2, and I3 corresponded to the threshold values in the reference feature spaces of Figures 5 to 8.

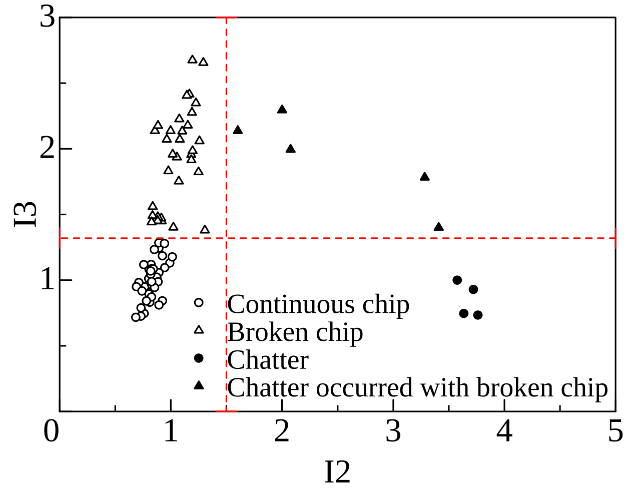


Figure 7. Illustration of the experimentally obtained reference feature space between I2 and I3.

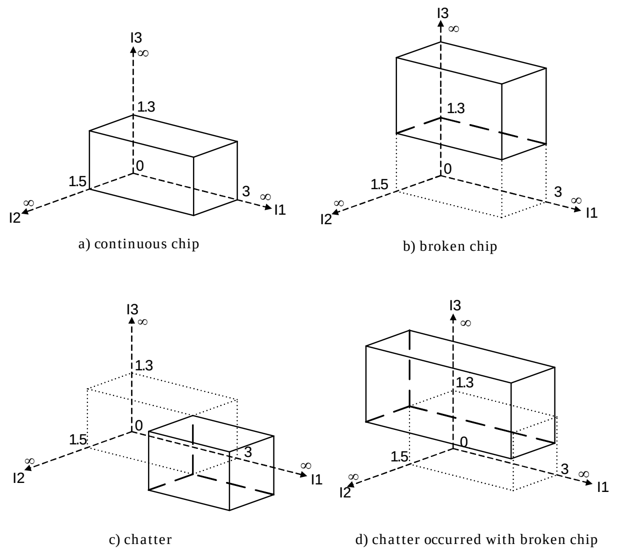


Figure 8. Illustration of the experimentally obtained three-dimensional reference feature spaces.

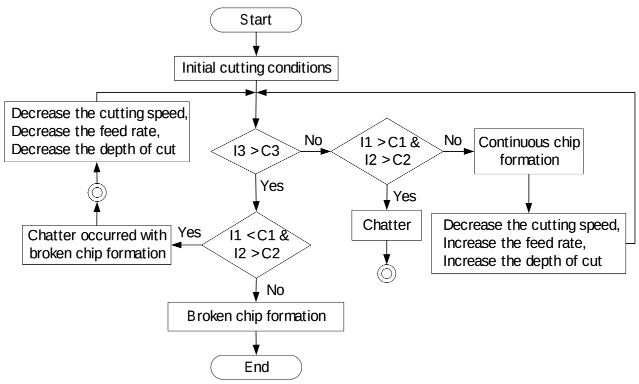


Figure 9. Flow chart of the algorithm to identify the states of cutting.

5. Conclusions

A method has been developed for in-process identification of cutting states, which are continuous chip formation, broken chip formation, chatter, and chatter occurred with broken chips, for CNC turning based on proposed pattern recognition technique. A method proposed introduces three parameters I1, I2, and I3, which are calculated and obtained by taking the ratio of the average variances of the dynamic cutting forces.

The method developed is applied to actual turning operations, and it has been proved that the four states of the cutting situations are sufficiently classified by method proposed under wide range of cutting conditions. The reference feature spaces and the proper threshold values C1, C2, and C3 are determined for classification of the cutting states.

The states of cutting can be simply identified during the in-process cutting regardless of the cutting conditions by mapping the experimentally obtained values of parameters I1, I2, and I3 referring to the threshold values C1, C2, and C3 in the reference feature spaces.

References

Journal

[1] T. Moriwaki, T. Shibasaka, and T. Somkiat, "Development of in-process chip-breaking detection system in turning", Memoirs of graduate school of science and technology, Kobe University, No. 22-A, 2004, pp. 1-19.

[2] J. L. Andreasen, and L. D. Chiffre, "Automatic chip-breaking detection in turning by frequency analysis of cutting force", Annals of the CIRP, Vol. 42, No. 1, 1993, pp. 45-48.

[3] W. Grzesik, and P. Bernat, "An investigation of the cutting process for chip breaking monitoring in turning of steels", Trans. ASME, J. Manufacturing Science and Engineering, Vol. 120, No. 3, 1998, pp. 555-562.

[4] S. Sawai, and I. Inasaki, "Identification of chip form in turning process", International Journal of Japan Society of Mechanical Engineers, Vol. 34, No. 4, 1991, pp. 553-560.

[5] I. S. Jawahir, and C. A. Luttervelt, "Recent developments in chip control research and applications", Annals of the CIRP, Vol. 42, No. 2 1993, pp. 659-685.

[6] B. E. Clancy, and Y. C. Shin, "A comprehensive chatter prediction model for face turning operation including tool wear effect", International Journal of Machine Tools & Manufacture, Vol. 42, 2002, pp. 1035-1044.

[7] T. R. Sisson, and R. L. Kegg, "An explanation of low-speed chatter effects", Trans. ASME, J. Engineering for Industry, Vol. 91, 1969, pp. 951-958.

[8] B. Y. Lee, Y. S. Tarng, and S. C. Ma, "Modeling of the process damping force in chatter vibration", International Journal of Machine tools & Manufacture, Vol. 35, No. 7, 1995, pp. 951-962.

[9] Y. S. Liao, and Y. C. Young, "A new on-line spindle speed regulation strategy for chatter control", International Journal of Machine tools & Manufacture, Vol. 36, No. 5, 1996, pp. 651-660.

[10] Y. S. Chiou, E. S. Chung, and S. Y.Liang, "Analysis of tool wear effect on chatter stability in turning", Int. J. Mech. Sci., Vol. 37, No. 4, 1995, pp. 391-404.

[11] Y. Altintas, and M. Weck, "Chatter stability of metal cutting and grinding", Annals of the CIRP, Vol. 53, No. 2, 2004, pp. 619-642.

[12] Y. Altintas, and P. K. Chan, "In-process detection and suppression of chatter in milling", International Journal of Machine Tools & Manufacture, Vol. 32, No. 3, 1992, pp. 329-347.

[13] M. Rahman, "In-process detection of chatter threshold", Trans. ASME, J. Engineering for Industry, Vol. 110, 1988, pp. 44-50.

[14] S. Smith, and J. Tlusty, "Stabilizing chatter by automatic spindle speed regulation", Annals of the CIRP, Vol. 41, No. 1, 1992, pp. 433-436.

[15] J. Hino, C. Su, and T. Yoshimura, "A study on chatter prediction in high-speed end milling process by fuzzy neural network", International Journal of Japan Society of Mechanical Engineers, Series C, Vol. 47, No. 3, 2001, pp. 825-831.

[16] K. Matsushima, and T. Sata, "On-line control of the cutting state by the pattern recognition technique", Annals of the CIRP, Vol. 23, No. 1, 1974, pp.151-152.

[17] T. Sata, K. Matsushima, T. Nagamura, and E. Kono, "Learning and recognition of the cutting states by the spectrum analysis", Annals of the CIRP, Vol. 22, No. 1, 1973, pp. 41-42.

[18] L. C. Lee, K. S. Lee, and C. S. Gan, "On the correlation between dynamic cutting force and tool wear", International Journal of Machine Tools & Manufacture Vol. 29, No. 3, 1989, pp. 295-303.

Conference

[19] T. Moriwaki, T. Somkiat, and T. Shibasaka, "Intelligent monitoring and optimization of cutting process for CNC turning", Proceedings of the 14th International Conference on Flexible Automation and Intelligent Manufacturing, Toronto, Canada, 2004, pp. 82-89.

[20] T. Moriwaki, and Y. Mori, "Sensor fusion for in-process identification of cutting process based on neural network approach", Proc. IMACS/SICE Int. Symp. on Robotics, Mechatronics and Manufacturing systems, Kobe, Japan, 1992, pp. 245-250.

[21] K. Ueda, S. Miyamoto, and T. Sugita "An approach to adaptive control based on pattern recognition of cutting states", Proceedings of the 6th International Conference on Production Engineering, Osaka, 1987, pp. 212-217.

Book

[22] G. Tlusty, Manufacturing process and equipment, Prentice-Hall, Inc., Upper Saddle River, NJ 07458, 2000, pp. 586-587.