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Advance in chatter detection in ball end milling process by utilizing wavelet transform

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Abstract This paper presents an advance in chatter detection in ball end milling process. The dynamic cutting forces are monitored by utilizing the wavelet transform. The new three parameters are introduced to classify the chatter and the non-chatter by taking the ratio of the average variances of dynamic cutting forces to the absolute variances of themselves. The Daubechies wavelet is employed in this research to analyze the chatter. The experimental results showed that the chatter frequency occurred in the different levels of wavelet transform due to the different cutting systems. The new algorithm is developed to detect the chatter during the in-process cutting. The experimentally obtained results showed that the chatter can be easier to detect referring to the proposed parameters under various cutting conditions.

Keywords Dynamic cutting forces · Wavelet transform · Ball end milling process · Chatter detection

Introduction

The ball end milling process is one of the most important processes to produce the mechanical parts in the automotive and aerospace industries. The higher productivity is preferred by increasing the cutting parameters such as the depth of cut, the cutting speed, and the feed rate. However, an increase in those cutting parameters may cause the chatter during the cutting, which affects the surface finish, the dimensional accuracy, the tool life and the machine life.

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The fast fourier transform (FFT) is commonly used to detect the chatter (Kuljanic et al. 2009; Somkiat and Narongsak 2013; Somkiat 2012). It has a good resolution only in the frequency domain but the disadvantage of the use of FFT is the lack of information in the time domain. Since it is difficult to detect the chatter in time domain. The neural network and the fuzzy logic had been proposed based on the surface roughness adaptive control system in the ball end milling operations (Zuperl et al. 2012; Quintana et al. 2011). Unfortunately, the adaptive control cannot effectively control the cutting forces. Since the controller cannot response quickly enough to sudden changes in the cut geometry to eliminate the large spikes in the cutting forces. The use of an adaptive resonance theory (ART) network to detect the milling chatter correctly, the long training times are required during the training process with respect to a stable cutting (Tarng and Chen 1994; Tansel et al. 1993). The dynamometers accurately detect the chatter in the turning process. However, the system considered the cutting force only in the time domain (Somkiat 2011). Hence, the in-process chatter detection system in the time domain and the frequency domain is required to develop in this research by employing the wavelet transform technique. The wavelet transform is the time-frequency analysis tool which can perform a good resolution in both time domain and frequency domain. The extensive researches have been utilized it to detect the chatter in the cutting processes (Kwak 2005; Bickraj et al. 2007; Yao et al. 2010).

It is already known that the cutting force signals obtained from the cutting process is one of the most promising methods (Altintas and Lee 1998; Altintas and Budek 1995; Altintas and Park 2004), which provides a good result for the chatter detection by applying the wavelet transform to the dynamic cutting forces (Kwak 2005; Addison 2002; Graps 1995). The cutting force and toque signals have been used

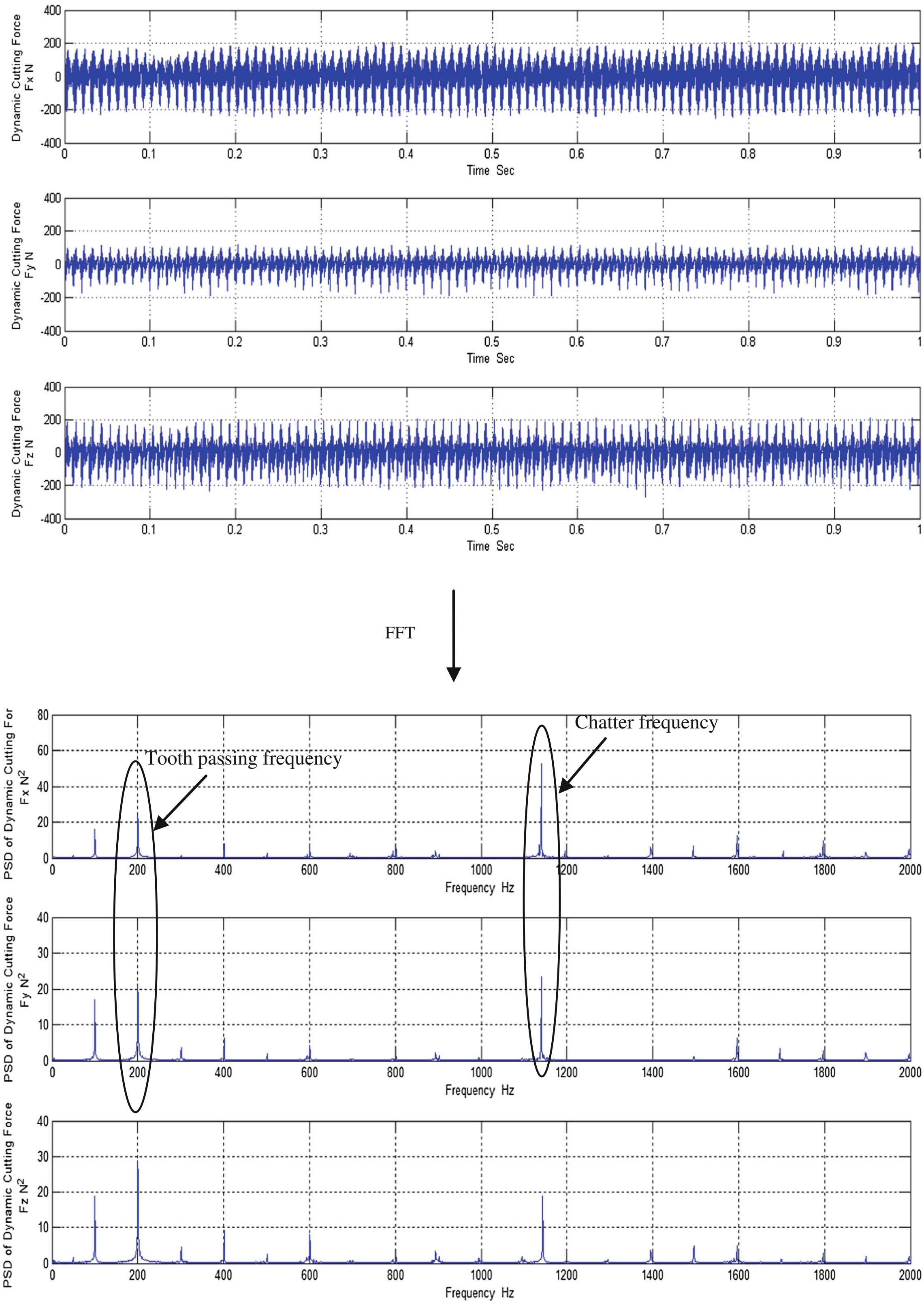

Fig. 1 Chatter: Spindle speed 6,000 rpm, depth of cut 3 mm, feed rate 0.03 mm/tooth, Tool diameter 8 mm

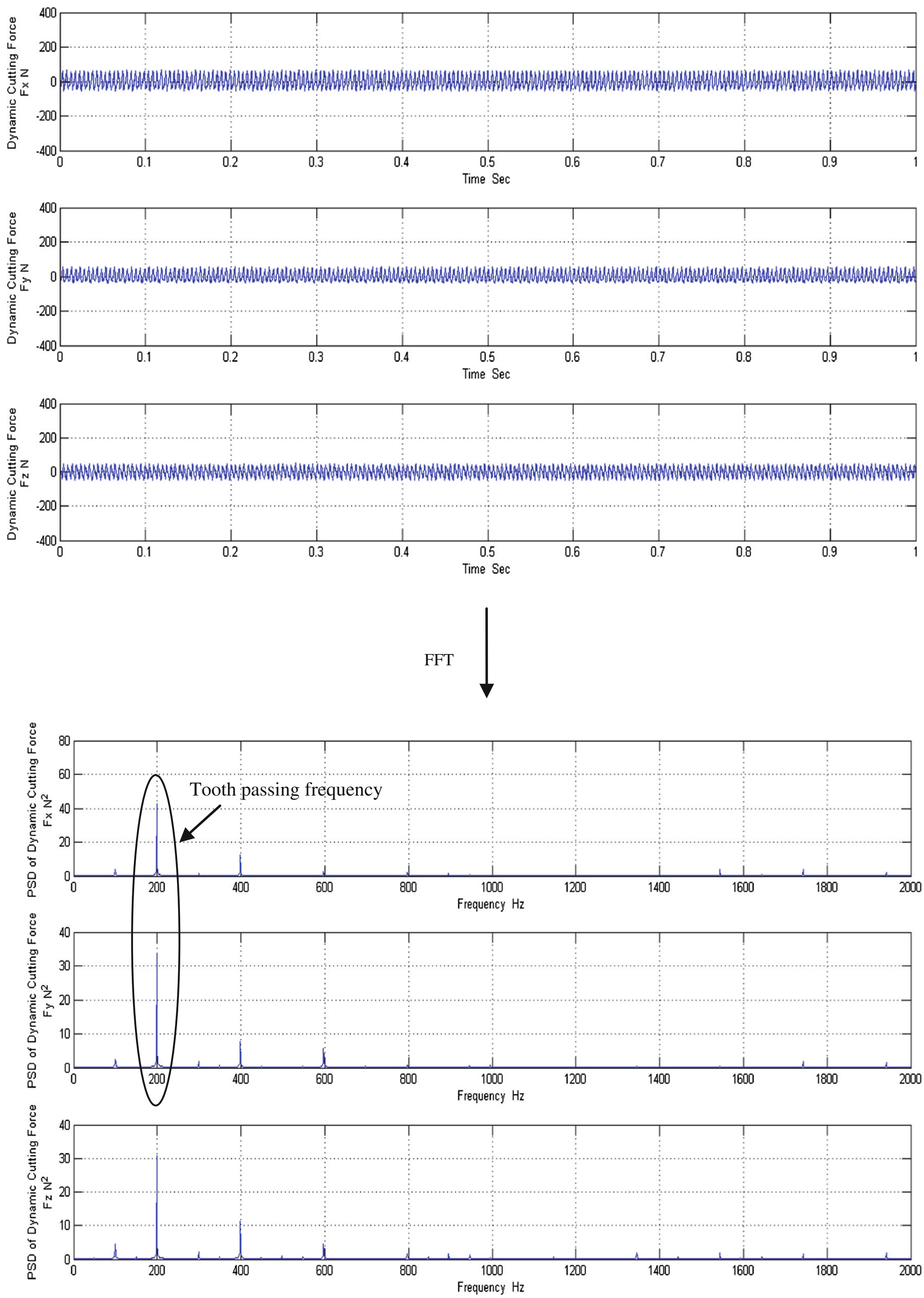

Fig. 2 Non-Chatter: Spindle speed 6,000 rpm, depth of cut 1 mm, feed rate 0.02 mm/tooth, Tool diameter 6 mm

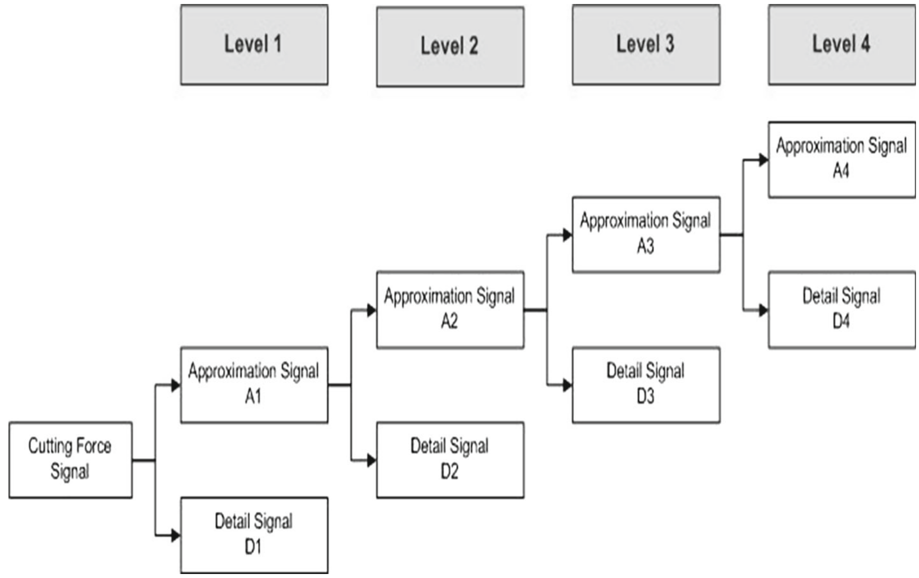

Fig. 3 Illustration of wavelet decomposition of dynamic cutting forces

to design the better machine tools and improve the diagnostic systems such as chatter detection (Rubio and Teti 2009; Tansei et al. 2013). The dynamic cutting force signals can be analyzed by the wavelet transform into four levels for the detail signals and the approximate signals. The low level of the wavelet transform may be better to monitor the high chatter frequency while the high level of the wavelet transform will be suitable to check the low chatter frequency (Somkiat 2012). If the obtained level of the wavelet transform is predetermined properly, hence the chatter will be detected easily.

The aim of this research is to prove and develop the in-process chatter detection from the previous researches (Somkiat and Narongsak 2013; Somkiat 2012) of the authors by employing the wavelet transform to decompose the dynamic cutting forces in the ball end milling process with the new cutting tools and cutting conditions. The algorithm to detect the chatter and the non-chatter will be proposed for the real applications.

In-process monitoring and detection of cutting states

Dynamic cutting forces and chatter

The amplitudes of three dynamic cutting force components are expected to be larger when the chatter appears. The chatter and the non-chatter in the ball-end milling process can be classified by monitoring the dynamic cutting force components, which are Fx, Fy, Fz. The preliminary experiments have been conducted to examine the dynamic cutting forces and their FFT to check the frequency of the tooth passing and the chatter. However, the chatter frequency, which depends on the cutting systems such as the feed rate, the tool holder, and the machine tool, must be different due to the different cutting systems. The carbon steel AISI 1050 and the 2 fluted ball end mill are used to check the chatter and the non-chatter as shown in Figs. 1 and 2, respectively. The spindle equipped with the tool diameter of 8 mm has the chatter frequency about 1.15 kHz.

Normally, the chatter is affected by the cutting parameters and the cutting systems. Hence, the proposed method requires the pretests to check the dynamic response of the cutting system whenever it is changed. The modal test had been employed to examine and check the dynamic response of the cutting system before the cutting tests. The dynamic response of the dynamometer is 2.3 kHz, but its natural frequency which is equipped with the jig, and the workpiece on the table of 5-axis CNC machining center becomes 730 Hz.

Chatter and wavelet transform

The wavelet transform has been recently proposed as a new tool in the signal analysis that can analyze the signals in the time domain and frequency domain. The Daubechieswavelet is one of the most powerful mother wavelet, which is utilized in this research to analyze the mechanical signals (Kwak 2005). The wavelet decomposition of the dynamic cutting forces can be separated into two signals and repeated in more levels, which are the approximation signal and the detail signal as shown in the Fig. 3.

The different levels have been sensitive to the different frequency intervals. Hence, it is very important to select the suitable level to detect the chatter. In this research, the wavelet transform is used to calculate for four levels due to the previous results obtained from the recent researches (Xiaoli et al. 1999; Yoon and Chin 2005; Yao et al. 2010). It has been

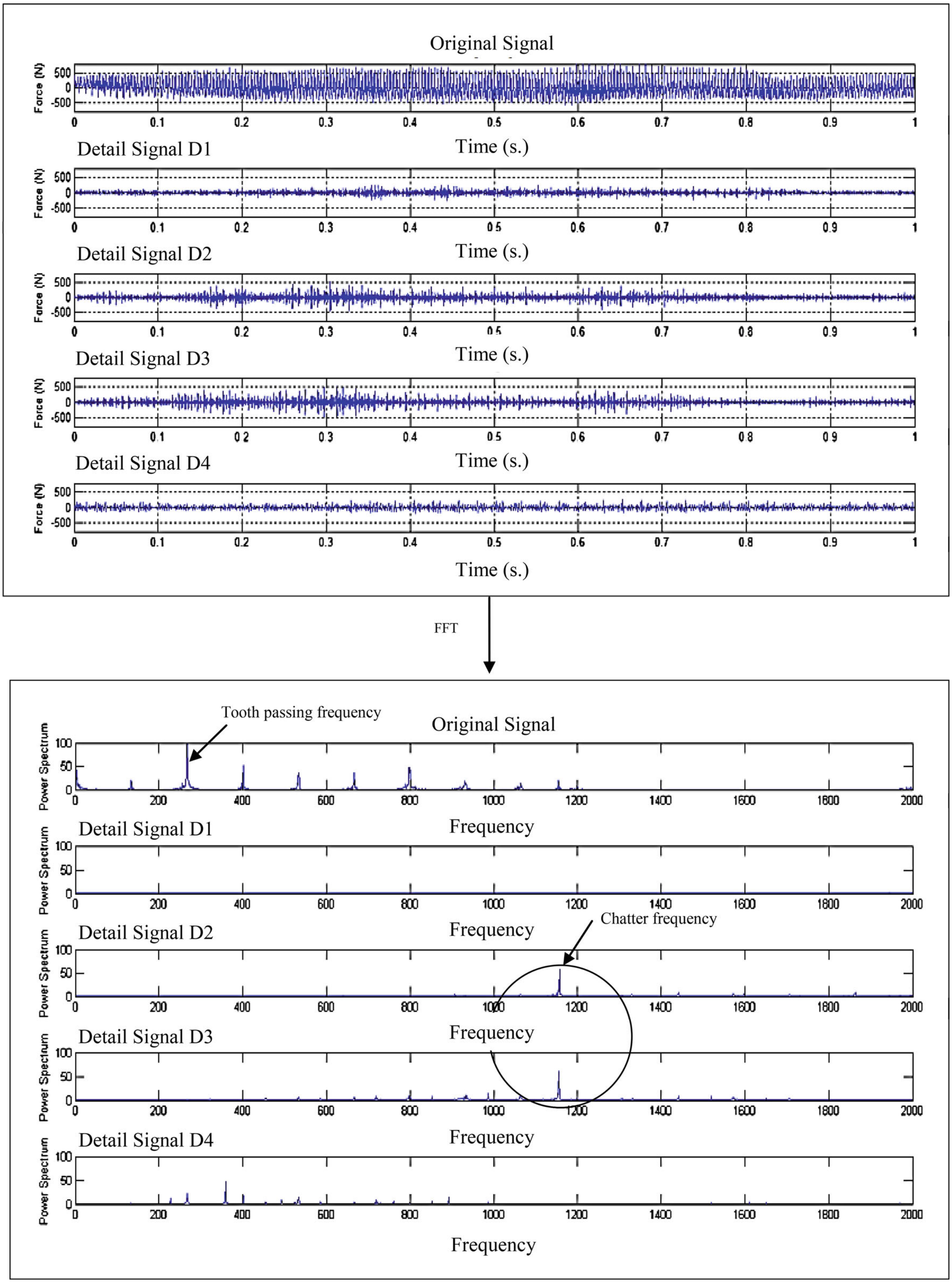

Fig. 4 Illustration of the dynamic cutting forces in *x*-axis (Fx) and detail signals from level 1 to level 4. Chatter: spindle speed 8,000 rpm, depth of cut 4 mm, feed rate 0.03 mm/tooth, Tool diameter 8 mm

shown that the chatter frequency can be detected clearly from level 2 to level 4,which depends on the cutting systems.

Figures 4 and 5 illustrate the dynamic cutting forces in the time domain when the chatter and the non-chatter appeared and their frequency domain by taking the FFT. It is noticed that it is difficult to detect the chatter frequency from the original signal but it can be detected clearly in the level 2 and the level 3 in the detail signals of the Fx as shown in Fig. 4.

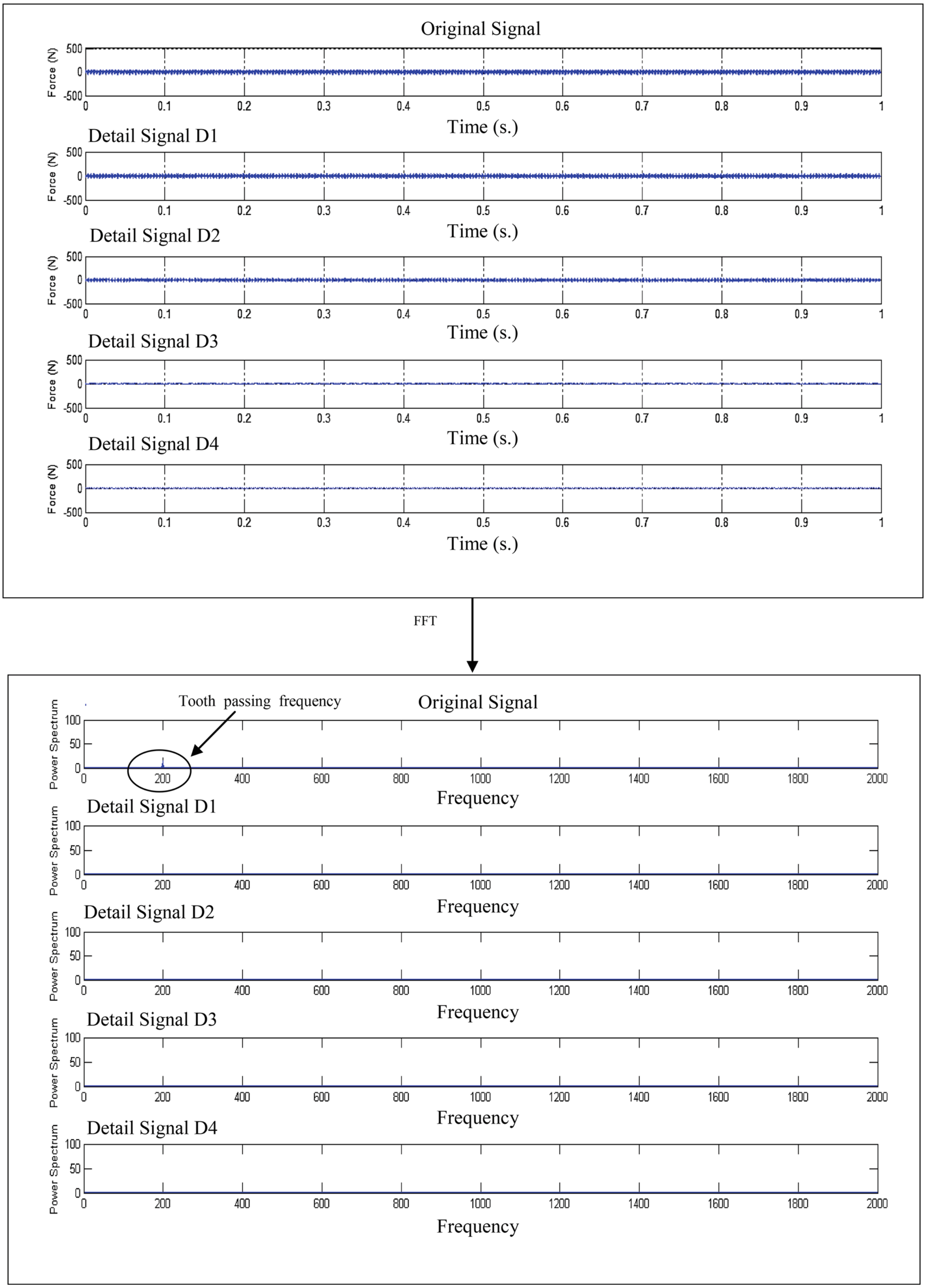

Fig. 5 Illustration of the dynamic cutting forces in *x*-axis (Fx) and detail signals from level 1 to level 4. Non-Chatter: spindle speed 6,000 rpm, depth of cut 1 mm, feed rate 0.02 mm/tooth, Tool diameter 6 mm

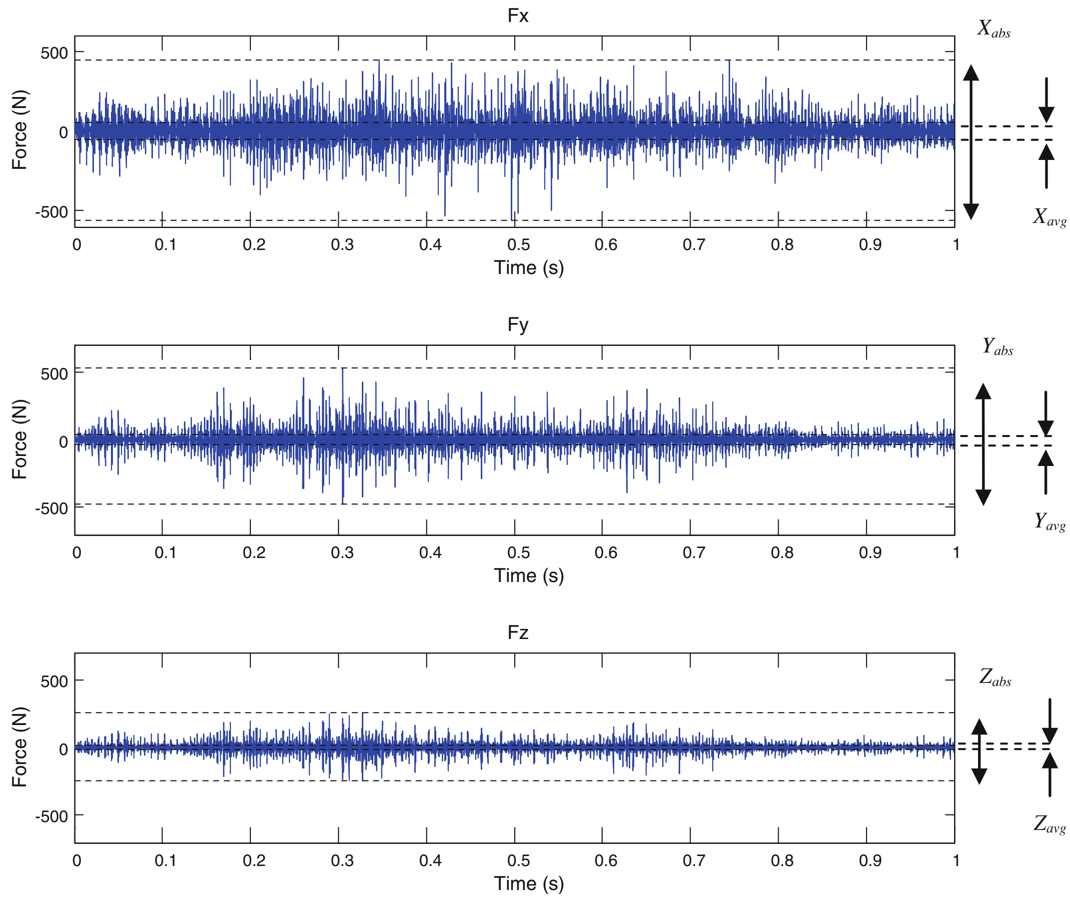

Fig. 6 Illustration of the average variances of the dynamic cutting forces, the absolute variances of dynamic cutting forces and the new parameters Rx, Ry, and Rz in the detail signal level 2 of chatter

Identification of chatter

In order to detect the chatter during the in-process ball end milling, the proposed method introduces three parameters (Rx, Ry, Rz), which are adopted from the previous research of the author (Somkiat 2012) by taking the ratio of the average variance of dynamic cutting force to the absolute variance of dynamic cutting force as shown in Figs. 6 and 7. The proposed method requires the preliminary tests to obtain the critical values,which will be used to classify the cutting states of the chatter and the non-chatter.

When the chatter happens, the absolute variances of dynamic cutting forces will become larger as shown in Fig. 6. In the other hand, the average variances of dynamic cutting forces are relatively small as compared to the non-chatter as shown in Fig. 7. It is understood that the values of Rx, Ry, and Rz will be small when the chatter appears.

The following procedures are adopted to obtain the relations between the new parameters (Rx, Ry, Rz) and the chatter in the ball-end milling process;

1. Start cutting with the major cutting conditions.
2. Calculate the dynamic cutting forces in each component (Fx, Fy, Fz).
3. Apply the wavelet transform to calculate four levels of detail signals with the dynamic cutting force in each component.
4. Calculate the average minus dynamic cutting force ($X^-_{avg}, Y^-_{avg}, Z^-_{avg}$) and calculate the average positive dynamic cutting force ($X^+_{avg}, Y^+_{avg}, Z^+_{avg}$) in each level of detail signals.
5. Calculate the average variances of dynamic cutting forces in (1)–(3).

$$X_{avg} = X^+_{avg} - X^-_{avg} \quad (1)$$

$$Y_{avg} = Y^+_{avg} - Y^-_{avg} \quad (2)$$

$$Z_{avg} = Z^+_{avg} - Z^-_{avg} \quad (3)$$

6. Calculate the maximum minus dynamic cutting force ($X^-_{max}, Y^-_{max}, Z^-_{max}$) and calculate the maximum positive dynamic cutting force ($X^+_{max}, Y^+_{max}, Z^+_{max}$).
7. Calculate the absolute variances of dynamic cutting forces in (4)–(6).

$$X_{abs} = X^+_{abs} - X^-_{abs} \quad (4)$$

$$Y_{abs} = Y^+_{abs} - Y^-_{abs} \quad (5)$$

$$Z_{abs} = Z^+_{abs} - Z^-_{abs} \quad (6)$$

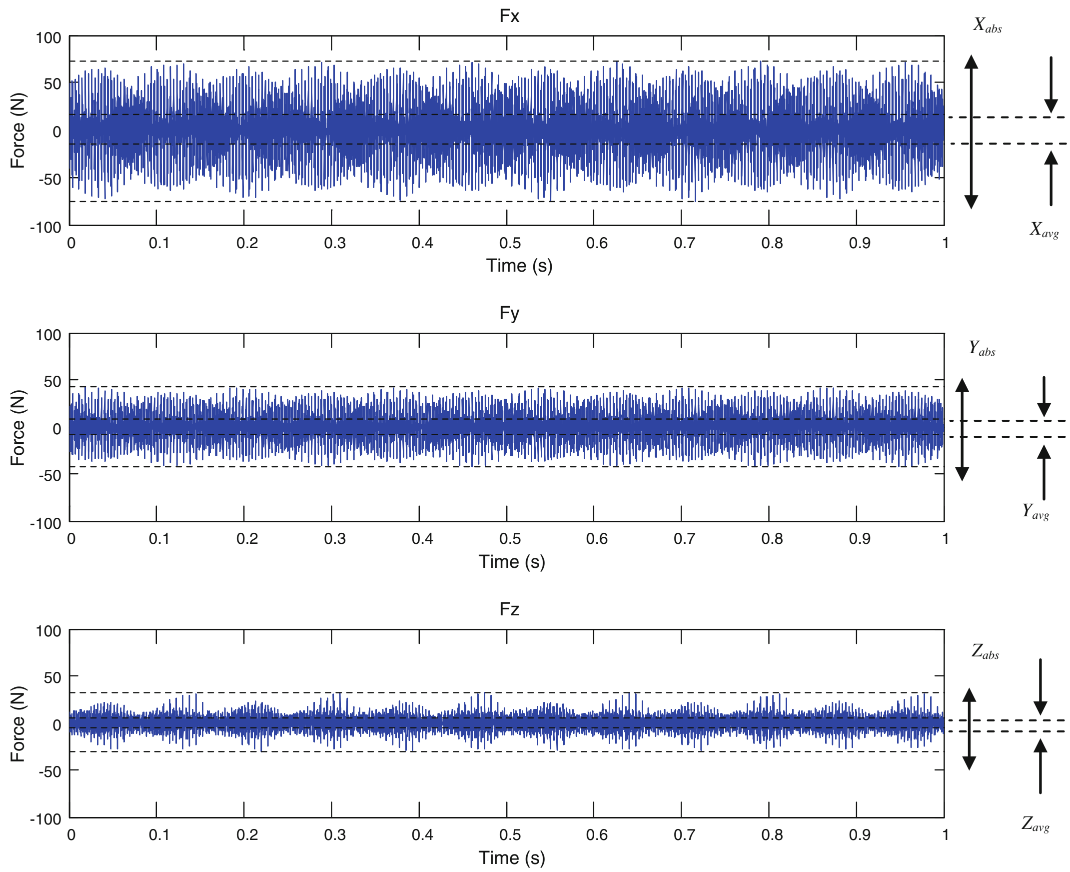

Fig. 7 Illustration of the average variances of the dynamic cutting forces, absolute variances of dynamic cutting forces and the new parameters Rx, Ry, and Rz in the detail signal level 2 of non-chatter

8. Calculate Rx, Ry, and Rz by taking the ratio of the average variances of the dynamic cutting forces to the absolute variances of themselves in (7)–(9).

$$R_x = X_{avg}/X_{abs} \tag{7}$$

$$R_y = Y_{avg}/Y_{abs} \tag{8}$$

$$R_z = Z_{avg}/Z_{abs} \tag{9}$$

9. Plot the parameters Rx versus Ry; Rx versus Rz, and Ry versus Rz.
10. Repeat procedures 1–8 with another cutting condition.
11. Determine the proper critical values of Cx, Cy, and Cz to detect the chatter by using the k-means clustering technique.

Experimental equipment and cutting conditions

The cutting tool used in this research is the coated carbide ball end mill (TiAlN) with two cutting edges. The carbon steel (AISI 1050) is adopted as a workpiece with the dimension of L 64 mm × W 64 mm × H 45 mm. The 5-axis CNC machining center of Mazak Variaxis 500 is employed in this research. The force sensor or the dynamometer (Kistler 9257B) has been installed onto the table of the 5-axis CNC machining center as shown in Fig. 8. The major cutting conditions are shown in Table 1.

The dynamic cutting forces obtained by the force sensor are amplified (Kistler 5073) and low-pass filtered with the cutoff frequency of 5 kHz prior to digitization in the high speed oscilloscope (Yokogawa DL750) and calculation within the personal computer. The natural frequency of the jig and the workpiece on the tableof 5-axis CNC machining center is 730 Hz. The natural frequencies of the spindle equipped with the tool diameters of 6 and 8 mm are about 1.3 and 1.15 kHz, respectively. Hence, the dynamic cutting forces are detected well by the force sensor. The sampling rate used in this research is 10 kHz for all components of the dynamic cutting forces. Hence, the dynamic cutting forces are well detected by the force sensor.

Experimental results and discussions

The chatter frequency occurs at 1,150 Hz in the level 3 of wavelet transform when the tool diameter of 8 mm is applied

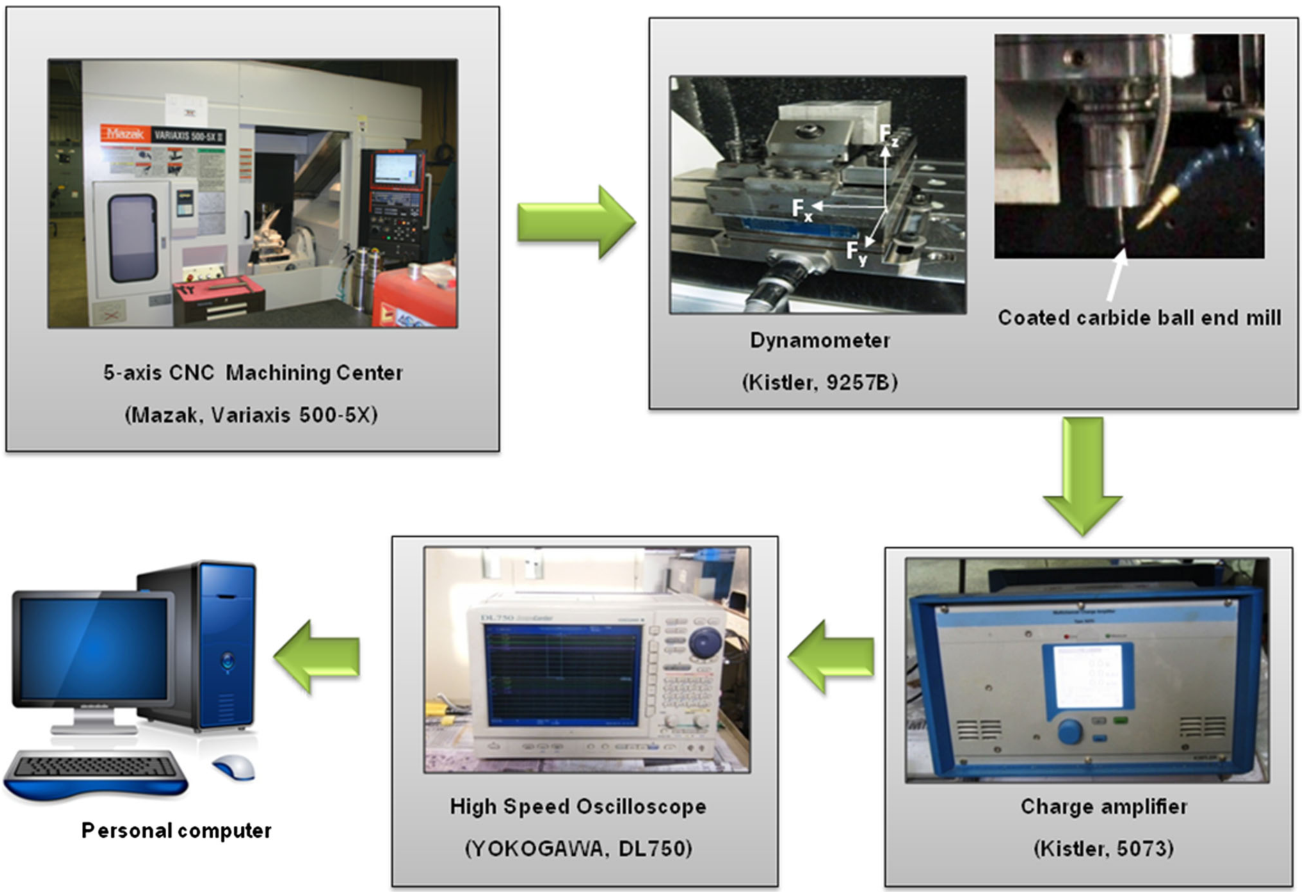

Fig. 8 Illustration of the experimental setup

Table 1 Major cutting conditions

Workpiece	Carbon steel (AISI 1050)
Cutting tool	Coated carbide ball end mill
Diameter (mm)	4, 8, 12
Spindle speed (rpm)	1,000, 2,000, 3,000, 4,000, 5,000, 8,000, 9,000, 10,000
Depth of cut (mm)	2, 3, 4, 6, 7, 8, 10
Feed rate (mm/tooth)	0.01, 0.02, 0.03

as shown in Fig. 9. In the other hand, the chatter frequency becomes 790 Hz at the level 4 while using the tool diameter of 12 mm as shown in Fig. 10. Hence, the suitable level of the wavelet transform can detect the chatter easier in both time and frequency domains. It is noticed that the higher chatter frequency can be detected at the low level of the wavelet transform.

Figure 11 shows all experimentally obtained results from the major cutting conditions in Table 1 in order to determined the critical values to detect the chatter and the non-chatter in the reference feature spaces between Rx versus Ry, Rx versus Rz, and Ry versus Rz that calculated from the detail signals in each level obtained from the wavelet transform. The results showed that the chatter seems to be detected clearly in level 3 and level 4. However, the chatter cannot be detected well in the detail signals of level 1 and level 2. Since the chatter detectability is different in each level of the detail signals. The chatter frequency depends on the cutting system such as the cutting tool diameters and the cutting conditions. In other word, the detectable level of chatter may be different when the cutting conditions are changed. It is understood that an increase in diameter of the cutting tool will cause a decrease in the chatter frequency.

The chatter is classified and determined when the ratios of the average variances of the dynamic cutting forces to the absolute variance of themselves (R_x, R_y, and R_z) are less than the critical values (C_x, C_y, and C_z) as shown in Fig. 11. It means that the chatter can be detected easily during the cutting process regardless of the cutting conditions.

According to the k-mean clustering technique, the critical values (Cx, Cy, Cz) are calculated and obtained in Fig. 11, which are 0.15, 0.17, and 0.20 respectively. It is implied that the chatter and the non-chatter can be detected easily even though the cutting conditions are changed by

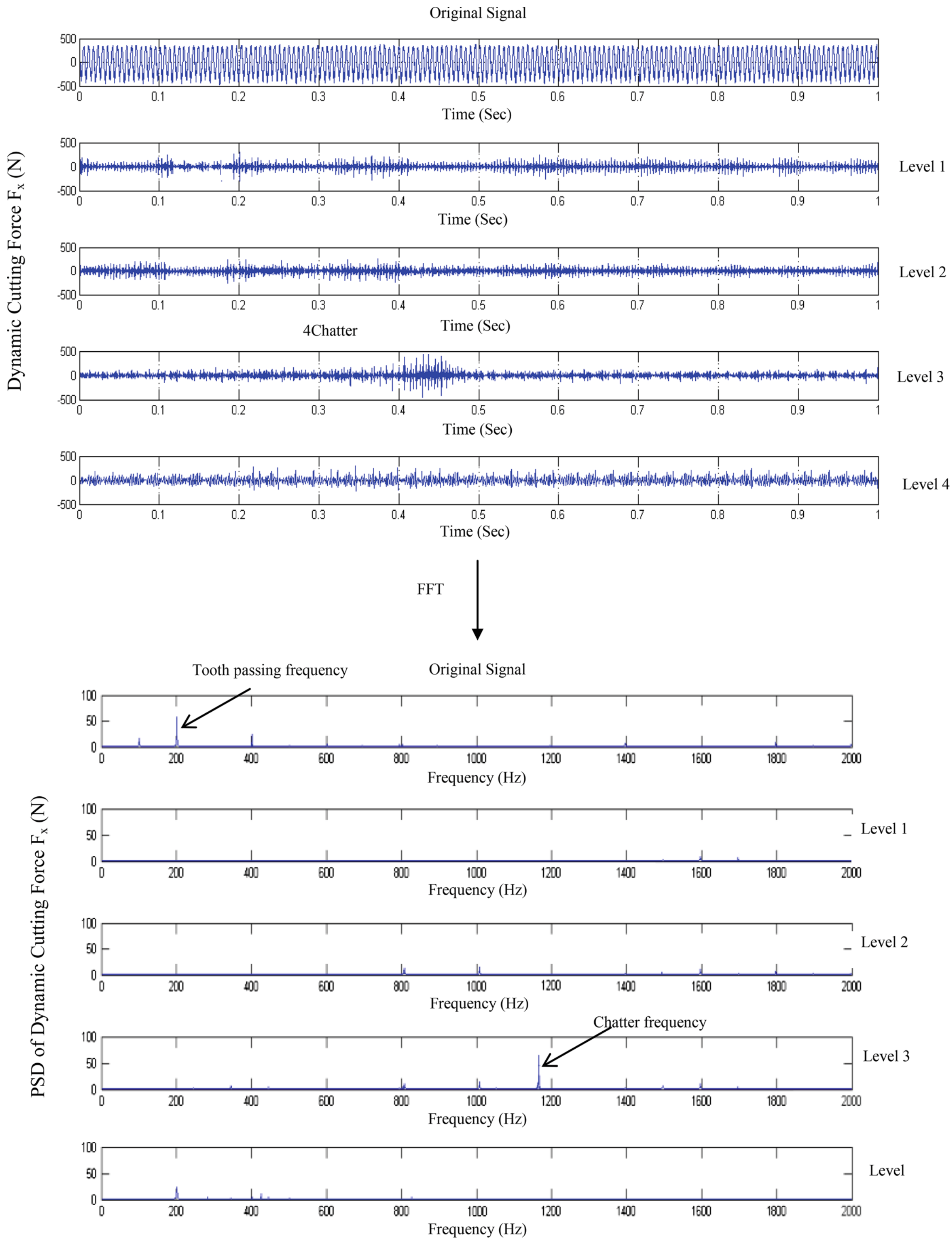

Fig. 9 Illustration of Chatter in level 3:Spindle speed 6,000 rpm, Depth of cut 4 mm, Feed rate 0.03 mm/tooth, Tool diameter 8 mm

mapping the obtained Rx, Ry, and Rz on the reference feature spaces referring to the critical values of Cx, Cy, and Cz.

However, the efficiency of the chatter detection by using the wavelet transformation depends on the level of the wavelet decomposition. Hence, it is very important to apply the proper level to detect the chatter during the process. The suitable level obtained in this research is from the level 2 to the level 4, which are consistent with the previous research (Somkiat 2012).

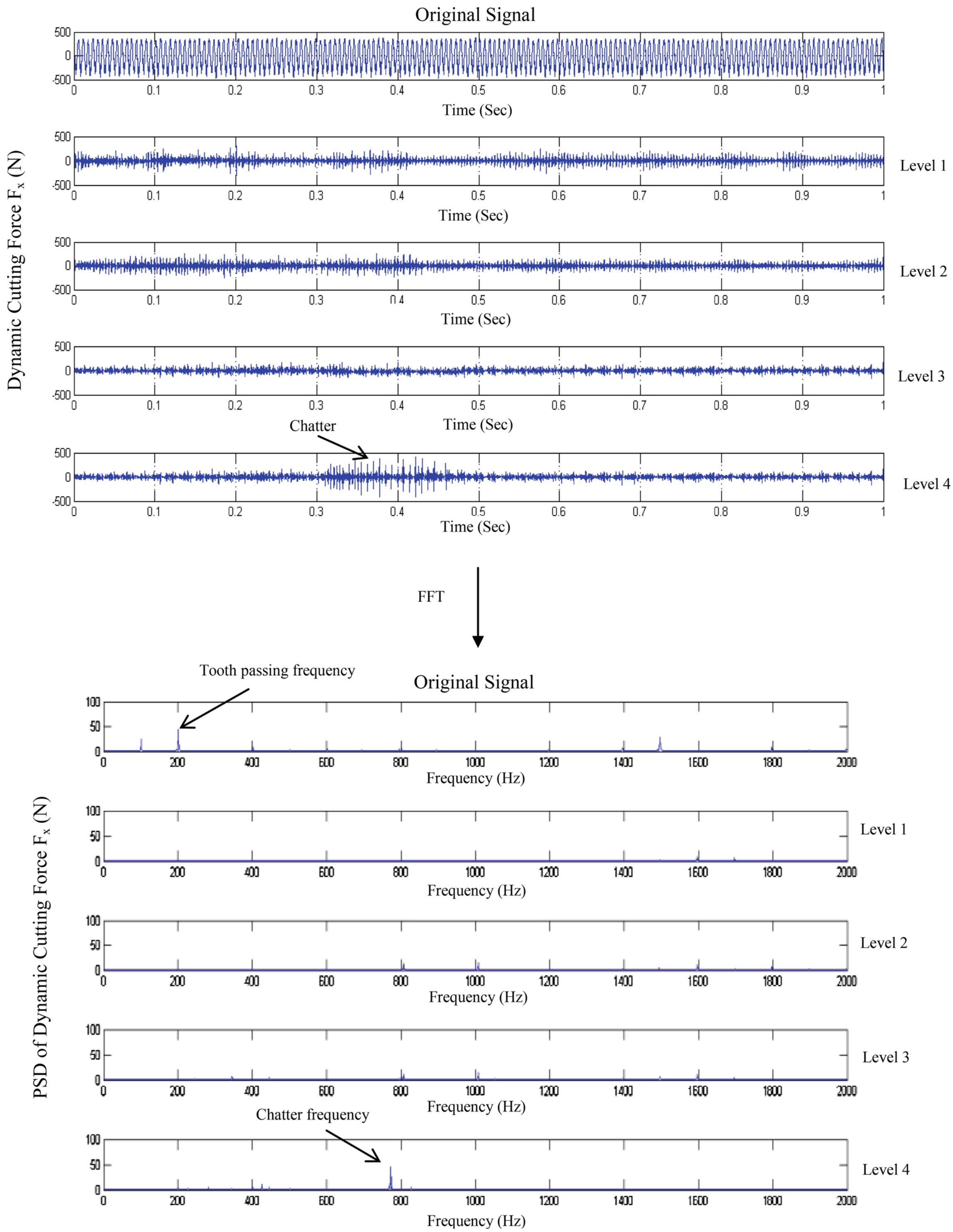

Fig. 10 Illustration of Chatter in level 4:Spindle speed 6,000 rpm, Depth of cut 4 mm, Feed rate 0.03 mm/tooth, Tool diameter 12 mm

Referring to the critical values of Cx, Cy, and Cz obtained in Fig. 11, the algorithm to check and avoid the chatter from the first level to the fourth level is proposed and shown in Fig. 12. The new cutting tests are employed to check the performance of the proposed method and verify the critical values in the reference feature spaces as shown in Table 2. Figure 12 also illustrates the algorithm to avoid the chatter referring to the precaution by decreasing the depth of cut, the spindle speed, and the feed rate, respectively during the in-process cutting. However, the use of precautions has to be

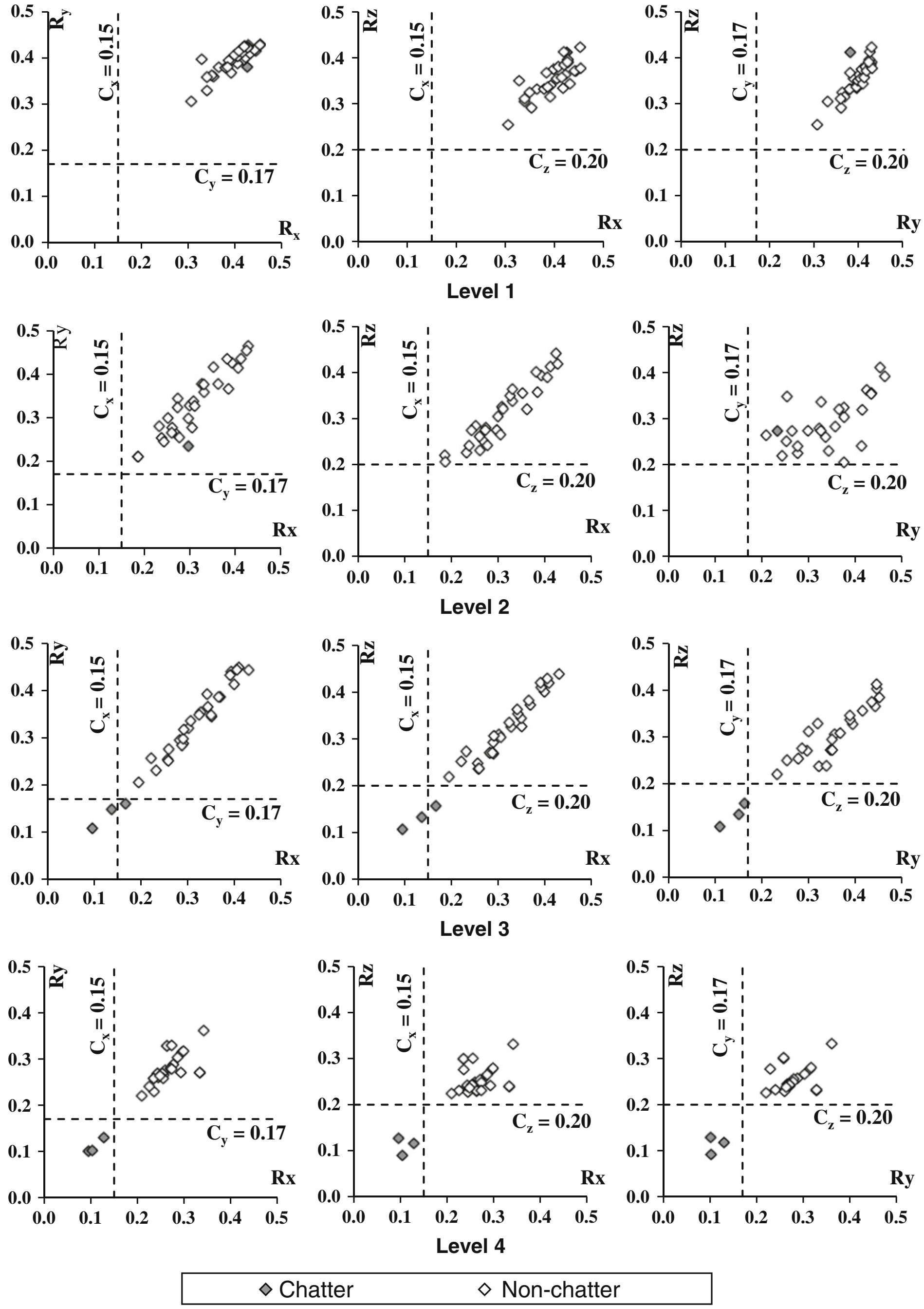

Fig. 11 Illustration of the reference feature spaces between R_x versus R_y; R_x versus R_z and R_y versus R_z of the detail signals in each level for all cutting conditions

considered for the being used combination of cutting conditions and the cutting processes which affect the phenomena of chatter.

The verification of the proposed algorithm in Fig. 12, which is developed from Fig. 11, has been examined as shown in Fig. 13 by using the new cutting conditions in Table 2. Figure 13 shows the examples of the experimentally obtained chatter detection diagram between the parameters of R_x, R_y, R_z, and the depths of cut at various spindle speeds and feed rates. The experimentally obtained values of parameters R_x, R_y and R_z corresponded to the critical values C_x, C_y and C_z in the reference feature spaces as shown in Fig. 11. The chatter happens when the values of R_x, R_y and R_z are lower than the critical values, which are 0.15, 0.17, and 0.20 respectively. It is understood that the parameter R_x, R_y and R_z can be used to detect the chatter in the ball

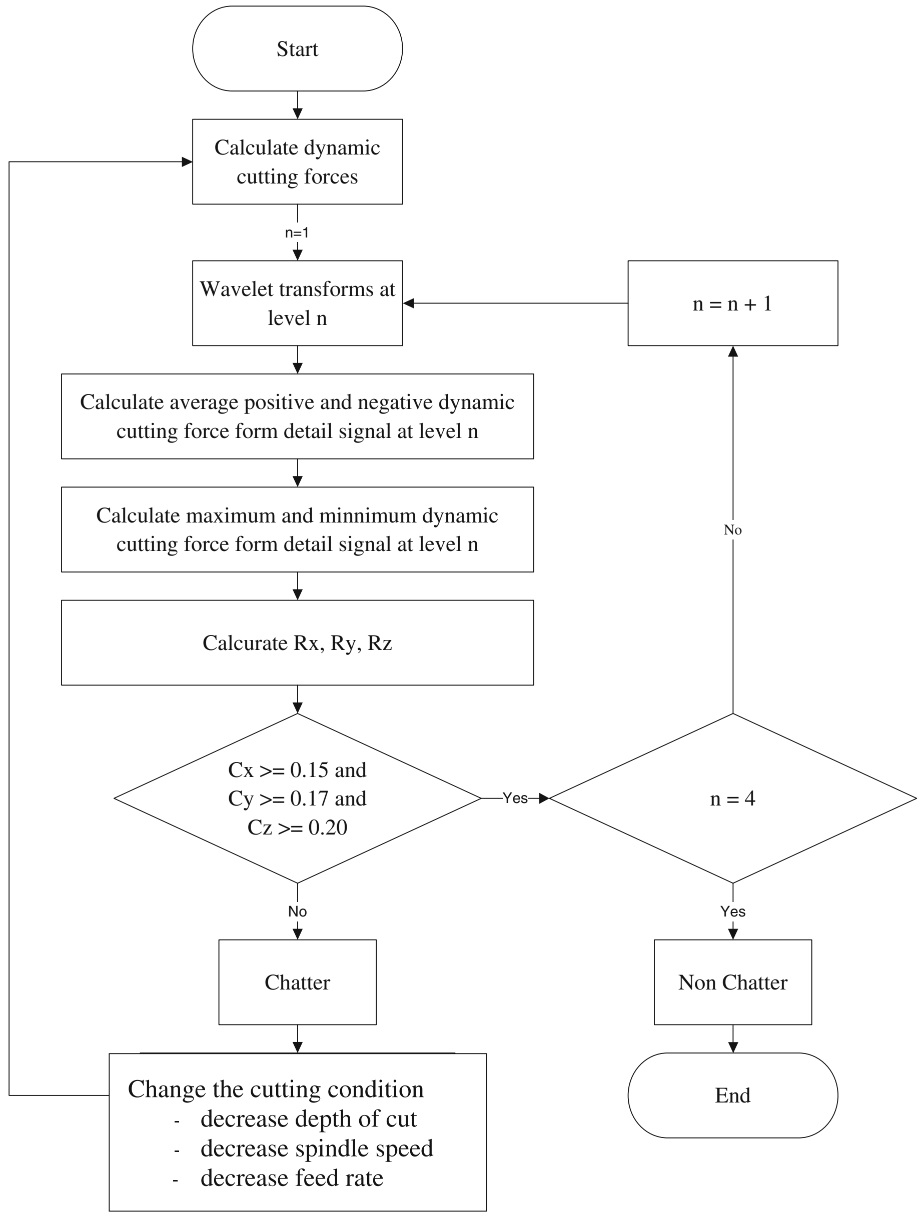

Fig. 12 Illustration of algorithm to check and avoid the chatter

Table 2 New cutting conditions

Workpiece	Carbon steel (AISI 1050)
Cutting tool	Coated carbide ball end mill
Diameter (mm)	4, 10
Spindle speed (rpm)	5,000, 6,000, 7,000, 8,000, 9,000, 10,000
Depth of cut (mm)	1, 2, 3, 4
Feed rate (mm/tooth)	0.01, 0.02, 0.03

end milling process during cutting regardless of the cutting conditions.

It is noticed that a number of chatter happen at the larger depth of cut due to the higher cutting forces which lead to the chatter vibration. Hence, the non-chatter will be obtained at the lower depth of cut. However, the cutting parameters are not necessary to be decreased in order to eliminate the chatter always. Since, the being used combination of cutting conditions and the cutting processes may affect the change in chatter.

The largest advantage of the proposed method using wavelet transform is that the chatter can be detected easily under any cutting condition in both time domain and frequency domain during the in-process cutting by simply mapping the obtained values of R_x, R_y and R_z referring to the critical values C_x, C_y and C_z in the reference feature spaces by using the proposed algorithm as shown in Fig. 12. However, the preliminary experiments are required to obtain the critical values to classify the chatter and the non-chatter.

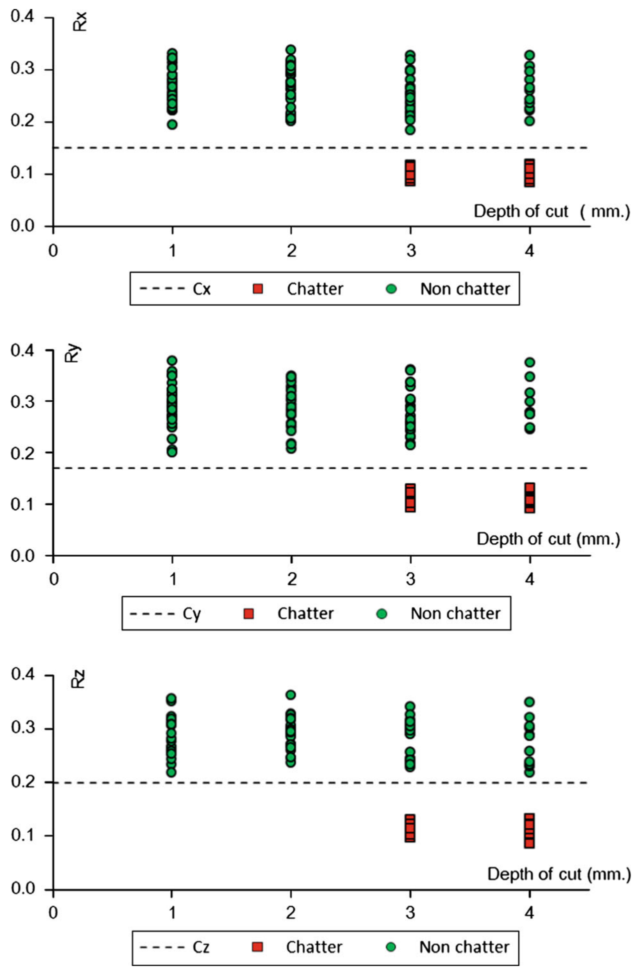

Fig. 13 Illustration of chatter detection diagram between R_x, R_y, R_z and depths of cut under various spindle speeds and feed rates

Since, the chatter frequency depends on the cutting systems such as the cutting conditions and the tool diameters. The detectable level of chatter may be different for the different cutting conditions.

Conclusions

A method has been developed and proved to detect the chatter in both time domain and frequency domain during the in-process ball end milling based on the wavelet transform of the dynamic cutting forces by employing the Daubechies wavelet. A proposed method introduces new parameters R_x, R_y, and R_z, which are calculated and obtained by taking the ratios of the average variances of the dynamic cutting forces to the absolute variances of themselves. The reference feature spaces and the proper critical values of C_x, C_y, and C_z are determined to classify the chatter and the non-chatter regardless of cutting conditions.

It is difficult to detect the chatter from the original signal but the chatter can be detected clearly in different levels of the wavelet transform in the detail signal. The ability to detect the chatter frequency in each level is different. The detectable level of chatter may be different when the cutting conditions are changed. It is noticed that the higher chatter frequency can be detected at the low level of the wavelet transform.

It has been proved that the chatter can be detected easily under any cutting condition during the in-process cutting by using the proposed algorithm and parameters which are developed and obtained in this research. The largest potential advantage of the proposed method here is that the chatter can be readily detected in both time domain and frequency domain during the in-process cutting under any cutting condition.

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