# Analysis of Chatter in Ball End Milling by Wavelet Transform

S. Tangjitsitcharoen

*Abstract*—The chatter is one of the major limitations of the productivity in the ball end milling process. It affects the surface roughness, the dimensional accuracy and the tool life. The aim of this research is to propose the new system to detect the chatter during the ball end milling process by using the wavelet transform. The proposed method is implemented on the 5-axis CNC machining center and the new three parameters are introduced from three dynamic cutting forces, which are calculated by taking the ratio of the average variances of dynamic cutting forces to the absolute variances of themselves. It had been proved that the chatter can be easier to detect during the in-process cutting by using the new parameters which are proposed in this research. The experimentally obtained results showed that the wavelet transform can provide the reliable results to detect the chatter under various cutting conditions.

*Keywords*—Ball end milling, wavelet transform, fast fourier transform, chatter.

## I. INTRODUCTION

THE chatter is an unstable state which normally happened while cutting the aerospace and automotive parts in the ball end milling process. It is one of the major causes of the unacceptable surface roughness and the tool deterioration. It is required to detect the chatter during the process. Hence, the in-process chatter detection in the ball end milling process is important to provide a rapid decision for the unstable situation. However, it is difficult to detect the chatter in the time domain. The simple method to detect the chatter is better in the frequency domain. The fast fourier transform (FFT) is commonly used to detect the chatter [1], [2]. But it has a good resolution only in the frequency domain and the disadvantage of the FFT is lack of information in the time domain.

The time-frequency analysis has then become an important approach. The wavelet transform has recently been proposed as a new tool to detect the chatter. The wavelet transform is the time-frequency analysis tool which can perform a good resolution in both time domain and frequency domain. The recent researches have been utilized the wavelet transform to detect the chatter in metal cutting processes [3]-[5]. All of those results have shown that the wavelet transform is a powerful tool to detect the chatter. The method can be helpful for the operator in the early detection of the chatter or the unstable process. However, those chatter detection systems are

S. Tangjitsitcharoen, is Associate Professor with the Faculty of Engineering, Department of Industrial Engineering, Chulalongkorn University, Phayathai Rd., Patumwan, Bangkok 10330 Thailand (phone: +66-2218-6853, Fax: +66-2218-6853 E-mail: somkiat.t@eng.chula.ac.th).

not applicable and implemented yet. Hence, it is necessary to develop an in-process monitoring system to detect the chatter automatically during the in-process cutting.

The dynamic cutting force is normally used as a signal to detect the chatter in the cutting process in many researches which provides a good result for the chatter detection by applying the wavelet transform to the dynamic cutting forces [3], [6], [7]. The amplitudes of dynamic cutting forces are relatively when the chatter occurs. The input signals can be analyzed by the wavelet transform into four levels for the detail signals and the approximate signals. The different levels are expected to suit with the specific frequency intervals. For example, the low level of the wavelet transform may be proper to monitor the high frequency of chatter. In the other hand, the high level of the wavelet transform will be better to check the low frequency of chatter. Hence, if the obtained level of wavelet transform is decided properly, the chatter will be detected efficiently.

The aim of this research is to develop an in-process chatter detection by utilizing the wavelet transform in the ball end milling process by using the dynamic cutting forces. The proposed method will be used to optimize the cutting parameters in the future research for the 5-axis CNC machining center.

## II. DETECTION OF CHATTER AND WAVELET TRANSFORM

The wavelet transform has been applied to a various problems in engineering [8], [9]. It has recently been proposed as a tool in signal analysis that can analyze the signals in the time domain and frequency domain. The original signal can be seperated into two signals, approximation signal and detail signal or can be called "wavelet decomposition". The wavelet decompositon of the signal can be repeated as the number of levels increases that can illustrated in the Fig. 1.
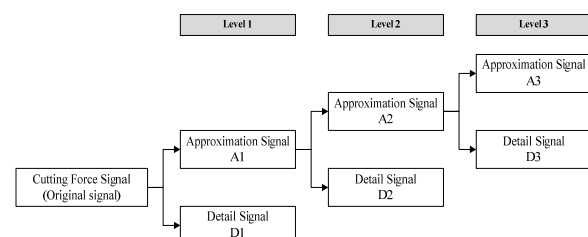


Fig. 1 Illustration of the wavelet decompostion

The wavelet transform is used to analyze the signal formed by the wavelet basic function or the mother wavelet. The Daubechies wavelet is utilized in this research as the mother wavelet because of the Daubechies wavelet is one of the most powerful mother wavelet for analysis in mechanical signals [3].

The wavelet transform is used to calculate for four levels due to the previous results obtained from the recent researches. It has shown that the chatter can be detected clearly in the level 2 to level 4 [10]-[12] which depends on the chatter frequency of the system.

Fig. 2 and Fig. 3 illustrate the dynamic cutting forces when the chatter and the non-chatter appeared and their frequency domain by using Fast Fourier Transform (FFT). It is noticed that it is difficult to detect the chatter from the original signal but the chatter can be detected clearly in level 2 and level 3 in the detail signal of the $F_x$ as shown in Fig. 2
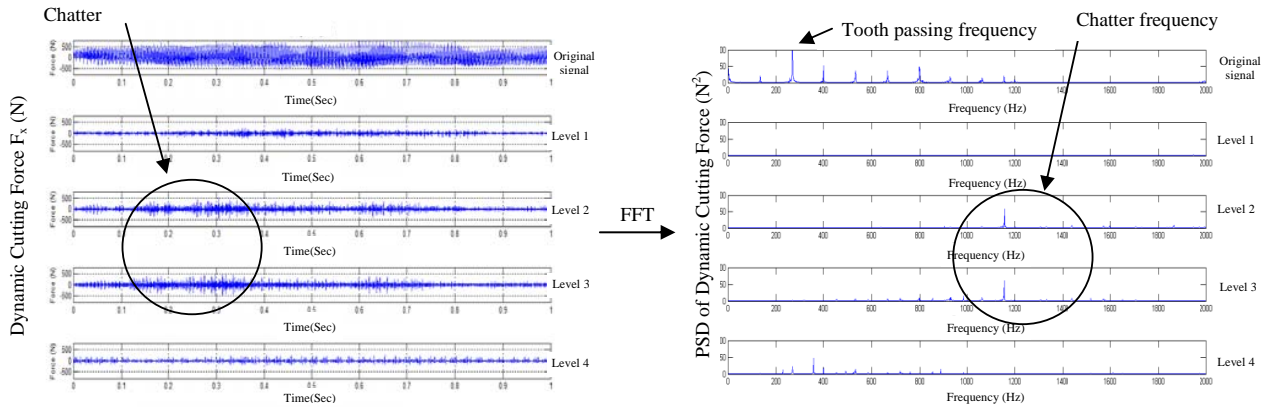


Fig. 2 Illustration of the dynamic cutting forces in x-axis ($F_x$) and detail signal level 1 to level 4
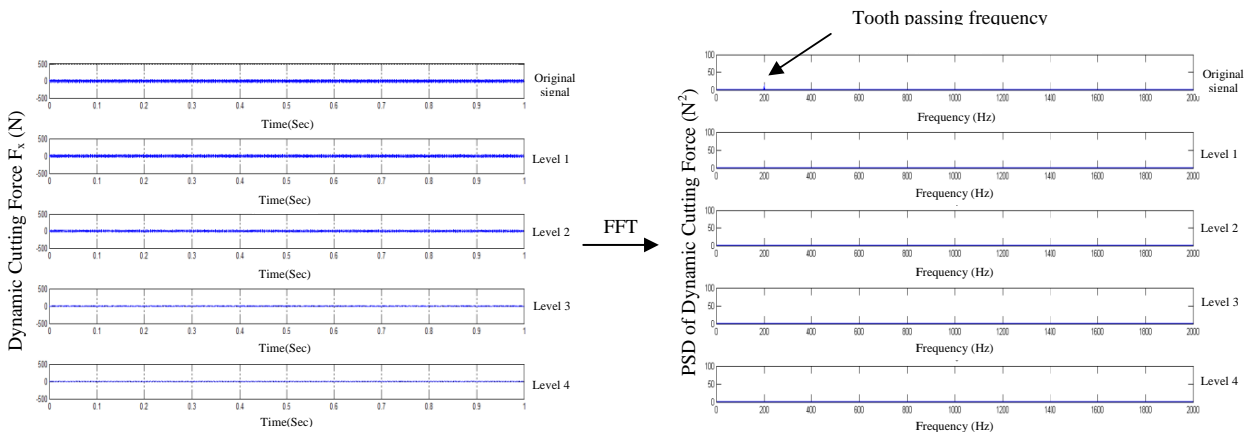Chatter : spindle speed 8000 rpm, depth of cut 4 mm, feed rate 0.03 mm/tooth



Fig. 3 Illustration of the dynamic cutting forces in x-axis ($F_x$) and detail signal level 1 to level 4.
Non-Chatter : Spindle speed 6000 rpm. Depth of cut 1 mm. Feed rate 0.02 mm./tooth

## III. IN-PROCESS CHATTER DETECTION

The dynamic cutting force has its own pattern when the chatter occurred during the process the higher amplitude of the dynamic cutting forces are expected when the chatter appears. The proposed method introduces three parameters ($R_x$, $R_y$, $R_z$) in this research by taking the ratio of the average variance of dynamic cutting force to the absolute variance of dynamic cutting force as shown in Fig. 4 and Fig. 5 The proposed method requires the preliminary tests to obtain the critical values which will be used to classify the cutting states. When the chatter happens, the absolute variances of dynamic cutting force will become larger as shown in Fig. 4. In the other hand, the average variances of dynamic cutting force are relatively small as compared to the non-chatter as shown in Fig. 5 It means that the values of $R_x$, $R_y$, and $R_z$ will be low when the chatter occurs.
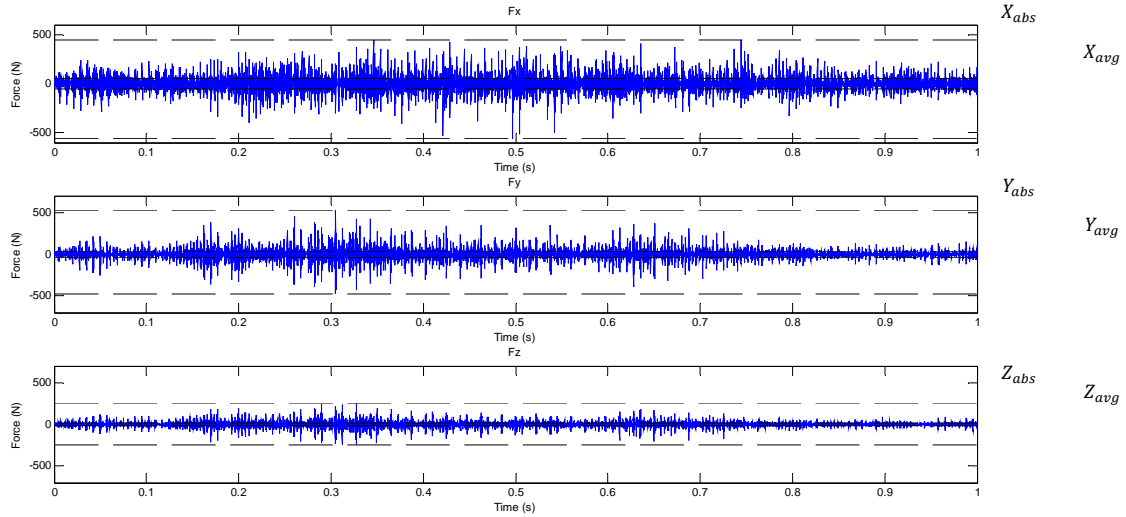
Fig. 4 Illustration of the average variances of the dynamic cutting forces, the absolute variances of dynamic cutting forces and the new parameters $R_x$, $R_y$, and $R_z$ in the detail signal level 2 of chatter
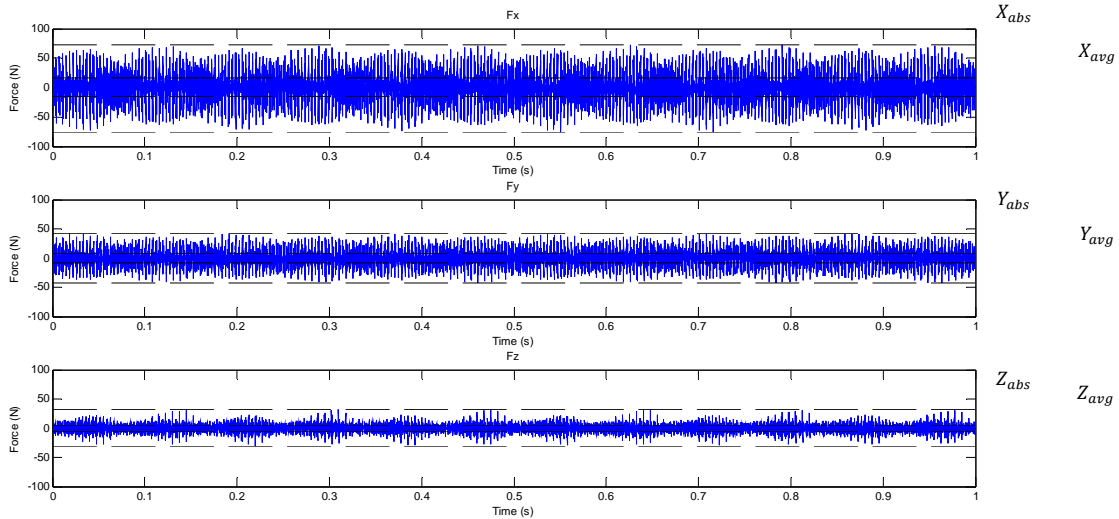


Fig. 5 Illustration of the average variances of the dynamic cutting forces, absolute variances of dynamic cutting forces and the new parameters $R_x$, $R_y$, and $R_z$ in the detail signal level 2 of non-chatter

In order to obtain the reference feature spaces and the critical values ($C_x$, $C_y$, and $C_z$) the following experimental procedures are adopted to obtain the relation between the parameters 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 ($F_x$, $F_y$, $F_z$).
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).

$$X_{avg} = X_{avg}^+ - X_{avg}^- \tag{1}$$
$$Y_{avg} = Y_{avg}^+ - Y_{avg}^- \tag{2}$$
$$Z_{avg} = Z_{avg}^+ - Z_{avg}^- \tag{3}$$

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).

$$X_{abs} = X_{abs}^+ - X_{abs}^- \tag{4}$$
$$Y_{abs} = Y_{abs}^+ - Y_{abs}^- \tag{5}$$
$$Z_{abs} = Z_{abs}^+ - Z_{abs}^- \tag{6}$$

8. Calculate $R_x$, $R_y$, and $R_z$ by taking the ratio of the average variances of the dynamic cutting forces to the absolute variances of themselves in (7) – (9).

$$R_x = X_{avg}/X_{abs} \qquad (7)$$
$$R_y = Y_{avg}/Y_{abs} \qquad (8)$$
$$R_z = Z_{avg}/Z_{abs} \qquad (9)$$

9. Plot the parameters $R_x$ versus $R_y$ ; $R_x$ versus $R_z$, and $R_y$ versus $R_z$.

10. Repeat procedures 1 to 8 with another cutting condition Determine the proper critical values of $C_x$, $C_y$, and $C_z$ to detect the chatter by using the k-means clustering [13] which aims to classify n observations into k groups as shown in the Fig. 6.
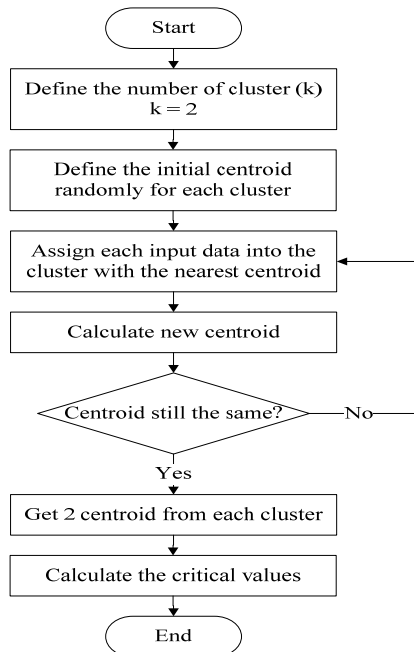
Fig. 6 Illustration of the K-means clustering algorithm

## IV. EXPERIMENTAL EQUIPMENT AND 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 x W 64 mm x 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. 7. The cutting conditions are shown in Table I.

The dynamic cutting forces obtained by the focce sensor are amplified and low-pass of 5 kHz. The sampling rate is 10 kHz.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 with tool diameters of 6 mm and 8 mm are about 1.3 kHz. and 1.15 kHz, respectively. Hence, the dynamic cutting force are detected well by the force sensor.
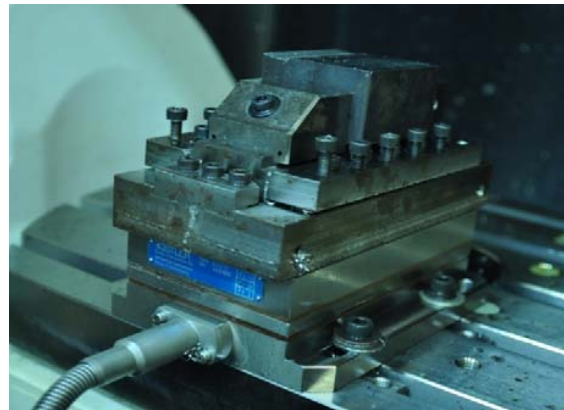
Fig. 7 Illustration of the experimental setup

TABLE I
MAJOR CUTTING CONDITIONS

| | |
|---|---|
| Workpiece | carbon steel (AISI 1050) |
| Cutting tool | coated carbide ball end mill (diameters 6mm. and 8 mm) |
| Spindle speed (rpm) | 5000, 6000, 7000, 8000, 9000 |
| Depth of cut (mm) | 1, 2, 3, 4, 5 |
| Feed rate(mm) | 0.01, 0.02, 0.03 |

## V. CLASSIFICATION OF CHATTER AND NON-CHATTER

The chatter and the non-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 $C_z$). It means that the chatter appears during the cutting process.

Fig. 8 shows the experimentally obtained results of the reference feature spaces between $R_x$ versus $R_y$ ; $R_x$ versus $R_z$, and $R_y$ versus $R_z$ that calculated from the detail signals in each level obtained from the wavelet transform. The results show that the chatter can be detected clearly in level 2. However, the chatter cannot be detected clearly in the detail signals of level 3 and level 4 because of the ability to detect the chatter frequency in each level which are different. Since it depends on the types of the cutting tools and their weights. In other word, the weights of the cutting tool increase and cause the chatter frequency decrease. It is understood that the suitable and detectable level of chatter may change when the cutting conditions are different.

According to the k-mean clustering as shown in Fig.6, the critical values ($C_x$, $C_y$, $C_z$) are calculated and obtained, which are 0.15, 0.17, and 0.20 respectively. It is implied that the chatter and the non-chatter can be detected by referring to the critical values of $C_x$, $C_y$, and $C_z$.
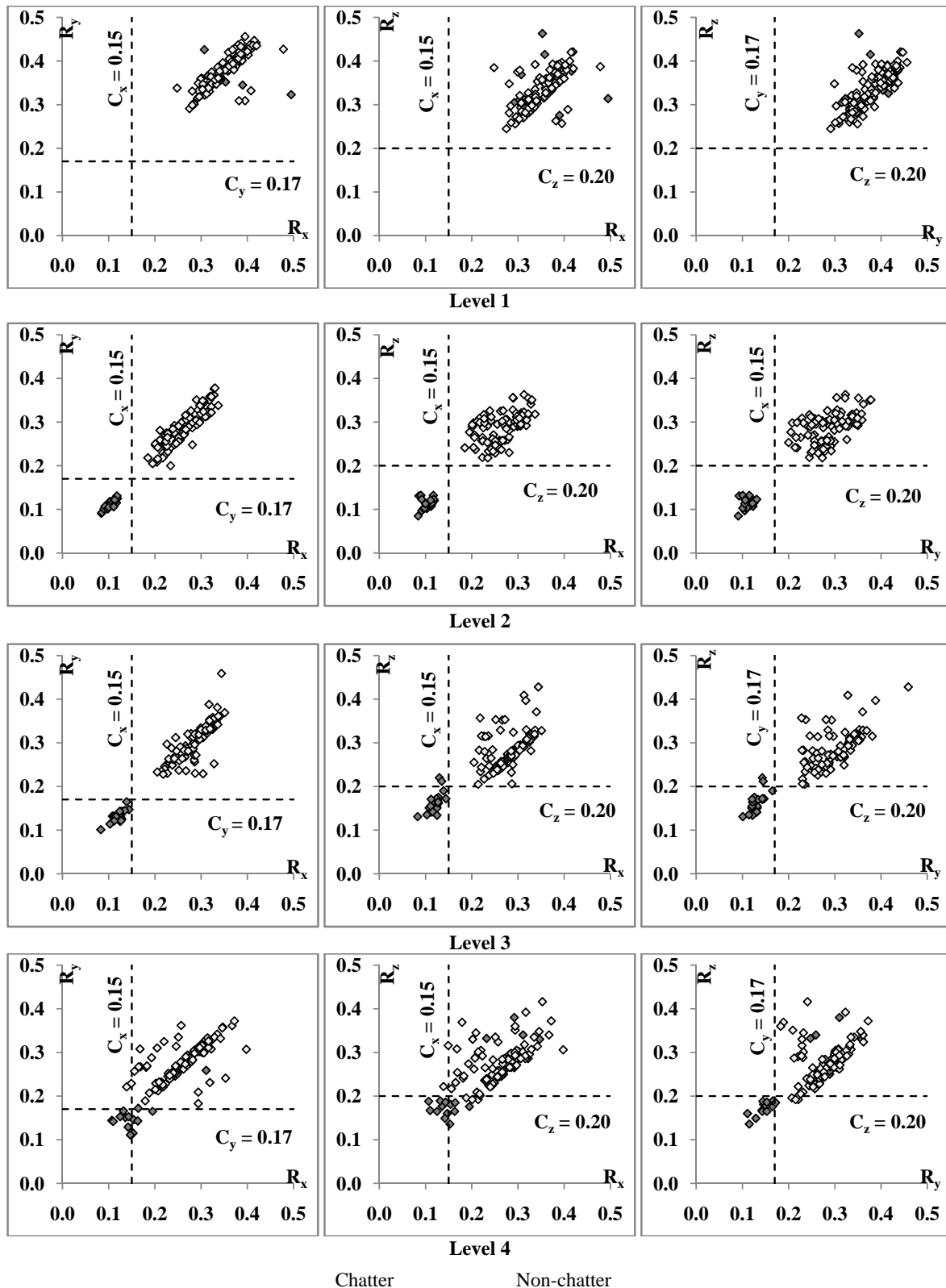
Fig. 8 Illustration of the reference feature spaces between $R_x$ versus $R_y$ ; $R_x$ versus $R_z$
and $R_y$ versus $R_z$. of the detail signal in each level

According to the experimental results, it means that the suitable and detectable level of the chatter cannot be specified here but it can be checked for all levels to detect the chatter which happens during the process referring to the critical values in Fig. 8. Hence, the algorithm to check the chatter from the first level to the fourth level is proposed and shown in Fig. 9
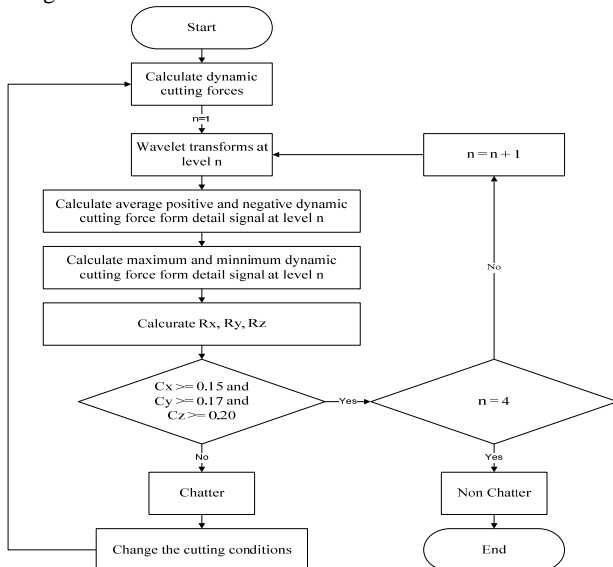


Fig. 9 Flow chart of the chatter detection by utilizing wavelet transform

TABLE II
NEW CUTTING CONDITIONS

| Diameter (mm.) | Spindle speed (rpm) | Depth of cut (mm) | Feed rate (mm/tooth) |
|---|---|---|---|
| 4 | 2000 | 2 | 0.01 |
| 4 | 8000 | 2 | 0.01 |
| 4 | 4000 | 2 | 0.02 |
| 4 | 10000 | 3 | 0.02 |
| 4 | 2000 | 2 | 0.02 |
| 4 | 5000 | 3 | 0.02 |
| 4 | 8000 | 2 | 0.02 |
| 4 | 1000 | 2 | 0.03 |
| 4 | 5000 | 3 | 0.03 |
| 4 | 10000 | 2 | 0.03 |
| 10 | 2000 | 3 | 0.01 |
| 10 | 8000 | 4 | 0.01 |
| 10 | 3000 | 6 | 0.02 |
| 10 | 8000 | 3 | 0.02 |
| 10 | 2000 | 7 | 0.02 |
| 10 | 5000 | 4 | 0.02 |
| 10 | 8000 | 6 | 0.02 |
| 10 | 1000 | 7 | 0.03 |
| 10 | 5000 | 4 | 0.03 |
| 10 | 9000 | 6 | 0.03 |
| 12 | 2000 | 8 | 0.01 |
| 12 | 8000 | 6 | 0.01 |
| 12 | 4000 | 10 | 0.02 |
| 12 | 9000 | 6 | 0.02 |
| 12 | 2000 | 8 | 0.02 |
| 12 | 5000 | 8 | 0.02 |
| 12 | 8000 | 6 | 0.02 |
| 12 | 2000 | 8 | 0.03 |
| 12 | 4000 | 8 | 0.03 |
| 12 | 8000 | 10 | 0.03 |

The new cutting tests are employed to detect the chatter during the ball end milling process in order to check the performance of the proposed method, and verify the critical values in Fig. 9 by utilizing the new cutting conditions as shown in Table II.

It has been proved that the proposed algorithm can be used to check the chatter during the process very well.

## VI. CONCLUSION

A method has been proposed and developed for in-process chatter detection in the ball end milling processes on 5-axis CNC machining centre based on the wavelet transform of dynamic cutting forces. A proposed method introduces new parameters $R_x$, $R_y$, and $R_z$, which are calculated and obtained by taking the ratio 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 of the chatter and the non-chatter.

It had been proved that the chatter can be easier to detect during the in-process cutting for the ball end milling machine by using the wavelet transform and the new parameters which are proposed in this research.

The largest potential advantage of the proposed method here is that the chatter and the non-chatter can be readily identified during the in-process cutting under any cutting condition by simply checking the experimentally obtained values of parameters $R_x$, $R_y$, and $R_z$ referring to the determined critical values of $C_x$, $C_y$, and $C_z$ in the reference feature spaces.

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