Concurrent Monitoring of Chip Formation and Prediction of Roundness in CNC Turning Using Wavelet Transform

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Abstract. The aim of this research is to investigate the chip formation, the roundness and the dynamic cutting forces in CNC turning process. The dynamic cutting forces are decomposed to classify the signals of the broken chip and the roundness. The Daubechies wavelet transform is utilized to identify those signals into different levels due to the different frequencies of itself. The experimentally obtained results showed that the decomposed cutting forces can be used to estimate the roundness under various cutting conditions.

1. Introduction

According to the previous researches, the dynamic cutting forces have been proposed to monitor the broken chip formation and the roundness in CNC turning [1,2]. The dynamic cutting forces have been used to be decomposed to monitor the straightness in order to avoid the broken chip and noise signals by using the wavelet transform [3].

Many methods have been proposed to monitor the roundness. Guo and Han [4] analysed the machining conditions to predict the diametral error of slender bar. Bugra et al. [5] utilized the cutting forces which is accurate enough to estimate the bar deflection. Bodi and Rongdi [6] proposed an artificial neural network model to investigate the influence of cutting parameters on the dimensional errors. It is proved that the diameter of the workpiece depends on the radial force and the feed force during the turning process. Xuefeng Bi et al. [7] presented that the dimensional error increases with the cutting velocity, the cutting time, the tool nose radius and the clearance angle. Shawky and Elbestawi [8] proposed an on-line measurement system in the bar turning to evaluate of workpiece size based on cutting forces.

The previous research has presented that the radial force (Fx) and the feed force (Fy) influence on the diameter error and the roundness error of the workpiece [9]. It is known that the peak-to-valley height depends on the feed rate and the tool nose radius [10] which causes the roundness error.

It is found that the decomposed cutting forces by using the Daubechies wavelet transform can be used to classify the roundness and straightness frequency effectively in both time and frequency domains, which appear on 8th level [1,3]. Hence, the aim of this research is to propose the Daubechies wavelet transform to decompose the dynamic cutting forces into 10 levels in order to differentiate the broken chip and roundness signals in CNC turning process.

2. Monitoring of chip formation and roundness

Figure 1 illustrates the dynamic cutting forces of broken chip and the corresponding time record of roundness profile. It is noticed that the amplitudes of dynamic cutting forces are larger than that of
continuous chip as shown in figure 2 [2]. It is implied that the chip breaking signals are included in the dynamic cutting forces. If those noise and chip breaking signals can be separated out from the dynamic cutting forces, the roundness will be estimated correctly from the use of dynamic cutting forces. The Daubechies wavelet transform is hence proposed to classify those signals from dynamic cutting forces into different levels due to the different frequency ranges. It is known that the higher frequency signal will occur at the lower level of wavelet transform of decomposed cutting force. On the other hand, the lower frequency signal will appear at the higher level of the wavelet transform [1,3].

**Figure 1.** Illustration of dynamic cutting forces of broken chip and roundness profiles in time domain at cutting speed of 100 m/min, feed rate of 0.15 mm/rev, depth of cut of 0.8 mm, tool nose radius of 0.8 and rake angle of 11°.

Since, the dynamic radial force (Fx) affects the roundness profile. While the dynamic feed force (Fy) may cause the roundness error, which is perpendicular to the roundness [2]. The dynamic radial force and the dynamic feed force are hence decomposed to monitor the roundness error during the cutting. The cutting forces are generalized by taking the ratio of the average variation of decomposed radial force to that of the decomposed feed force (AVFx/AVFy) as shown in figure 3. The relation between the decomposed cutting force ratio and the in-process roundness will be examined under various cutting conditions.

**Figure 2.** Illustration of dynamic cutting forces of continuous chip and roundness profile in the time domain at cutting speed of 150 m/min, feed rate of 0.15 mm/rev, depth of cut of 0.6 mm, tool nose radius of 0.8 and rake angle of -6°.
3. **Prediction of roundness**

The relation of the roundness error, the decomposed cutting force ratio and the cutting parameters are examined and proposed by employing the exponential function for the sake of it as shown in equation (1):

\[
R_0 = C_1 \cdot (V)^{a_1} \cdot (f)^{a_2} \cdot (D)^{a_3} \cdot (R_n)^{a_4} \cdot (\frac{AVF_x}{AVF_y})^{a_6}
\]  \hspace{1cm} (1)

Where \( R_0 \) is the roundness error in micrometer, \( V \) is the cutting speed in m/min, \( f \) is the feed rate in mm/rev, \( D \) is the depth of cut in mm, \( R_n \) is the tool nose radius in mm, \( \gamma \) is the rake angle in degrees, \( \frac{(AVF_x)}{(AVF_y)} \) is the decomposed cutting force ratio, \( a_1, a_2, a_3, a_4, a_5, a_6 \), and \( C_1 \) are the powers and the coefficients of the model, respectively.

4. **Experimental setup and procedure**

The cutting tests are conducted on CNC turning machine. The coated carbide cutting tools are used for the experiments with the different tool nose radiuses and the rake angles. The cutting conditions are summarized in the table 1.

The experimental setup is illustrated in figure 4. The dynamic cutting forces detected by dynamometer are sampling at 10 kHz and amplified through the low-pass filtered with cut-off frequency of 5 kHz prior to digitization and calculation within PC.

| Cutting Tool | Coated carbide tool |
|--------------|---------------------|
| Tool geometry | DNMG150604FN       | DCMT11T304HQ       |
|               | DNMG150608FN       | DCMT11T308HQ       |
| Rake angle    | -6°                 | 11°                |
| Tool nose radius | 0.4, 0.8 mm      |                   |
| Workpiece     | AISI 1045 Carbon Steel |
| Cutting speed | 100, 150, 200 m/min |
| Feed rate     | 0.15, 0.20, 0.25 mm |
| Depth of cut  | 0.4, 0.6, 0.8 mm    |
The following procedures are proposed to obtain the relation of the roundness, the cutting force ratio and the cutting conditions.

1. Start cutting and monitor the decomposed cutting forces referring to the cutting conditions.
2. Check the relations of the roundness and the decomposed cutting forces in time domain and frequency domain by using the minimum zone circle (MZC) method [11].
3. Take the ratio of the average variation of decomposed radial force to that of decomposed feed force (AVFx/AVFy).
4. Repeat the procedures (1) to (3) for other cutting conditions.
5. Model the in-process prediction of roundness and ratio of decomposed cutting forces under various cutting condition at 95% confident level.
6. Verify the obtained model with the new cutting conditions.

5. Experimental results and discussions
The examples of the cutting tests are illustrated in figure 5. The dynamic cutting forces are decomposed into 10 levels in both time domain and frequency domain by using the Daubechies wavelet transform. It is shown that the decomposed cutting force corresponds with the roundness profile at the 8th level, which are the same as previous research [3]. Hence, the decomposed cutting force from the 8th level can be monitored to estimate the in-process roundness as shown in figure 5.

As shown in figure 5, the broken chip and noise signals have been separated out from roundness signal to other levels due to the different frequency ranges of noise and chip breaking which appear in lower levels of wavelet transform. It means that the higher frequency signal will happen at the lower levels which correspond with the previous research [2,3].

6. Verification of roundness model and accuracy
The experimentally obtained in-process roundness model is expressed in equation (2);

\[
R_0 = e^{2.3410 - 0.0937 \cdot V - 0.1589 \cdot D - 0.0568 \cdot R_n - 0.0395 \cdot \gamma - 0.004420 \cdot \left(\frac{AVFx}{AVFy}\right)^{0.3040}}
\] (2)
The in-process roundness model is obtained at 95% confident level, which consists of the cutting speed, the feed rate, the depth of cut, the tool nose radius, the rake angle and the decomposed cutting force ratio. The new cutting tests are conducted as shown in table 2 for 32 experiments in order to verify the accuracy of the in-process roundness model by adopting the new cutting conditions as shown in figure 6.

The experimentally measured roundness versus the in-process predicted roundness obtained from the model is shown in figure 6. The prediction accuracy of the model within the ±10% error lines is about 95.51%. It indicates that the developed model can aid to predict the in-process roundness which is close to the measured ones during the cutting regardless of the cutting conditions.

7. Conclusion

The concurrent monitoring of chip formation and prediction of roundness has been proposed under various cutting conditions. The broken chip and noise signals can be detected and classified to other levels of decomposed cutting forces by using the Daubechies wavelet transform. The ratio of average variation of decomposed radial force to that of decomposed feed force is proposed to estimate the roundness. The exponential function is employed to represent the relation of roundness and decomposed cutting force ratio with cutting parameters. The multiple regression analysis has been utilized to calculate the powers of the in-process prediction of roundness model using the least square method at 95% confident level. It is proved by the cutting tests that the in-process roundness can be well predicted within ±10% of measured ones.

Figure 5. Illustration of decomposed feed forces of broken chip in time domain obtained at cutting speed of 150 m/min, feed rate of 0.25 mm/rev, depth of cut of 0.8 mm, tool nose radius of 0.4 and rake angle of 11°.
Table 2. New cutting conditions.

| Cutting Tool                  | Coated carbide tool |
|-------------------------------|---------------------|
| Tool geometry                 | DNMG150604FN        |
|                               | DCMT11T304HQ        |
| DNMG150608FN                  | DCMT11T308HQ        |
| Rake angle                    | -6°                 |
| Tool nose radius              | 0.4, 0.8 mm         |
| Workpiece                     | AISI 1045 Carbon Steel |
| Cutting speed                 | 120, 250 m/min      |
| Feed rate                     | 0.18, 0.30 mm       |
| Depth of cut                  | 0.2, 0.5 mm         |

Figure 6. Verification of roundness model.

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