Stability analysis of regenerative vibration in turning operation using I-kaz3D™ signal processing approach

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Abstract. This paper presents a stability analysis to predict regenerative vibration during turning process. Although the stability of machining process has been widely studied in metal cutting it still presents a challenge as surface roughness, tool wear and productivity have to be considered. If the tool is vibrating as it removes material, these vibrations are imprinted on the workpiece surface as a wavy profile. However, the relative phasing between the surface waviness from one pass to the next determines the level of force variation and whether the operation is stable or unstable. Then we investigate the unstable and stable phenomena during the machining process by discussing the number of time-domain simulation to determine the force and surface roughness values these stability thresholds. A signal processing was carried out using I-Kaz3D technique to identify the effect between the unstable and stable phenomena. The results show that the relationship between I-kaz3D coefficients and surface roughness values can be considered very highly correlated.

1. Introduction
Machining process is involved dynamic instability that influence from interaction between the structural dynamics of the system and the metal cutting process. Effect of machine tool and workpiece system provides the regenerative vibrations due to self-excited vibrations which occur during cutting processes. Although regenerative vibration has been widely studied in machining processes, it still presents a challenge as cutting parameters such as cutting speed, feed rate and depth of cut have to be considered for optimum cutting conditions. Siddhpura and Paurobally [1] and Shrivastava et al. [2] identified regenerative vibration as regenerative chatter which it contributes the most important causes of inconsistent in the cutting process stability and the most destructive among all other vibrations have to be predicted and detected before it occurs. It also certainly guarantees the machine productivity causes reduces tool life and poor surface finish. Researchers have investigated and correlated between regenerative vibration and cutting parameters in turning operations. Okonkwo et al. [3] studied that the comparative analysis from regenerative vibration of turning AISI 4340 alloy steel which feed rate was very significant for higher regenerative vibration (chatter) frequency 89.84% meanwhile, cutting
speed 5.79% and depth of cut 3.92%. Taylor et al. [4] analysed at higher feed rates and low surface speeds, the cutting processes exhibited high amplitude vibrations due to the chip segmentation phenomenon. Patel and Gandhi [5] concluded that among the cutting parameters, feed rate is most significant parameter affecting the surface roughness followed by depth of cut and cutting speed. Sivaiah and Chakradhar [6] investigated the interaction effect of cutting variable on surface roughness. Lowest surface roughness can be obtained at the highest level of cutting velocity and lowest level of feed rate respectively. Meanwhile, lowest level of depth of cut and highest level of cutting velocity could produce low surface roughness respectively at the given condition. It is well known that the chatter stability depends on cutting conditions and tool geometry such as depth of cut and the spindle speed, it also depends on tool path/posture to dynamically cutting direction [7]. Several researchers have studied the correlation between chatter and surface roughness. Quintana et al. [8] observed that regenerative vibrations can be effected from the loud noise and the poor surface integrity due to chatter marks. Amin et al. [9] investigated that regenerative vibration has direct effect on surface roughness measured data (Ra) which is much higher with chatter compared to without chatter condition (at stable cutting process).

The objective of this paper was to investigate the effect of surface roughness due to the regenerative vibration by using the Integrated Kurtosis-Based Algorithm for Z-Notch Filter (I-kaz™). In stability analysis, surface roughness has been used for determining the chatter condition such as chatter marks, chatter prediction and etc. as mentioned by previous researchers. Force and vibration signals is choose by the researchers for the reason that it provides thorough insight into the dynamics of the cutting processes and it is very useful in the monitoring of the condition of the machining processes. The I-Kaz™ statistical analysis technique as a signal processing was developed by Nuawi et al. in 2008 [10]. This technique was applied in cutting processes such as tool wear detection, prediction and monitoring using force, vibration and acoustic signals in a series of papers [11-14] and was not been used for stability analysis in surface roughness measurement. In practice the I-kaz coefficients would have high values with increasing in flank wear values and amplitudes of force and vibration signals in cutting processes. Therefore, the research indicates the statistical significance of the I-kaz3D coefficient effects is able to increase or decrease the stability of the regenerative vibration.

2. Methodology

2.1 Materials and Equipment

In this paper, a workpiece material, medium carbon steel S45C of 59 HRB hardness was used as a round bar with the dimension of the work specimen was 75 mm diameter and 250 mm length. The nominal material composition of the workpiece of C = 0.42% - 0.48%, Si = 0.15 % - 0.35%, Mg = 0.6% - 0.9%, P = 0.03% and S = 0.035%. Figure 1 shows the experiments were performed on the CNC turning with the workpiece was mounted with the tailstock of the CNC Mazak 200MY turning machine and Mazatrol 640T PC-Fusion-CNC control software as shown in Figures 1(a) and 2(b). The cutting parameters under investigation were cutting speed, feed rate and depth of cut with the ranges selected as per the cutting tool manufacturer’s recommendation. The turning processes were conducted under dry cutting condition using CVD coated carbide insert, CNMG120404N-GU AC2000 with carbide tool holder, ECLNR-2020K12 designated by ISO was used to hold the insert. The vibration measurement during the machining process was measured using LMS TestLab and data acquisition system, LMS Scadas Mobile with 4 channels using 2048 Hz bandwidth, 163384 spectral lines and 0.125 Hz resolution. A tri-axial accelerometer (model Dytran 3263M8 sensitivities X axis = 100.55 mV/g, Y axis = 100.07 mV/g and Z axis = 99.62 mV/g) was mounted on the tool holder. A single-axial accelerometer (model Dytran 3145A sensitivity = 101.3 mV/g) was used as a reference in cutting or tangential direction to the signals. Then, the surface roughness measurement of the machined workpiece was measured by using a portable PS2 MarSurf PSp gage.

2.2 Experimental Procedures

In this work, the experimental procedure was done as shown in Figure 1. Firstly, the operator enters the numerically controlled (NC) program to CNC machine as shown in Figure 1(a). Secondly, install
the insert and tool holder on machine tool drive, then setup the tri-axial accelerometer on tool holder and single-axial accelerometer on the CNC machine as shown in Figure 1(b). Thirdly, the experimental design involves cutting parameters ranges of three factors such as cutting speed (50–250 m/min), feed rate was kept constant (0.1 mm/rev) and depth of cut (0.5–1.0 mm). An effort has been made in this work to determine whether the cutting parameters can influence the vibration signal responses in axial (X), tangential (Y) and radial (Z) directions and surface roughness arithmetic mean \( (R_a) \) values obtained from the experiments. Lastly, the vibration signals for thrust, cutting and feed forces were measured during the cutting processes as shown in Figure 1(c) and surface roughness was measured after the cutting processes as shown in Figure 1(d). The vibration signals were obtained in the time responses data from LMS DAQ, then the data was exported in text format. The data of \( R_a \) value was obtained by averaging surface roughness values at three location points around the circumference of the workpiece. All data were processed and analyzed with signal statistical analysis using MATLAB.

![Experimental setup](image)

**Figure 1.** Experimental setup.

| Test run | Cutting speed, \( V_c \) (m/min) | Feed rate, \( f \) (mm/rev) | Depth of cut, \( d \) (mm) |
|----------|----------------------------------|----------------------------|-----------------------------|
| 1        | 50                               | 0.1                        | 0.5                         |
| 2        | 100                              | 0.1                        | 1.0                         |
| 3        | 150                              | 0.1                        | 0.5                         |
| 4        | 200                              | 0.1                        | 0.5                         |
| 5        | 250                              | 0.1                        | 0.5                         |

### 2.3 Signal Processing using I-kaz3D Statistical Analysis

A signal processing using I-kaz3D statistical analysis was developed based on I-kaz\textsuperscript{TM} (Integrated kurtosis-based algorithm for Z-filter) technique. Some researchers investigated whole body vibration for driving and transportation were used I-kaz3D. This technique based on the signal statistical analysis approach of mean value, the standard deviation value, the root-mean-square \( (RMS) \) value, the
Kurtosis \((K)\) and the crest factor \((CF)\). The standard deviation values measures the spread of the data about the mean value. The RMS value, which is the 2\textsuperscript{nd} statistical moment is used to quantify the overall energy content of the signals. The kurtosis, \(K\) which is the fourth order statistical moment of signals, is highly sensitive to the spikiness of the data scattering about its mean. The crest factor which is commonly encountered in engineering applications is defined as ratio between the maximum value in the time domain and RMS value. On the other hand, the I-kaz3D technique provides a 3D graphical representation using the scattering of variance data distribution X-, Y- and Z-axes respectively. A tri-axial accelerometer for vibration signals measurement was also provided data of channels X-axis, Y-axis and Z-axis for radial force, cutting force and feed force respectively. The radial force that tends to push the tool away from the workpiece being machined, the cutting forces that forces acting on a cutting tool in turning and the thrust or feed force that in the direction of feed. For a discrete data set the RMS, Kurtosis and crest factor values are defined as:

\[
\text{RMS} = \sqrt{\frac{1}{N} \sum_{j=1}^{N} x^2_j} \tag{1} \\
K = \frac{1}{N(\text{RMS})} \sum_{j=1}^{N} (x_j - \mu)^4 \tag{2} \\
\text{CF} = \frac{x_{\text{max}}}{\text{RMS}} \tag{3}
\]

The variance, \(\sigma^2\) obtains the average magnitude deviation, \((x_i - \mu)\) of the instantaneous points, \(x_i\) with respect to the mean value, \(\mu\) as follows:

\[
\sigma^2_x = \frac{\sum_{i=1}^{N} (x_{i,x} - \mu_X)^2}{N}, \quad \sigma^2_y = \frac{\sum_{i=1}^{N} (x_{i,y} - \mu_Y)^2}{N}, \quad \sigma^2_z = \frac{\sum_{i=1}^{N} (x_{i,z} - \mu_Z)^2}{N} \tag{4}
\]

where \(\sigma^2_x\), \(\sigma^2_y\) and \(\sigma^2_z\) are the variances, \(x_{i,x}\), \(x_{i,y}\) and \(x_{i,z}\) are data for \(i\)-sample of time, and \(\mu_X\), \(\mu_Y\) and \(\mu_Z\) are the means of each frequency band in the X-, Y- and Z-axes respectively, and \(N\) is the number of data points. From equation (1), the sum of the root-mean square variance can be expressed as the sum of the intensities, each of which influences the RMS variance is known as I-kaz3D coefficient, \(Z_{3D_x}\) can be written as:

\[
Z_{3D_x} = \sqrt{\sigma_x^4 + \sigma_y^4 + \sigma_z^4} \tag{5}
\]

\[
Z_{3D_x} = \sqrt{\frac{\sum_{i=1}^{N} (x_{i,x} - \mu_X)^4}{N^2} + \frac{\sum_{i=1}^{N} (x_{i,y} - \mu_Y)^4}{N^2} + \frac{\sum_{i=1}^{N} (x_{i,z} - \mu_Z)^4}{N^2}} \tag{6}
\]

Equation (6) can be simplified as:

\[
Z_{3D_x} = \sqrt{K_x s_x^4 + K_y s_y^4 + K_z s_z^4} \tag{7} \\
\]

Equations (1), (2), (3) and (4) are considered in terms of the sum of RMS of the Kurtosis, \(K\) and the standard deviation, \(s\) for each number of the measured signal data, where, \(K_x\), \(K_y\) and \(K_z\) are the kurtosis of the vibration signals and \(s_x^2\), \(s_y^2\) and \(s_z^2\) are the standard deviation in X-, Y- and Z-axes respectively. Equation (5) is used for displaying the scattering of statistical signal analysis using I-kaz\textsuperscript{TM} technique in three-dimensional graphical representation. Meanwhile, equation (6) is used to measure I-kaz3D coefficient, \(Z_{3D_x}\) of the vibration signals. The data were processed using MATLAB.

3. Results and Discussion
As shown in Figures 2 to 6, the time domain from the five tests were analysed to access the fast Fourier transform (FFT), power spectral density (PSD), kurtosis, crest factor and I-kaz3D. All force signals from the time responses having different amplitude consist of the thrust, cutting and feed forces. In time domain, the cutting force for run 2 as shown in Figure 3 was highest amplitude, 2.45 g compared than other experiment runs. The purpose of the FFT was used is to find the frequency components of a signal buried in a noisy time domain signal. The highest amplitude 0.2 g for FFT was presented in Run 1 as shown in Figure 2. Meanwhile, the purpose of the PSD is to show the strength of the variation energy as a function of frequency from the experiment.

Figure 2. Force signals, FFT and PSD for radial, cutting and feed forces for Run 1

Figure 3. Force signals, FFT and PSD for radial, cutting and feed forces for Run 2
Figure 4. Force signals, FFT and PSD for radial, cutting and feed forces for Run 3

Figure 5. Force signals, FFT and PSD for radial, cutting and feed forces for Run 4
In PSD result, the vibration signals for run1 was produced the strong peaks as shown in Figure 2 compare to other experiment runs. The results for statistical analysis are shown in Table 2. Kurtosis and crest factor were measured for X-, Y- and Z-directions, then the average of the Kurtosis and crest factor were calculated. For kurtosis, the minimum and maximum values were 2.9173 and 3.018, and for crest factor the minimum and maximum values were 3.473 and 4.508. The different between kurtosis and crest factor are too small, therefore the relationship to vibration signals very difficult to predict and not suitable to be used for stability analysis based on the surface roughness measurement. I-kaz3D technique shows a significant difference between I-kaz3D coefficients and surface roughness, \( R_a \) as shown in Table 2. The minimum and maximum values of the I-kaz3D coefficients were \( 3.6748 \times 10^{-5} \) and \( 27.620 \times 10^{-5} \), and surface roughness were \( 0.669 \) µm and \( 6.203 \) µm. Higher I-kaz3D coefficients will have higher surface roughness values. Figure 7 shows the three-dimensional graphical representation of the I-kaz3D technique for X-, Y- and Z-directions. It is noted that the I-kaz3D coefficient relation decreases with decrease of the surface roughness measurement. This can be summarized that the significance of the I-kaz3D effect which may increase or decrease regenerative vibration stability.

![Figure 6. Force signals, FFT and PSD for radial, cutting and feed forces for Run 5](image)

Table 2. Results for signal statistical analysis, I-kaz3D and surface roughness

| Test run | Kurtosis | Crest factor | \( Z_{ID} \) (10^-5) | \( R_a \) (µm) |
|----------|----------|--------------|----------------------|---------------|
| run | \( K_x \) | \( K_y \) | \( K_z \) | \( K_{ave} \) | \( CF_x \) | \( CF_y \) | \( CF_z \) | \( CF_{ave} \) | \( 27.620 \) | \( 6.203 \) | \( 5.7811 \) | \( 1.832 \) | \( 5.6022 \) | \( 1.215 \) | \( 3.6748 \) | \( 0.669 \) |
| 1 | 2.814 | 2.864 | 3.241 | 2.973 | 3.421 | 3.429 | 3.568 | 3.473 | 27.620 | 6.203 |
| 2 | 2.993 | 3.050 | 2.956 | 3.000 | 3.722 | 3.845 | 4.111 | 3.893 | 5.7811 | 1.832 |
| 3 | 3.000 | 2.996 | 2.964 | 2.987 | 4.589 | 4.236 | 4.095 | 4.307 | 5.6022 | 1.215 |
| 4 | 3.054 | 2.948 | 3.051 | 3.018 | 5.071 | 3.846 | 4.606 | 4.508 | 3.6748 | 0.669 |
| 5 | 2.977 | 3.009 | 2.986 | 2.991 | 3.789 | 4.273 | 3.951 | 4.004 | 4.6874 | 0.771 |
4. Conclusions
This paper presented regenerative vibration signals from turning process with cutting, feed and thrust forces. We find that the I-kaz3D technique is suitable for stability analysis in the turning process with surface roughness values monitoring. It is concluded that the relationship between I-kaz3D coefficients and surface roughness values is considered to be good correlation.

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