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A Comparative Study of I-kaz Based Signal Analysis Techniques: Application to Detect Tool Wear during Turning Process

Muhammad Rizal[a,b], Jaharah A. Ghani[a*], Mohd Zaki Nuawi[a], Mohamad Amir Shafiq Mohd Tahir[a], Che Hassan Che Haron[a]

[a]*Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia*
[b]*Department of Mechanical Engineering, Faculty of Engineering, Syiah Kuala University, 23111 Darussalam, Banda Aceh, Indonesia*

*Corresponding author: jaharah@eng.ukm.my; muh.rizal@unsyiah.ac.id

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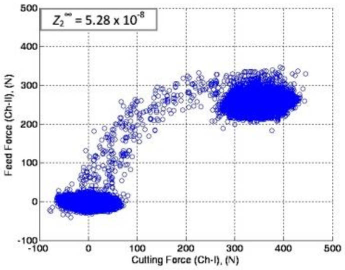
Graphical abstract



Abstract

Detection of tool wear during in-progress machining process is a significant requirement to assure the quality of machined parts that helps to improve the productivity. The cutting force is one of the signals in machining process that has been widely used for tool wear monitoring. In the present paper three derived I-kaz^{TM} based methods explained and compared for monitoring tool wear changes during turning process. The aim of this work is to study the performance of I-kaz^{TM}, I-kaz 2D and I-kaz Multilevel techniques to detect flank wear width using the cutting force signal. The experiments were carried out by turning hardened carbon steel, and cutting force signals were measured by two channels of strain gauges that were mounted on the surface of tool holder. The analysis of results using I-kaz 2D, I-kaz^{TM} and also I-kaz Multilevel methods, revealed that all methods can applied to determine tool wear progression during turning process and feed force signal change is very significant due to flank wear.

Keywords: Tool wear detection; I-kaz method; cutting force; turning process

Abstrak

Pengesanan haus mata alat semasa proses pemesinan dijalankan adalah satu keperluan penting untuk memastikan kualiti bahagian dimesin yang boleh membantu untuk meningkatkan produktiviti. Daya pemotongan adalah salah satu isyarat dalam proses pemesinan yang telah digunakan secara meluas untuk memantau haus mata alat. Dalam pembentangan kertas kerja ini, terdapat tiga teknik yang berasaskan kaedah I-kaz yang dijelaskan dan dibandingkan dalam penggunaannya pada pemantauan perubahan mata alat semasa proses larik. Tujuan utama kerja ini adalah untuk mengkaji prestasi I-kaz^{TM}, I-kaz 2D dan teknik I-kaz berbilang aras untuk mengesan lebar haus rusuk menggunakan isyarat daya pemotongan. Kajian ini telah dijalankan dengan melarik keluli karbon keras dan isyarat daya pemotongan diukur dengan dua saluran tolok terikan yang dipasang pada permukaan pemegang alat. Analisis keputusan menggunakan keadah I-kaz 2D, I-kaz^{TM} dan I-kaz berbilang aras, memperlihatkan bahawa semua kaedah boleh digunakan untuk menentukan perkembangan haus mata alat semasa proses larik dan perubahan isyarat daya suapan adalah sangat bererti akibat haus rusuk.

Kata kunci: Pengesanan haus mata alat; kaedah I-kaz; daya pemotongan; proses larik.

■1.0 INTRODUCTION

Tool wear monitoring is important work in machining industries to improve the productivity. Tool wear is gradual failure due to rubbing action between tool and workpiece during machining operation. The worn tool can deteriorate the quality of machined part, increase the production time and cost, and even cause machine breakdown if the cutting tool suddenly brakes. To avoid catastrophic tool failure during machining run, the progression of cutting tool wear from the start of the cutting process should be monitored by online measurement of the machining signals. The cutting force signal is very suitable to be used as a reference for indirect measurement and monitoring of tool wear because of the cutting force increase due to tool wear. Among the indirect online tool wear monitoring methods, cutting force is one of the most commonly used variable as a tool wear indicator [1].

The cutting force signal that is generated from metal cutting process consist several features were extracted from time domain and frequency domain. There are several features that can be extracted from any time domain signal, including the average value, standard deviation, variance, skewness, kurtosis and root mean square (rms), etc. [1-2]. Whereas a signal can be also transformed into a frequency or time–frequency domain (fast Fourier transform, wavelet transform, etc.). In the previous study, numerous signal features of cutting force signals have been described by various researchers. Jemielniak *et al*. [3] used the average and standard deviations values of cutting forces to diagnose the tool wear. They reported that there is a conspicuous relation between tool wear and standard deviation of feed force. Dimla and Lister [1] analyzed static and dynamic cutting force in time and frequency domains. They concluded that the static force was the most sensitive indicator to cutting condition changes such as depth of cut and feed rate. While in the frequency domains, the amplitude of the signal is found to increase monotonically with tool wear and falls sharply prior to the point of entry into the tertiary wear zone. Das *et al*. [4] used cutting force average and analyzed using force ratio for tool wear estimation. They reported that the increasing of force ratio (F_y/F_x) with the progress of tool wear is evident. Chungchoo and Saini [5] applied skewness and kurtosis of force distribution in fixed frequency band. It is reported that the frequency distribution pattern of force signals is influenced by cutting conditions and tool wear. The cutting forces signals have characteristics that can be extracted in both time and frequency domain.

However, aforementioned studies arenot of those explaining the methods that based on comparison of I-kaz performance for detection tool wear.But, actually the case is the I-kaz^{TM} method has been used widely in various study such as to analyze strain signal for fatigue life evaluation [6], to analyze sound signals for sliding wear monitoring of commercial bearing [7], to analyze ultrasound signals for tool life monitoring [8], to detects mechanical property of material using I-kaz Multilevel [9], and also for tool wear monitoring by analyzing the cutting force signals in three channels using I-kaz 3D [10], and two channels using I-kaz 2D [11-13]. In order to investigation the significant techniques of I-kaz based methods to detect the progression of tool wear, then it is needed to study some signal analysis techniques based on I-kaz method.

In this present paper the I-kaz^{TM}, I-kaz 2D and I-kaz Multilevel techniques are deployed to interpret the cutting force signal for detection the tool wear progression during turning process. The focus is on the assessment of these methods via relationship between coefficient values of their techniques and tool wear progression then compared the performance results. The coefficient values including the I-kaz coefficient of main cutting force (Z_{Fc}^{∞}), feed force (Z_{Ff}^{∞}), I-kaz 2D coefficient (Z_2^{∞}) and I-kaz Multilevel coefficient ($^{7}Z^{\infty}$). The advantages of I-kaz^{TM} method are the characteristic of signals can be obtained in time and frequency domain and its sensitive to amplitude and frequency changes [14].

■2.0 I-KAZ BASED METHODS

The I-kaz^{TM} method was developed based on the concept of data scattering about the data centroid and classified the display according to inferential statistics. The I-kaz^{TM} method is used to model the data patterns, which accounts for the randomness and draws inferences from a larger population. These inferences are very useful for estimating and forecasting future observations.[14] The main idea of the I-kaz^{TM} method is decompose a dynamic signal into three frequency ranges including a low-frequency (LF) range of 0-0.25 f_{max}, a high-frequency (HF) range of 0.25 f_{max}– 0.5 f_{max} and a very high-frequency (VF) range of 0.5 f_{max}. In order to measure the scattering of the data distribution, the variance σ^2 for each frequency band is calculated, as shown in Equation (1). The variance determines the average magnitude deviation of instantaneous points with respect to the mean value.

$$\sigma_L^2 = \frac{\sum_{i=1}^{N}\left(x_i^L - \mu_L\right)^2}{N};\quad \sigma_H^2 = \frac{\sum_{i=1}^{N}\left(x_i^H - \mu_H\right)^2}{N};\quad \sigma_V^2 = \frac{\sum_{i=1}^{N}\left(x_i^V - \mu_V\right)^2}{N}; \tag{1}$$

Where σ_L^2, σ_H^2, σ_V^2 and x_i^L, x_i^H, x_i^V are the variances and data for the *i*-sample of time in the *LF*, *HF* and *VF* range, respectively. Whereas μ_L, μ_H and μ_V are the means of each frequency bands, and *N* is the number of data points. Since the I-kaz^{TM} method was developed based on the concept of data scattering about the data centroid and classified the display according to inferential statistics, the I-kaz coefficient can be symbolized by Z^{∞} and written in terms of the variance, σ^2, as shown in Equation (2) and Equation (3).

$$Z^{\infty} = \sqrt{\left(\sigma_L^2\right)^2 + \left(\sigma_H^2\right)^2 + \left(\sigma_V^2\right)^2} \tag{2}$$

$$Z^{\infty} = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i^L - \mu_L\right)^2}{N^2} + \frac{\sum_{i=1}^{N}\left(x_i^H - \mu_H\right)^2}{N^2} + \frac{\sum_{i=1}^{N}\left(x_i^V - \mu_V\right)^2}{N^2}} \tag{3}$$

Equation (3) can be simplified in terms of the kurtosis and standard deviation. The kurtosis, *K*, is the signal's 4th statistical moment, which is the global signal statistic and is highly sensitive to the spikiness of the data. The Gaussian distribution of the kurtosis value is approximately 3.0. A higher kurtosis value indicates the presence of more extreme values than should be normally found in a Gaussian distribution. The kurtosis can be defined as:

$$K = \frac{1}{Ns^4}\sum_{i=1}^{N}\left(x_i - \mu\right)^4 \tag{4}$$

Where *N* is the number of data, *s* is the standard deviation. Therefore, Equation (2) can be written in terms of the kurtosis, *K*, and the standard deviation, *s*, as:

$$Z^{\infty} = \frac{1}{N}\sqrt{K_L s_L^4 + K_H s_H^4 + K_V s_V^4} \tag{5}$$

Where K_L, K_H, and K_V are the kurtosis of the signal in the LF, HF and VF ranges, and s_L, s_H, s_V are the standard deviations of signal in the LF, HF and VF ranges, respectively.

The I-kaz 2D derived from I-kaz^{TM} method, which analyzed signals from two channels or two sensors. It differs from the I-kaz^{TM} method, whereby the signal does not need to be decomposed to three different frequency ranges. But, each signal is computed directly by using kurtosis and standard deviation. Therefore, the I-kaz 2D coefficient can be symbolized by Z_2^{∞} and written as following:

$$Z_2^{\infty} = \frac{1}{N}\sqrt{K_I s_I^4 + K_{II} s_{II}^4} \tag{6}$$

Where *N* is the number of data points, K_I and K_{II} are the kurtosis of signal in channel I and channel II, and s_I and s_{II} are the standard deviation of signal in channel I and channel II respectively.

The I-kaz Multilevel coefficient ($^{L}Z^{\infty}$) was also derived from I-kaz^{TM} method, in which *L* is referring to the number of frequency bands in the signal decomposition ranges. The frequency ranges of F_1, F_2, to F_L of frequency maximum of the signals. The related I-kaz Multilevel coefficient can be calculated as:

$$ {}^{L}Z^{\infty} = \frac{1}{N}\sqrt{K_1 s_1^4 + K_2 s_2^4 + K_3 s_3^4 \ldots + K_L s_L^4} \quad (7) $$

■3.0 EXPERIMENTAL

The machining tests were performed on a CNC Colchester Master Tornado T4 lathe machine under dry cutting conditions. An orthogonal insert was used in the experiments for machining of a hardened JIS S45C carbon steel bar. This material is suitable for a wide variety of automotive-type applications, including axles, connecting rods and shafts [13]. The Brinell hardness after the tempering process was 248 HB, and the tensile strength was in the range of 570-700 MPa. The composition of this material is shown in Table 1. The dimensions were 200 mm in length and 85 mm in diameter. The tool insert used was a coated carbide insert (Toolmex CNMG120404-MB) with NC30P grade 5. The tool had a rhombic 80º shape, 4.76 mm thickness and a 0.4 mm nose radius. The complete illustration of experimental set up is shown in Figure 1.

The experiment conducted in this study was deployed by using low cost sensors which consist of two strain gauges as shown in Figure 1. The data acquisition system consists of a signal conditioner (OM2-163 and OM2-8608-230AC), a data acquisition device (DT9836) and MATLAB software. A simple tool holder (PDJNR2020-43) that has a sectional shape of 20 x 20 mm was used for mounting the strain gauges on the top and the left side of the tool holder to measure the cutting forces due to the deflection in both the tangential direction, F_c (main cutting force) and feed direction, F_f (feed force). The distance of strain gauge to the tip of tool insert was fixed at about 43 mm as optimum location [15]. The sensor configuration used a quarter-bridge strain gauge set in the signal conditioning device. The cutting force signals were collected at sampling rate of 1 kHz, and then analyzed by the computer using signal analysis based on the I-kaz^{TM}, I-kaz 2D and I-kaz Multilevel methods.

The experiment test in this study was conducted cutting speed equal to 200 m/min, feed rate equal to 0.20 mm/rev, and depth of cut equal to 1.2 mm. This cutting condition was selected based on the real turning operation of hardened carbon steel carried out in one of the local automotive industries. During the turning operation, the insert was periodically removed from the tool holder, and the flank wear on the flank face was measured using a Mitutoyo toolmaker's microscope. The measured parameter to represent the progress of wear was the average flank wear land, *VB*. The flank wear data were recorded since the first cutting pass until the flank wear reached 0.3 mm. It is a standard recommended value in defining a tool life end-point criterion based on ISO 3685-1993.

Table 1 Composition of hardened carbon steel JIS S45C [16]

Element percentage(%)									
C	Si	Mn	P	S	Cu	Ni	Cr	Al	Fe
0.44	0.23	0.75	0.010	0.014	0.10	0.04	0.08	0.023	Bal.

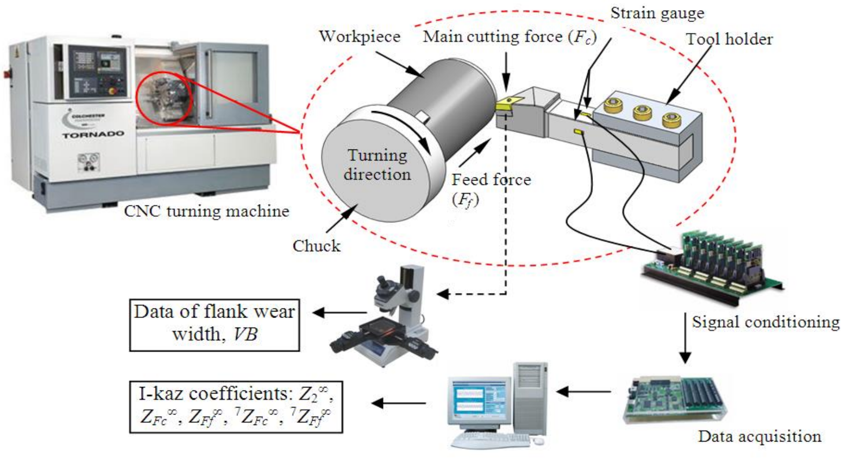


Figure 1 Illustration of experimental setup

■4.0 RESULTS AND DISCUSSION

The cutting force signal from turning process can be extracted to time and frequency domain. The changes of tool wear during cutting process cause amplitude and frequency of signals increases. The measured force signals from initial first cutting until end of cutting are recorded as shown in Figure 2. Noise in the cutting force signal is due to non-homogeneity of the tool and the workpiece materials, vibrations from various sources, measurement errors and other unaccounted factors [17]. It was observed that the changes of tool wear followed by changes of the cutting force signal. From the signals display, the main cutting force (F_c) is greater than the feed force (F_f) during the turning process. But, the feed force rapidly increases than cutting force as flank wear increases. This is possibly due to the rubbing friction on the flank surface that contributes to more feed force. The present findings are similar with previous researcher's findings [5]. The effect of friction on the surface of the flank face is clearly visible as shown in Figure 2. The several recorded cutting force signals are shown in Figure 3. It can be observed that flank wear about 0.102 mm, the average cutting force is 310 N. After cutting about 17 minutes or flank wear = 0.306 mm, the average cutting force increases to 357 N or 13.16%. Meanwhile, the average feed force at the initial first cutting is only 158 N, and at the end of cutting it increases to about 285 N or 44.56%.

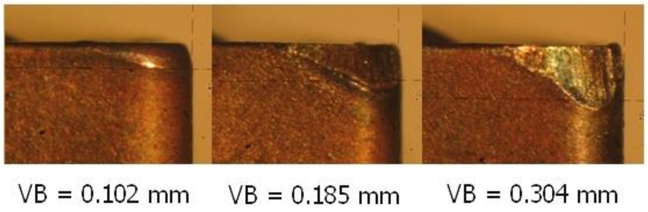
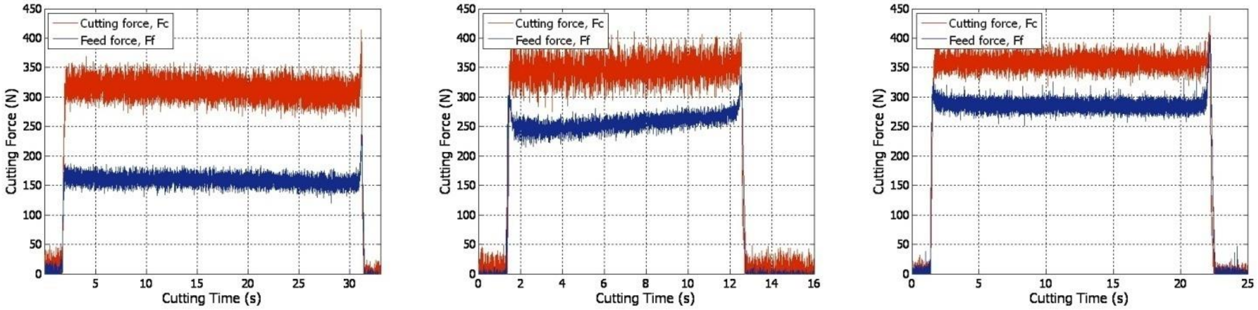


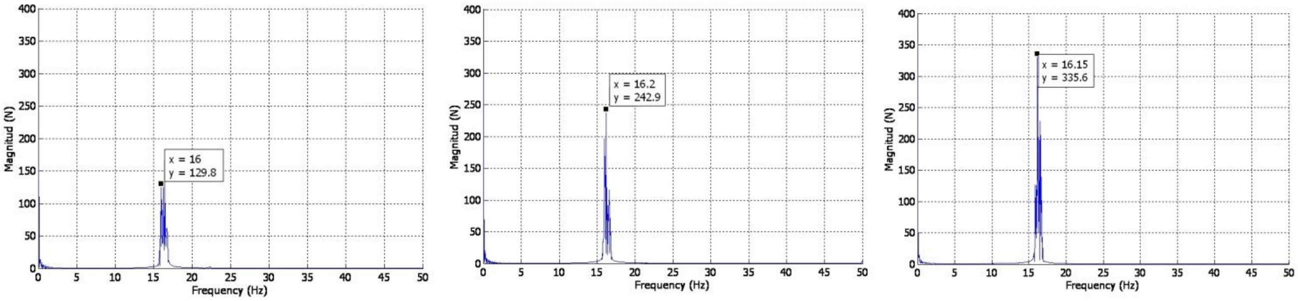
Figure 2 Progression of flank wear during cutting

Besides that, frequency analysis involved performing a forward FFT on the cutting force signal, and the results interpreted through spectra plot as shown in Figure 4. It appears that the harmonics of the tool passing cutting frequency was about 16 Hz. Where, in our study the spindle rotation was 1000 rpm. The increase in amplitude of the peak frequencies with increasing tool wear was more obvious at the frequencies of 16.15 Hz by over two times more than the first cutting or when using a sharp tool. It is clear that the amplitude of frequency increases steadily with increasing tool wear. Thus, the change of flank wear during turning process can be detected clearly by analysis both in time domain and frequency domain.



(a) (b)(c)

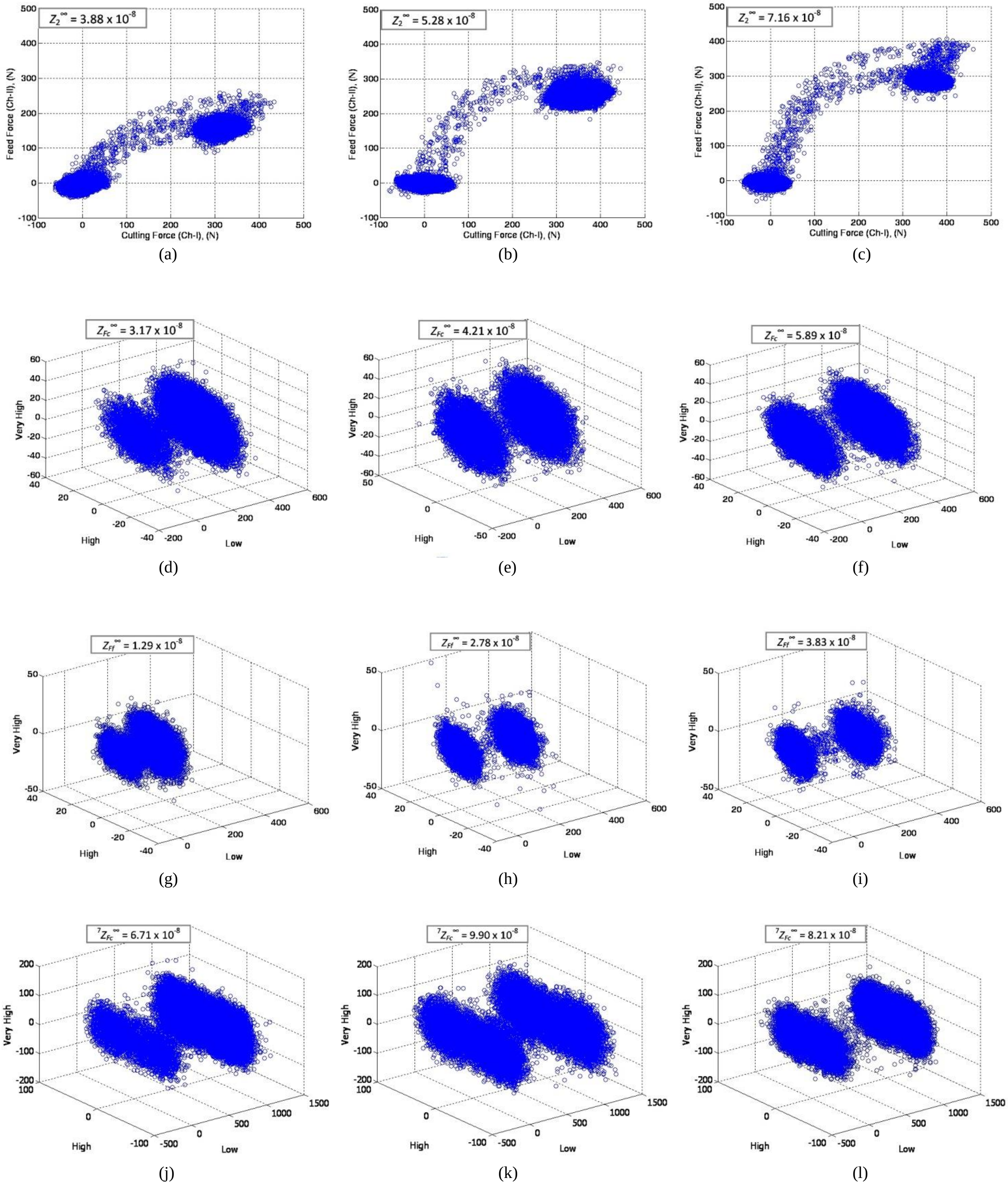
Figure 3 Time domain plot of the cutting forces during turning process: (a)at flank wear = 0.102 mm, (b) at flank wear = 0.185 mm, and (c) at end of cutting, flank wear = 0.306 mm



(a) (b) (c)

Figure 4 Frequency domain plot of the cutting forces during turning process: (a) at flank wear = 0.102 mm, (b) at flank wear = 0.185 mm, and (c) at end of cutting, flank wear = 0.306 mm

The results of the I-kaz based analysis of the force signals along the cutting process, i.e. sharp tool or flank wear is 0.102 mm, intermediate sharp (flank wear = 0.185 mm), and worn tool or the end cutting (flank wear = 0.306 mm) in turning process are shown in Figure 5. The raw signals from machining are directly calculated using the Equation (5) and Equation (6). Figure 5(a), 5(b), 5(c) show the plots of I-kaz 2D in two dimensional graphical representations of amplitude scattering for main cutting force and feed force signals. It can be observed that the changes of data scattering are very significant due to progression of flank wear. Figure 5(d), 5(e), 5(f), and 5(g), 5(h), 5(i) show the results of the I-kaz analysis plots for each channel i.e. main cutting force and feed force signals. Prior to plotting in three axis representations, the signals are decomposed into three frequency ranges. The results visually show that the space of scattering in both main cutting force and feed force are increased due to progression of flank wear. But, the feed force increases prominently and more apparent than the main cutting force. Whereas the I-kaz Multilevel displays graphical representations are similar to I-kaz^{TM} plot that is in three dimension of frequency range. The effect of progression of flank wear can also seen by changes of I-kaz coefficient as shown in Figure 6.

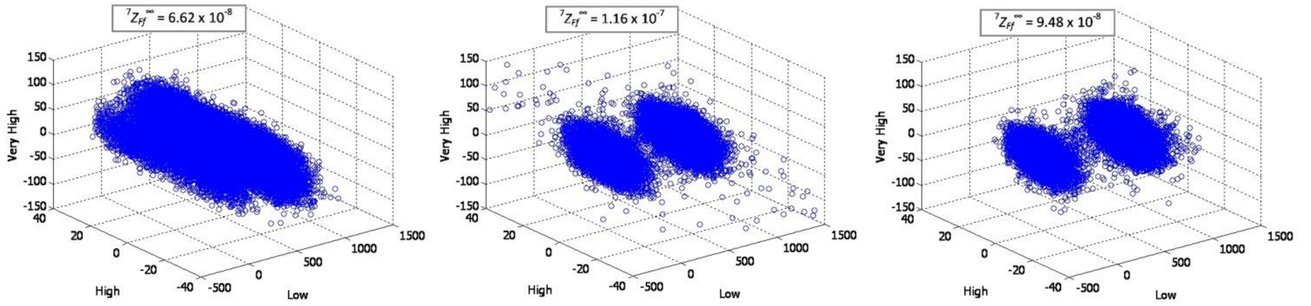


(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

(j) (k) (l)



(m) (n) (o)

Figure 5 I-kaz display of graphical representations for cutting force during turning process from the sharp tool (*VB* = 0.102 mm), middle cutting or still sharp tool (*VB* = 0.185 mm), and worn tool or the end cutting (*VB* = 0.306); (a), (b), (c)are I-kaz 2D display; (d), (e), (f)are I-kaz three dimensional of main cutting force;(g), (h), (i)are I-kaz three dimensional of feed force; (j), (k), (l)are I-kaz multilevel display of main cutting force; and (m), (n), (o)are I-kaz multilevel display of main cutting force

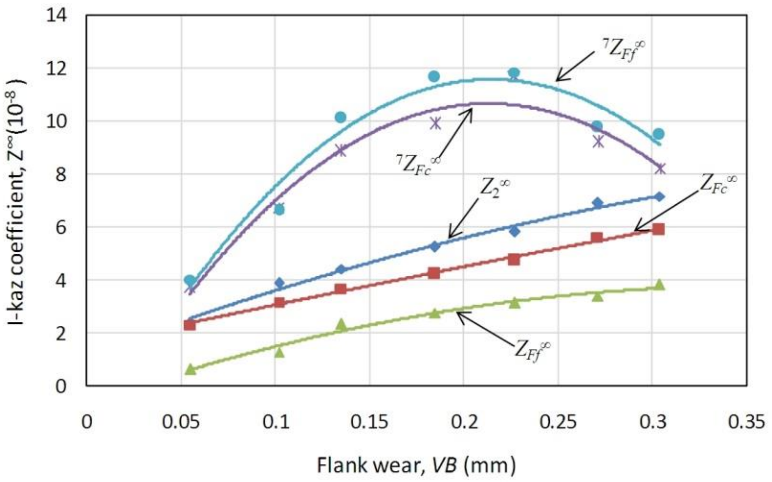


Figure 6 Correlation of tool wear and I-kaz coefficients

An interesting correlation between I-kaz coefficients and tool wear progression is shown in Figure 6. It can be seen that the increasing in flank wear value causes the I-kaz coefficient values to increase. As a percentage of increases, we have determined the average slope of the curve of correlation tool wear and I-kaz coefficients. The results show that the increase coefficients of I-kazin feed force has the biggest percentage of about 69.58%, followed by I-kaz 2D coefficient of about 37.52%, and the lowest is I-kaz coefficient in cutting force of about 28.64%. But, the increase in the values of I-kaz Multilevel to changes of flank wear is not straight. It formed a parabolic curve that has peaks when flank wear reached was 0.2 mm. It can be indicated that amplitude frequency of cutting force signal when flank wear formed is decreasing beyond tool pass frequency range, meanwhile the I-kaz Multilevel calculate all levels of frequency decomposition in range of Nyquist frequency [8]. This phenomenon can be interpreted that the I-kaz Multilevel less suitable for studying low frequency signal such as cutting force signal, and very suitable for analysis high frequency such as vibration signal [9]. Increasing of I-kaz coefficients in all cases from this study is similar with earlier findings that I-kaz coefficient increases due to changes in signals amplitude and frequency of the cutting forces [8, 14]. By comparing these three techniques, the highest increasing is I-kazcoefficient in feed force. But, the flank wear can also be determined by visualization of I-kaz representation, and the I-kaz 2D display of graphical representations is more significant than other displays. Therefore, I-kaz 2D, I-kaz$^{\text{TM}}$ and also I-kaz Multilevel methods can applied to determine tool wear progression during turning process.But, suitability to detect tool wear depends on the type of signal are used. It can be utilized to be the parameters for monitoring of tool wear by using threshold values on certain cutting condition.

4.0 CONCLUSION

I-kaz$^{\text{TM}}$ methods and its derivation like I-kaz 2D and also I-kaz Multilevel are suitable to analyze force signals in turning process for tool wear monitoring. It provides a multi-resolution analysis which can be used in both coefficient values and graphical display representations. These results reveal that feed force is very significant due to flank wear change during cutting, and I-kaz 2D is suitable to detect tool wear change based on cutting force signal using coefficient value and also visualization of I-kaz representation. Whereas, the I-kaz Multilevel is less suitable to analyze the cutting force signal during turning process due to its low frequency.

Nomenclature

K	kurtosis
N	number of data
s	standard deviation
x_i	data for *i*-sample
VB	flank wear width (mm)
Z_2^∞	I-kaz2D coefficient in two integrated channels of signal
Z_{Fc}^∞	I-kaz coefficient in main cutting force
Z_{Ff}^∞	I-kaz coefficient in feed force
$^7Z_{Fc}^\infty$	I-kazmultilevel 7th order coefficient in main cutting force
$^7Z_{Ff}^\infty$	I-kazmultilevel 7th order coefficient in feed force
σ_L	variance of data of low frequency
σ_H	variance of data of high frequency
σ_V	variance of data of very high frequency

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