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Statistical investigation for cutting force and surface roughness of S45C steel in turning processes by I-kaz^{TM} method

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Abstract. This paper presents a statistical analysis to investigatethe correlation between cutting forces and surface roughness values in turning process. Although the correlation of machining processes has been widely studied in metal cutting, it still presents a challenge as surface roughness has to be considered for product quality and it is hard to ensure that this requirement will be achieved. The paper also presents a statistical analysis of signal processing from the force signal in time domain. The cutting force was measured during machining using Kistler 9129AA dynamometer to monitor the force signals and the data was analysed using statistical methods such as skewness, kurtosis and I-kaz^{TM} method. The statistical methods were used to data analysis to assess the effect of force signals during the machining process. The results show that the relationship between I-kaz coefficients (Z^{∞}) from the I-kaz^{TM} method and surface roughness values (*Ra* and *Rz*) can be considered very highly correlated.

Keywords: statistical analysis, CNC turning, I-kaz^{TM} method, signal processing, skewness, kurtosis

1.Introduction

Metal cutting processes involve structural dynamic behaviour during the machining operation, which in turn influences any material cutting to be produced a part of the required shape and dimensions with the specified quality and surface finish. A variety of process parameters in basic machining process provides cutting parameters in turning with the application of statistical methods. Statistics is a mathematical science of collecting analysing, interpreting or describing and presenting information. In a wide range of industries, statistical methods are used to help researchers identify, analyse and solve a number of complex problems. These approaches enable decision-makers to make the right decisions on complexity processes through engineering applications.In the analysis of data, statistical methods have a very important role to play throughout evaluating the perception of output in making predictions and inferences. Nuawi et al. (2017) developed an alternative statistical analysis known asan integrated kurtosis-based algorithm for Z-filter (I-kaz^{TM}) method for calculating the degree of data centroid scattering for dynamic signal analysis. They used statistical parameters such as average, variance, root mean square and kurtosis to investigate dynamic variations in the processes of

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machining[1]. Georgiou and Voigt (2015) stated that the statistical moments and related quantities such as mean, variance, skewness and kurtosis are important in pattern recognition, neutral networks, signal processing and related fields but they do not seem to have computed stochastically as weights in a gradient descent process[2]. Statistical analysis approaches were extensively used in machining for finding out the significant of cutting conditions and parameters based on the modelling, prediction and optimization. Samin (2019) carried out kurtosis, crest factor and I-kaz 3D coefficient for surface roughness value (*Ra*) in turning process[3]. Zhou and Xue (2018) classified the nine time domain statistical parameters and eight frequency domain statistical parameters for tool condition monitoring in milling by a multisensory fusion method [4]. The objective of this paper is to investigate the correlation between statistical parameters (skewness, kurtosis and I-kaz^{TM} method) and surface roughness values (*Ra* and *Rz*), and then to evaluate the relationship of the feature extraction in signal processing between force signals and I-kaz coefficient with 3D graph representation.

2. Methodology

2.1 Experimental Setup

In this paper, the workpiece was used a medium carbon steel S45C with a diameter of 75 mm and length of 250 mm. The experiment was performed on the turning process using a computer numerical control (CNC) lathe machine (Mazak SQT 200MY) for performing the machining operation. The cutting tool materials were selected based on the workpiece materials to be cut. Based on the recommendations of the cutting tool manual and the cutting manual, cutting tool inserts of coated carbide were used for turning of mild steel S45C material. Table 1 shows that the cutting parameters in this experiment is 166 to 334 m/min for cutting speed, 0.50 to 1.84 mm for the depth of cut and 0.10 to 0.23 mm/rev for the feed rate. The machine tool was used the tool holder type ECLNR-2020K12 carbide by Chain designed with ISO 9001:2015 to hold the CVD-coated carbide insert type CNMG12044N-GU AC2000 by Sumitomo. This paper uses the arithmetic average of the roughness profile, *Ra* and mean depth of profile surface roughness, *Rz* values. On the machined workpiece, the surface roughness, *Ra* and *Rz* were measured using the MarSurf PS1 gauge. The *Ra* and *Rz* values are the commonly used roughness parameter and most appropriate for observing the surface quality of the machining processes [5][6][7][3]. A Kistler type 9129AA dynamometer was used to measure the cutting force and placed on the tool frame, measuring the force signals in the direction of feed (*Fx*), cutting and tangential to the moving workpiece (*Fy*) and in the direction of radial or thrust (*Fz*) as shown in Figure 1.

Table 1. Machining parameters in turning

Test run	Cutting speed, V_c (*m/min*)	Feed rate, f (mm /rev)	Depth of cut, d (mm)
1	250	0.15	1.84
2	200	0.10	1.50
3	200	0.10	0.50
4	250	0.07	1.00
5	334	0.15	1.00
6	250	0.23	1.00
7	250	0.15	1.00
8	166	0.15	1.00

2.2 Time Domain Statistical Parameters

In this paper, four statistical feature parameters related to the tool state from the time dimension of the sensor signal were extracted as candidate parameters, including two dimensional features such as the average value and the standard deviation and two dimensionless features such as the kurtosis factor and the skewness factors. The first central moment is the expectation value for average, which is the central location of a distribution as in equation (1). For the chosen workpiece and tool material combination, Wang et al. (2014) used average forces for *X* and *Y* directions [8]. The average value (μ) equation as in equation (1),

$$\mu = \mathrm{E}\left(\bar{x}\right) = \frac{\sum_{i=1}^{n} x_i}{n} \tag{1}$$

In practice it is estimated by the average or the mean deviation from the mean as in equation (2).

$$\bar{x} = \frac{\sum_{i=1}^{n}\left(x_i - \mu\right)}{n} \tag{2}$$

Since the first moment data is for mean, μ the second statistical moment is for variance and the standard deviation. The average deviation, $\left(x_i - \mu\right)$ is a more robust analysis tool of the width of the peak appearance. The variance of sample (*V*) as in equation (3) provides a measure of the data spread and it is frequently used interchangeably with its positive square root, defining the standard deviation (*sd*) as in equation (4).The sample size, *n* is used instead of (*n*- 1) due to the situation of measuring the variance of a distribution whose mean μ is known a priori rather than being estimated from the data.

$$V = \frac{\sum_{i=1}^{n}\left(x_i - \mu\right)^2}{n} \tag{3}$$

$$sd = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \mu\right)^2}{n}} \tag{4}$$

Equation 5 shows the third central moment, skewness (*S*) which identifies a distribution's degree of asymmetry around its mean. Wang et al. (2017) used skew, mean and kurtosis to assess surface roughness and used wavelet packet transform to extract surface texture [9]. They found that the mean, skewness and kurtosis values increased with the rise in noise, meaning that these statistical moments are influenced by noise much stronger than surface roughness values. The skewness (*SK*) is a non-dimensional quantity as in equation (5).

$$SK = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - \mu}{\sigma}\right)^3 \tag{5}$$

The fourth-order statistical moment is kurtosis (*K*). It measures the relative peakness or flatness of a distribution. Platykurtic is called flat-looking distributions, while peaked distributions are called leptokurtic distributions. In the I-kaz^{TM} method definition, the Gaussian distribution data for kurtosis is about 3.0 and the value of -3 has been ignored to create the zero value for the normal distribution as in equation (6). Higher kurtosis values show a Gaussian distribution with more extreme values. The Kurtosis as in equation (6) is also non-dimensional quantity and used in engineering to detect symptoms of fault owing to its sensitivity to elevated amplitude occurrences.

$$K = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - \mu}{\sigma}\right)^4 \tag{6}$$

Traditionally, sample data processes by root mean square and kurtosis were utilized as a measure of the impulsivity and energy of the signal for signal processing applications [10]. Joanes et al. (1998) stated that measures of skew and kurtosis are often utilized to describe the distribution shape. They found that with the larger sample sizes, the mean-square errors for skewness and kurtosis decreased, and with small sample sizes, error increased [11]. The study shows that the use of kurtosis is significant in the machining process because normally larger samples are used. Kurtosis is highly sensitive to raw data spikiness.

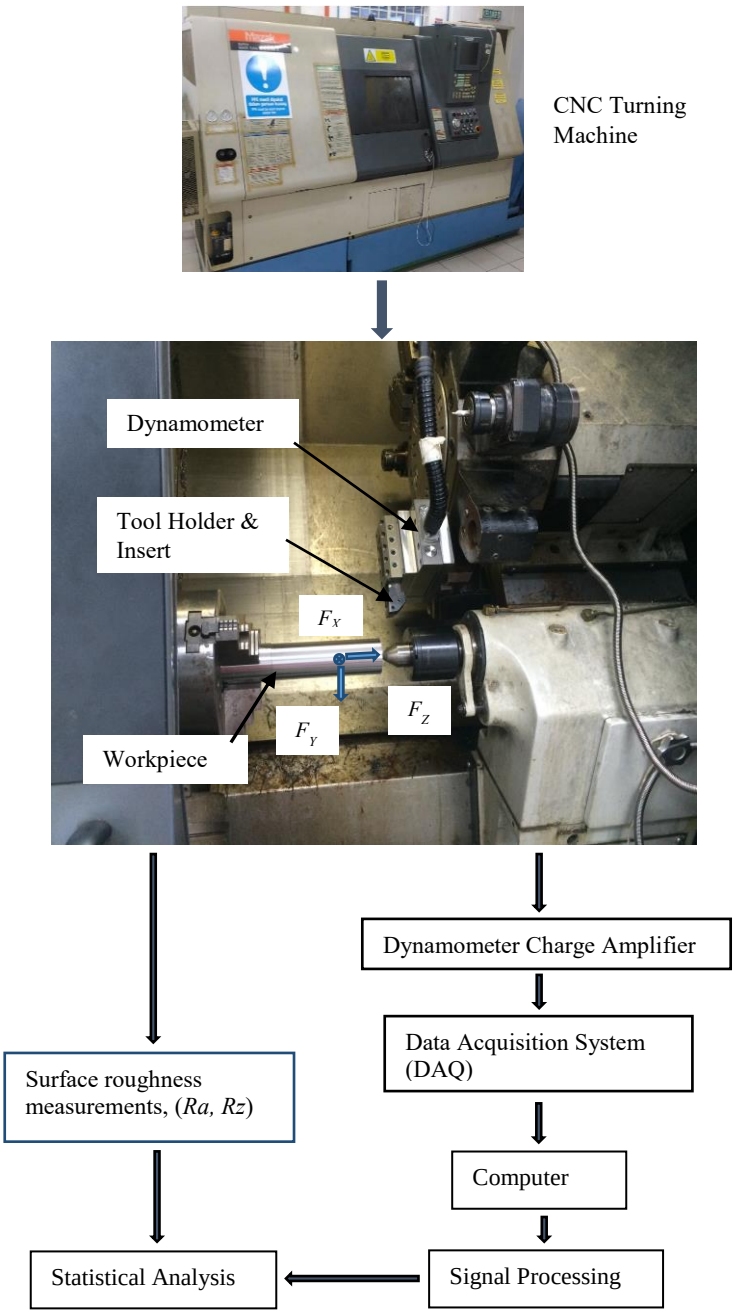

Figure 1. Experimental setup.

2.3Integrated kurtosis-based algorithm for Z-filter (I-kaz™)method

A statistical analysis approach, I-kaz™ is based on the fourth order statistical moment or kurtosis. In this paper, the statistical analysis method developed by Nuawi (2017) was used [1]. The method was an alternative statistical analysis for *Z*-filter. The integrated kurtosis-based algorithm was applied to evaluate the degree of dynamic signal analysis for scattering of the raw signal data with respect to the centroid. In this method the *Z*-notch filter was used due to the fact that the filter efficiently extracted the component of noise from the measured data of the machining signals [12]. The centroid is accessed by decomposition from the average position of all the points of the all data signal. The sample frequency of the raw signal needs to be properly selected in order to avoid aliasing effect. Most researchers were using 2.56 Nyquist number to decide the sampling frequency.Thenumber of samples refers to the quantity of individual measurements recorded. The sampling rateshould be *2.56* times greater than the highest frequency that the experiment want to measure; this is known as the Nyquist Frequency. Thus, the maximum frequency span as in equation (7).

$$f_{\max} = \frac{f_s}{2.56} \tag{7}$$

Where, $f_{\max}$ is maximum frequency span, f_s is the sampling frequency and 2.56 is the Nyquist number. The raw force signal of the time domain data is processed at three different frequency ranges as follows

Low Frequency (*LF*):

$$LF = 0 \rightarrow 0.25 f_{\max} \tag{8}$$

High Frequency (*HF*):

$$HF = 0.25 f_{\max} \rightarrow 0.5 f_{\max} \tag{9}$$

Very High (*VF*):

$$VF = 0.5 f_{\max} \rightarrow f_{\max} \tag{10}$$

For standard deviation (*sd*), the decomposition of the raw data resulted in three frequency ranges as in equations (8) to (10) that were assigned to three different axes, *x*, *y* and zin standard deviation equations as in equations (11) to (13).

$$sd_{LF} = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{LF,i} - u_{LF}\right)}{n}} \tag{11}$$

$$sd_{HF} = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{HF,i} - u_{HF}\right)}{n}} \tag{12}$$

$$sd_{VF} = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{VF,i} - u_{VF}\right)}{n}} \tag{13}$$

For kurtosis coefficient (*K*), the decomposition of the raw data resulted in three frequency ranges as in equations (8) to (10) that were assigned to three different axes, *x*, *y* and *z* in kurtosis equations as in equations (11) to (13).

$$K_{LF} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_{LF,i} - \mu_{LF}}{\sigma_{LF}}\right)^4 \tag{14}$$

$$K_{HF} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_{HF,i} - \mu_{HF}}{\sigma_{HF}}\right)^4 \tag{15}$$

$$K_{VF} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_{VF,i} - \mu_{VF}}{\sigma_{VF}}\right)^4 \tag{16}$$

Where sd_{LF}, sd_{HF} and sd_{VF} are the variances, $x_{LF,i}$, $x_{HF,i}$ and $x_{VF,i}$ are *i*–sample time of the mean data range, μ_{LF}, μ_{HF} and μ_{VF}, while *n* is the number of data points (samples). The I-kaz™method generates a graphical representation of three dimensions by scattering the signal decomposition for each frequency distribution, low, high and very high bands. The I-kaz coefficient ($Ƶ^{\infty}$) provides the mean deviation, (x_i-μ) between the immediate data, x_i and mean value, *u* for low, high and very high frequency bands as in equations (10).

2.4 I-kaz Coefficient ($Ƶ^{\infty}$)

The $Ƶ^{\infty}$ developed by Nuawi et al. (2008) was derived in term of the 4th order of moments with the kurtosis (*K*), standard deviation (*sd*) and number of data points (*n*).By combining equations (11) to (13) and (14) to (16) it is seen that,

$$Ƶ^{\infty} = \sqrt{\frac{\sum_{i}^{N}\left(x_{LF,,i} - u_{LF}\right)^4}{n^2} + \frac{\sum_{i}^{N}\left(x_{HF,,i} - u_{HF}\right)^4}{n^2} + \frac{\sum_{i}^{N}\left(x_{HF,,i} - u_{HF}\right)^4}{n^2}} \tag{17}$$

which $Ƶ^{\infty}$ can be simplified as in equation (18).

$$Ƶ^{\infty} = \frac{\sqrt{K_{LF}sd_{LF}^4 + K_{HF}sd_{HF}^4 + K_{Vf}sd_{VF}^4}}{n} \tag{18}$$

Equation (17) shows the sum of the fourth moment with number of samples can be expressed as the sum of levels of intensity. It is possible to simplify the $Ƶ^{\infty}$ from Equation (17). Equation (18) is the sum of the *K* and *sd*and, equation (18) is also used to help display the signal processing in three-dimensional (3D) graphical representation using the I-kaz™ method on three frequency rangessuch as *LF*, *HF* and *VF*for *X*-direction, *Y*-direction and *Z*-direction respectively to analyse the effect of each frequency band on the force signals.

3. Results and Discussion

Figures 2 to 9 show the measured force component values and I-kaz coefficients with 3D representation when turning S45C with CBN tool insert under dry cutting machine at different cutting parameters for run 1 to run 8. The stationary dynamometer transmits force signals in three part measuring directions F_X for *X*-direction, F_Y for *Y*-direction and F_Z for Z-direction, namely tangential or cutting force (F_Y), axial or feed force (F_X) and radial or thrust force (F_Z). Comparing the three forces, the strength of the cutting force (F_Y) is the most important criterion for quantifying the machinability of the material. The cutting force (F_Y) is very sensitive with the increase in the value of I-kaz coefficient as shown in the graphs with I-kaz™method in 3D graph representations and top views. The graphs also demonstrate that the tangential force also known as the main cutting force is a very dominant force in the metal cutting process. These results are in agreeable with [13][14] in turning and [15] in milling processes.

Table 2 shows the results of the experimental data tested using the methods of statistical analysis such as skewness, kurtosis, I-kaz coefficient ($Ƶ^{\infty}$) and surface roughness (*Ra* and *Rz*). The results were obtained from the cutting force signals for all experimental runs for F_X, F_Y and F_Z.For skewness, the maximum and minimum values were250.814×10^{-3} and $-70.447\times10^{-3}$for SK_X, 341.769×10^{-3} and $-174.667\times10^{-3}$for SK_Y, $70.234\times10^{-3}$and -58.509×10^{-3} for SK_Z. For kurtosis, the maximum and minimum values were 3.662 and 2.979 for K_X, 3.817 and 2.979 for K_Y, 3.534 and 2.956 for K_Z. For I-kaz coefficient, the maximum and minimum values were 36.552×10^{-9} and 3.861×10^{-9} for $Ƶ_X^{\infty}$, 69.067×10^{-9} and 5.834×10^{-9} for $Ƶ_Y^{\infty}$, $32.554\times10^{-9}$and $3.534\times10^{-9}$for $Ƶ_Z^{\infty}$. I-kaz coefficient values show a significant difference with surface roughness values compared to skewness and kurtosis values. Higher I-kaz coefficient will have higher surface roughness values, and I-kaz coefficient relation decrease with decrease of the surface roughness values. This can be summarized that the significance of the I-kaz coefficient effect which may increase or decrease surface roughness measurement.

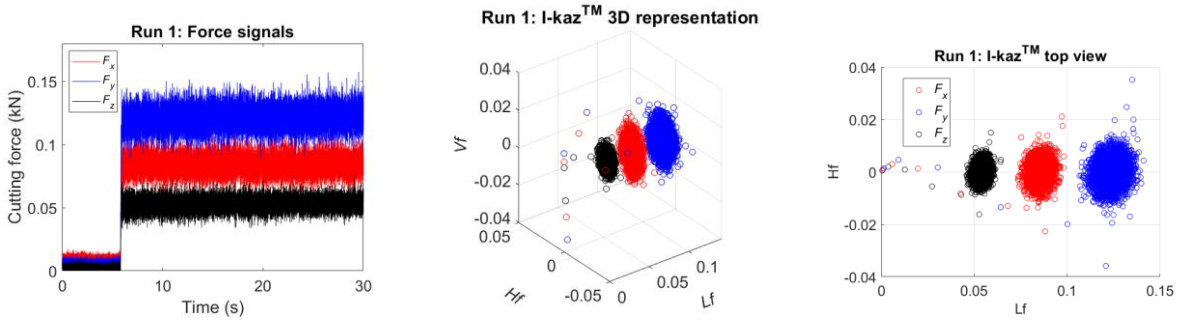

Figure 2. Signal processing with statistical analysisfor run 1

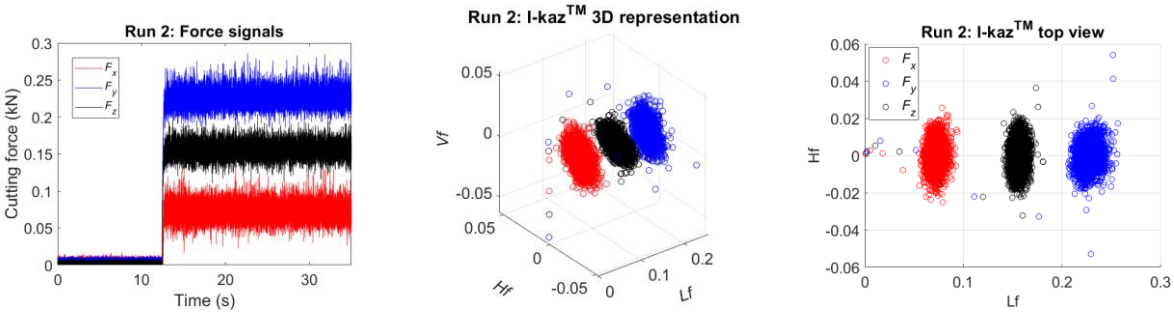

Figure 3. Signal processing with statistical analysisfor run 2

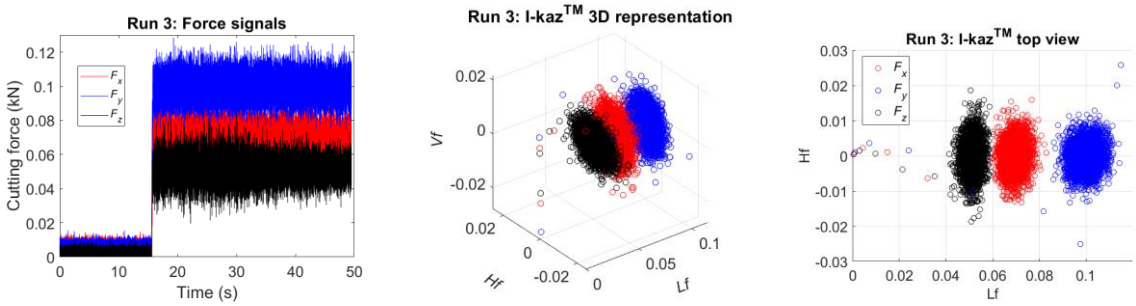

Figure 4. Signal processing with statistical analysisfor run 3

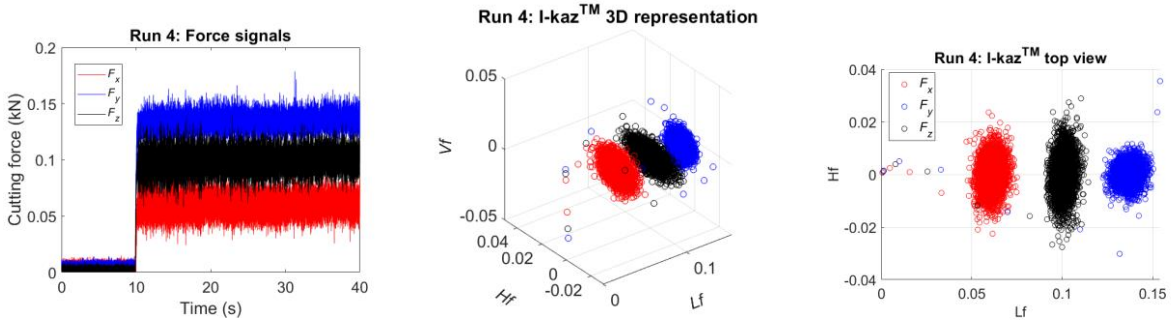

Figure 5. Signal processing with statistical analysisfor run 4

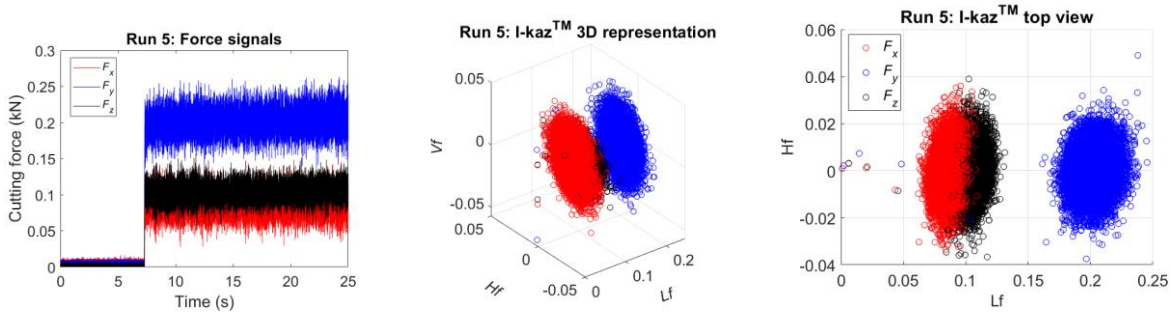

Figure 6. Signal processing with statistical analysisfor run 5

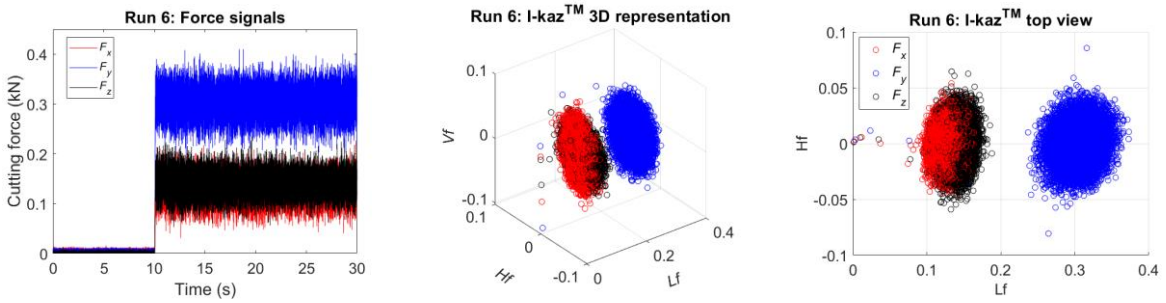

Figure 7. Signal processing with statistical analysisfor run 6

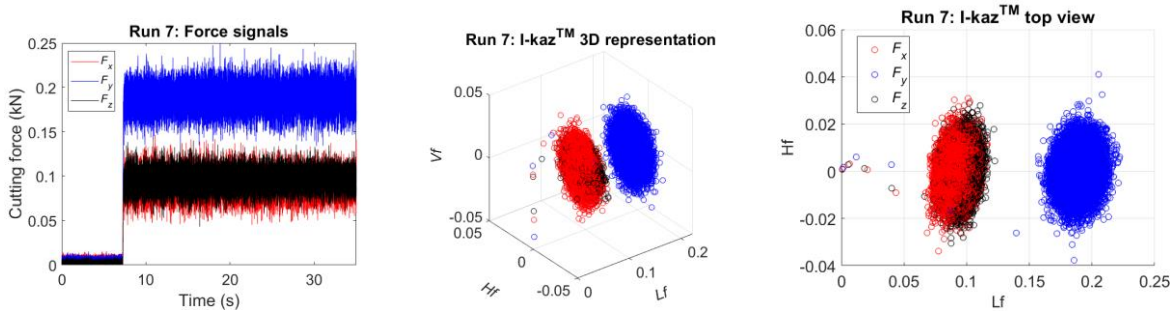

Figure 8. Signal processing with statistical analysisfor run 7

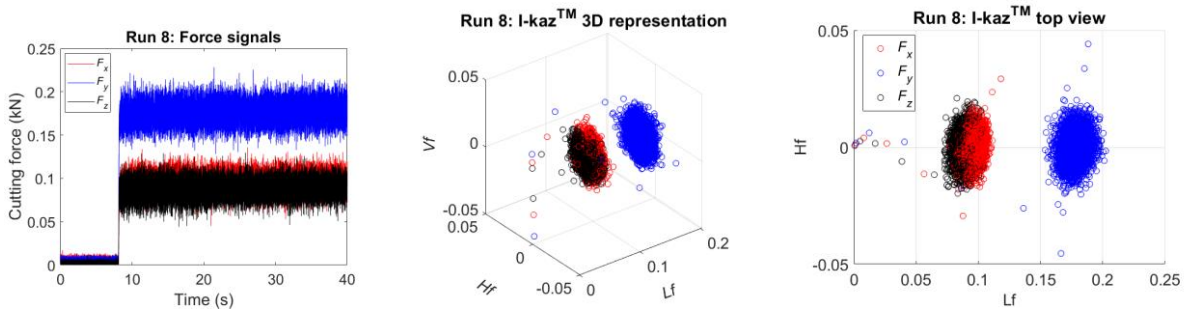

Figure 9. Signal processing with statistical analysisfor run 8

Table 2. Results of the surface roughness and statistical parameters

Test run	Skewness (*SK*) (10^{-3})			Kurtosis (*K*)			I-kaz Coefficients ($Ƶ^{\infty}$) (10^{-9})			Surface Roughness (μm)	
	SK_x	SK_y	SK_z	K_x	K_y	K_z	$Ƶ_X^{\infty}$	$Ƶ_Y^{\infty}$	$Ƶ_Z^{\infty}$	*Ra*	*Rz*
1	76.643	-27.104	69.260	3.104	2.943	3.072	5.593	11.399	5.404	0.99	6.54
2	250.814	341.769	70.234	3.662	3.817	3.349	7.815	27.623	13.709	0.92	6.09
3	125.842	20.884	29.090	3.143	2.980	3.534	3.861	5.855	3.534	0.88	5.46
4	68.617	64.167	-40.015	2.993	3.235	3.011	4.193	9.849	6.983	0.91	5.45
5	7.304	29.772	-10.834	2.979	2.993	3.129	16.530	32.809	12.746	1.38	7.77
6	-70.447	-174.667	54.843	2.988	2.931	2.946	36.552	69.067	32.554	1.66	9.07
7	-9.284	-25.226	-58.509	3.070	3.008	3.041	9.547	21.719	7.848	1.31	7.11
8	-15.072	-36.352	17.582	3.046	3.025	2.961	6.959	17.679	6.416	1.31	7.17

Figures 10 and 11 show that the main effect of the cutting parameters on surface roughness found that the feed rate is most influenced on the surface roughness values for *Ra* and *Rz* and followed by cutting speed. Meanwhile the depth of cut is less influenced as shown in Figures 10 and 11. Figures 12 and 13 show that the trend of the regression line for variation of statistical analyses for skewness, kurtosis and I-kaz coefficient. The statistical parameters for skewness and kurtosis decrease with increase of the surface roughness values *Ra* and *Rz*. Meanwhile, the statistical analysis for I-kaz™method was indicated that the I-kaz coefficient relation increases with increase of the surface roughness values *Ra* and *Rz*.

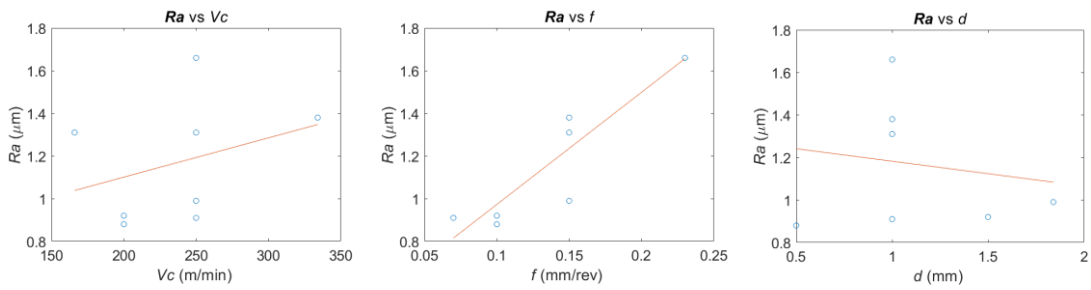

Figure 10. Main effect of cutting parameters on surface roughness *Ra*

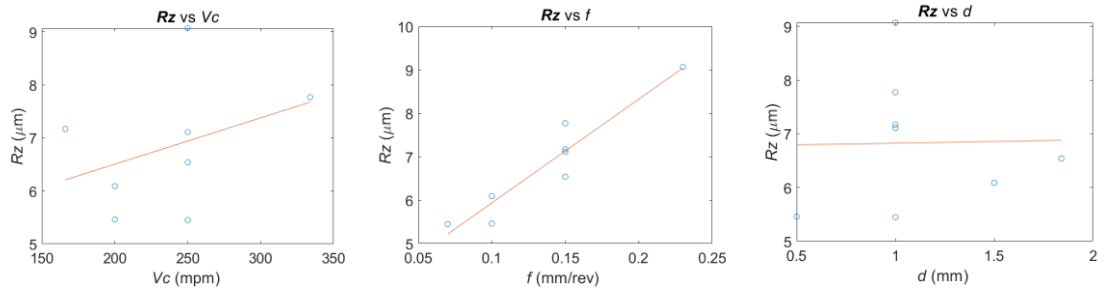

Figure 11. Main effect of cutting parameters on surface roughness *Rz*

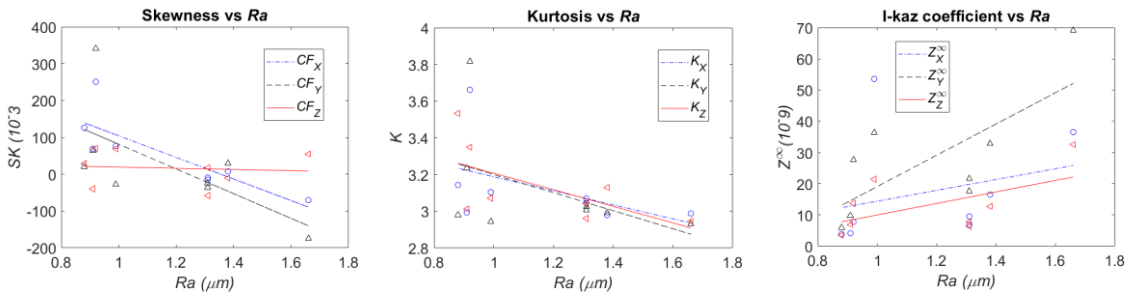

Figure 12. Variation of statistical analyses with surface roughness, *Ra*

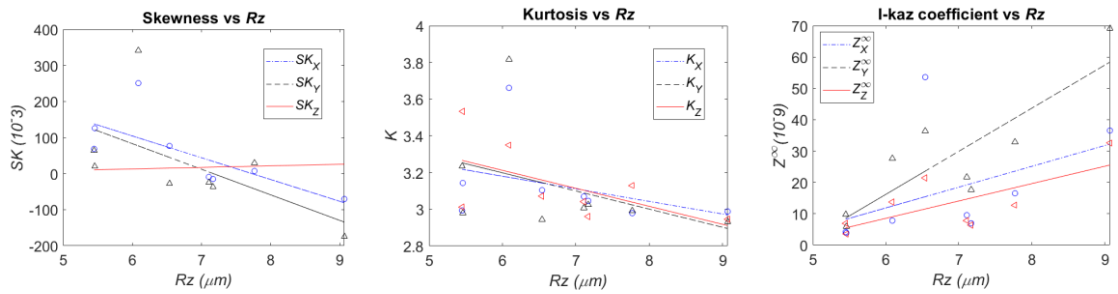

Figure 13. Variation of statistical analyses with surface roughness, *Rz*

4. Conclusions

This paper discussed the influence of cutting parameters using the I-kaz™ method. The value of Ƶ$^{\infty}$ was obtained from the force signal during turning process. It is found that the relationship between the I-kaz coefficient and the surface roughness is known to be a good correlation compared to the skewness and kurtosis coefficients. The I-kaz™ method identified clearly the signal forces relationship in three directions to 3D graph representation and the top view. The results show that the statistical analysis by I-kaz™method can be used for predicting and measuring of the surface roughness values and is very significant for scattering the force signals on machining processes.

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