

A Novel Machining Signal Filtering Technique: Z-notch Filter

Nuawi M. Z., Lamin F., Ismail A. R., Abdullah S., and Wahid Z.

Abstract—A filter is used to remove undesirable frequency information from a dynamic signal. This paper shows that the Z-notch filter filtering technique can be applied to remove the noise nuisance from a machining signal. In machining, the noise components were identified from the sound produced by the operation of machine components itself such as hydraulic system, motor, machine environment and etc. By correlating the noise components with the measured machining signal, the interested components of the measured machining signal which was less interfered by the noise, can be extracted. Thus, the filtered signal is more reliable to be analysed in terms of noise content compared to the unfiltered signal. Significantly, the I-kaz method i.e. comprises of three dimensional graphical representation and I-kaz coefficient, Z^∞ could differentiate between the filtered and the unfiltered signal. The bigger space of scattering and the higher value of Z^∞ demonstrated that the signal was highly interrupted by noise. This method can be utilised as a proactive tool in evaluating the noise content in a signal. The evaluation of noise content is very important as well as the elimination especially for machining operation fault diagnosis purpose. The Z-notch filtering technique was reliable in extracting noise component from the measured machining signal with high efficiency. Even though the measured signal was exposed to high noise disruption, the signal generated from the interaction between cutting tool and work piece still can be acquired. Therefore, the interruption of noise that could change the original signal feature and consequently can deteriorate the useful sensory information can be eliminated.

Keywords—Digital signal filtering, I-kaz method, Machining monitoring, Noise Cancelling, Sound.

I. INTRODUCTION

TECHNIQUES such as fault monitoring, detection, classification, and diagnosis have become increasingly essential in order to keep the machine performing at its best condition [1]. Different types of sensor have been used to monitor different aspect of the machine environments. The concept of sensing tool wear from the sound signal during a cutting process goes back more than thirty years [2]. There

have been several studies using sound signals in this context [3-10], and their results confirm the correlation between tool wear and the sound emitted during the turning process. Li Dan and J. Mathew [11] have reported that sound from a machining operation measured near the cutting zone on a lathe contains a variety of cutting information. Some components of this sound have been used to monitor conditions of the cutting edge. The sound pressure level at the characteristic frequency showed good correlation with tool wear but in a typical machining environment this technique was impractical. This is due to the high ambient noise levels in the factory environment.

If there is poor correlation between the sensor signal and the tool condition, it is unlikely that correct classification of tool state can take place. The success of any tool condition monitoring system depends on two factors which are the quality of the data acquired by the sensors and the diagnosis algorithm used to analyse the sensory information in determining the tool state [12]. In order to get the good quality data, the signal pre-processing is an important step to enhance the data's reliability and thereby, to improve the accuracy of the signal analysis. The core of signal pre-processing is to increase the signal-to-noise ratio that is, to remove the noise and to highlight the signals interested [13]. However, the noise is generally unavoidable, which is usually introduced into signals by various disturbances such as the disturbance from the exotic environment, the testing instrument itself and etc. De-noising and extraction of the weak signals are very important for fault diagnostics, especially for early fault detection in which cases features are often very weak and masked by the noise [13]. The noises are often stochastic signals with broadband, whose frequency band will overlap with the interested signals' [13]. Therefore, it is difficult to eliminate the noise from the signals effectively with general filtering methods.

Because of a variety of the noise that generated during the cutting process, the analysis of the recorded acoustic signals requires an appropriate filter. A novel de-noising technique called Z-notch filter was introduced by Lamin [14]. In this paper, the applicability of the Z-notch filter de-noising technique was demonstrated on machining signal. The Z-notch filter technique was applied in order to eliminate the noise nuisance that contains in the machining signal. The reliability of the Z-notch filter to eliminate noise components in machining signal was discussed.

The effectiveness of the Z-notch filter filtering technique in

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removing background noise was quantified by the significant value of the correlation coefficient between both signals. With the minimal amount of noise interference in the interested machining signal, the tool condition monitoring system using sound signal can be done more accurately.

II. METHODOLOGY

Machining signal was measured during a turning operation using a high frequency microphone. The machining process was performed by a Cincinnati Milacron 200T CNC Turning Centre Lathe machine. Since the CNC machine generates a broad range of sound when operating, the sound generated from the machine components itself such as hydraulic system, motor and its environment was measured and identified as the background noise of the machining operation. The noise signal was generated while operating the machine without hitting the work piece material. The noise measurement was done using the similar cutting parameter as the machining process. The Z-notch filter algorithm was then applied to the machining signal in order to remove the identified background noise interference from the machining signal. In verifying the applicability of the Z-notch filter de-noising technique, the next task was important.

Since the filtering process using the Z-notch filter algorithm was done based on the frequency components, the measured signal which was in time domain was then transformed into the frequency domain using the Fast Fourier Transform (FFT) algorithm. The magnitude of frequency components for the filtered and the unfiltered signal was comparatively observed. This is important to ensure the existing of the net machining frequency component and the reliability of the noise cancellation by this kind of de-noising technique. Therefore, the applicability of the Z-notch filter de-noising technique can be accordingly determined.

The effectiveness of the Z-notch filter de-noising technique in removing background noise may be proved by producing a correlation between the filtered and unfiltered signal. For that reason, the correlation coefficient was utilised in order to quantify the similarity of the filtered and unfiltered signal against noise. The correlation coefficient, R which can be calculated from Eq. (2) represents the normalized measure of the strength of linear relationship between variables [16].

$$R = \frac{\sum_{t=1}^n (x_t - \bar{x})(x_{t+k} - \bar{x})}{\sqrt{\sum_{t=1}^n (x_t - \bar{x})^2 \sum_{t=1}^n (x_{t+k} - \bar{x})^2}} \quad (2)$$

where x_t is the data value at time step t , n is the number of data, k is the lag and \bar{x} is the mean. The value of R will determine the effectiveness of the Z-notch filter de-noising technique. The lower value of R indicates that the smaller correlation between signals exists and the other way accordingly.

In addition, the I-kaz analysis, which was introduced by Nuawi *et al.* [15] was done to the filtered and unfiltered signals in order to evaluate the noise content contained in a signal. The I-kaz coefficient, \mathcal{Z}^∞ can be calculated as in Eq. (1):

$$\mathcal{Z}^\infty = \frac{1}{n} \sqrt{\sum_{i=1}^N (x_i^L - \mu_L)^4 + \sum_{i=1}^N (x_i^H - \mu_H)^4 + \sum_{i=1}^N (x_i^V - \mu_V)^4} \quad (1)$$

where x_i^L , x_i^H , x_i^V are the value of discrete data in low (L), high (H) and very high (V) frequency range respectively at the i -samel of time. The expression of μ_L , μ_H and μ_V are the mean

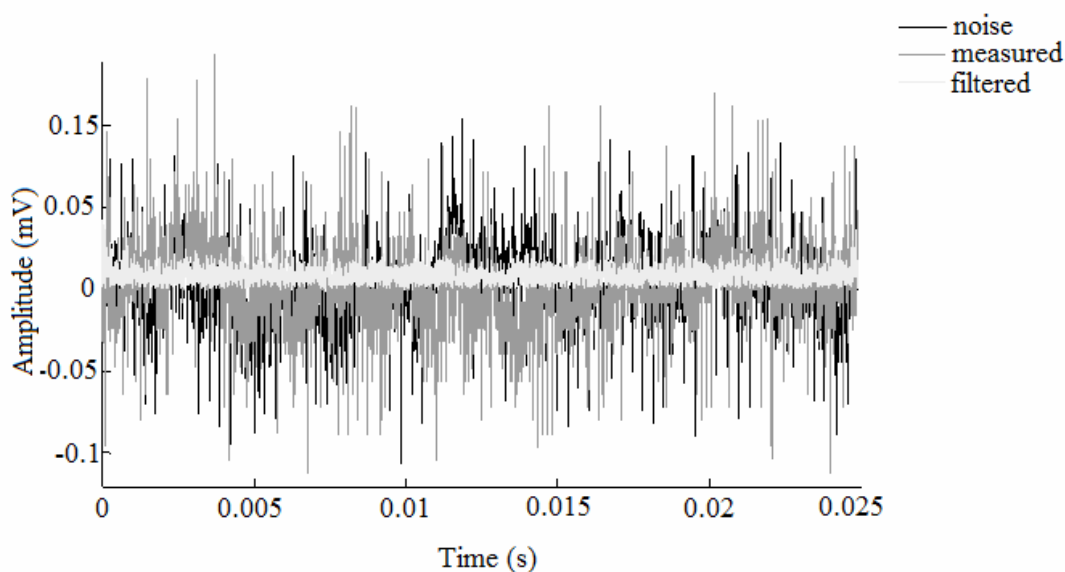


Fig. 1 Plot of the filtered signal, the measured signal and the noise signal in time domain

of each frequency band and n is the number of data. The I-kaz analysis provides a three dimensional data distribution along with the I-kaz coefficient, Z^∞ . The Z^∞ measures the degree of data scattering with respect to the data centroid. The graphic display and the Z^∞ values gained for both filtered and unfiltered signal were comparatively interpreted.

III. RESULTS AND DISCUSSIONS

A. Z-notch Filter in De-noising Machining Signal

In this study, experimental test has been done to measure the machining signal generated during the cutting operation and the noise of the machining process. The measured machining signal, the noise signal and the Z-filtered signal were plotted in the same graph for the comparison purpose as presented in Fig. 1. The figure illustrates the differences between Z-filtered signal (plotted in light grey), non-filtered signal (plotted in dark grey) and the noise signal (plotted in black). The noise components which were generated from the machine environment and the machine components itself were

mostly occurring at the relatively low frequency.

The effect of the low frequency component gave high impact to the pattern of the measured machining signal. Consequently, it can be seen from the time domain representation (see Fig. 1) that the sound signal which was measured from the machining operation was highly perturbed by the noise component. Meanwhile, the filtered signal was less likely to be biased by the noise interference. Based on the figure, the affect of low frequency component has been eliminated from the measured signal and thus remaining the high frequency component in the filtered signal. The high frequency component was generated by the interaction between the asperities of the cutting tool and the work piece surfaces during the machining operation.

Next, the frequency domain of the measured signal was gained by the FFT algorithm as shown in Fig. 2. As a result, it was proven that the Z-notch filter de-noising technique had removed most of the background noise frequency components contained in the measured machining signal. In detail for example, the noise frequency components such as 697.8 Hz

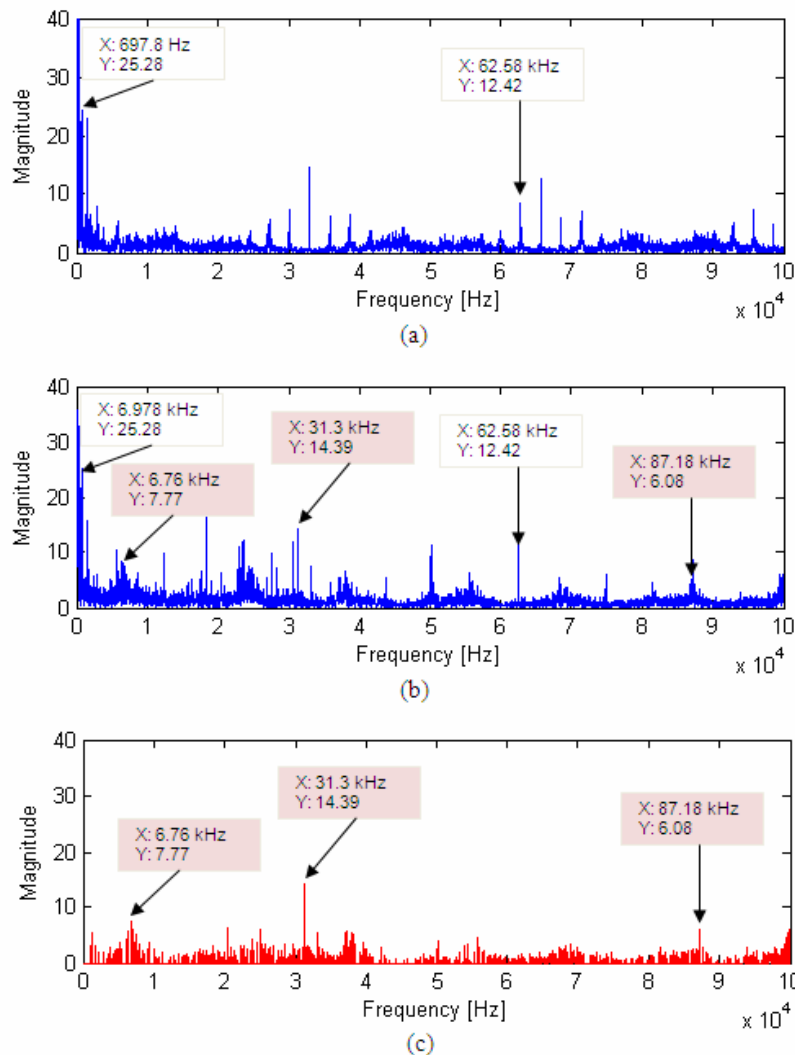


Fig. 2 Plot of frequency domain: (a) noise (b) the measured machining signal, (c) the Z-filtered signal

and 62.58 kHz (see Fig. 2(a) and Fig. 2(b)) did not exist in the filtered signal (see Fig. 2(c)). This means that those noise frequency components have been eliminated by the Z-notch filter de-noising technique.

Besides, the mission frequency components were retained in the filtered signal. For example, the mission frequency components such as 6.76 kHz, 31.3 kHz and 87.18 kHz were not disturbed (or cancelled out) by this kind of de-noising technique (see Fig. 2(b) and Fig. 2(c)). In addition, the similar magnitude of frequency gained has confirmed that the existing of the mission frequency component in both of the measured signal and the filtered signal.

The value of correlation coefficient, R was then calculated for the measured and filtered signal against noise in order to quantify the effectiveness of the Z-notch filter technique. The smaller value obtains for the signals in the correlation test means that the similarity between the signals that being tested was less. Using the Eq. (2), the R value for all test samples were presented in Table I.

TABLE I
RESULT OF CORRELATION TEST BETWEEN THE MEASURED MACHINING
SIGNAL AND THE FILTERED SIGNAL AGAINST NOISE

No. of test sample	Correlation coefficient (%)	
	$R_{\text{machining-noise}}$	$R_{\text{filtered-noise}}$
1	45.06	10.58
2	50.95	10.16
3	37.19	9.92
4	45.76	10.1
5	40.52	10.07
6	39.17	10.24
7	43.51	9.63
Average	43.17	10.10

Based on the Table I, the value of R for the correlation between the measured machining signal and noise for the first test sample was 45.06%. The value explains that 45.06% of the measured machining signal was comprised of the noise component. Unlike the measured machining signal, the filtered signal only has 10.58% of noise component remaining. In overall, the filtered signal was less similar to the noise as it has less R value for all test samples. The Z-notch filter filtering technique was very effective in de-noising machining signal as the average percentage of noise that still remaining in the filtered signal was only 10.10%. This percentage is comparatively higher than the unfiltered signal that almost half of the component in the signal (43.17%) was interrupted by the existence of noise. The values explain that the filtered signal was better in terms of noise content compared to the raw signal which was heavily interrupted with noise disturbance. The elimination of noise from the measured machining signal can be understood graphically based on the bar height reduction from blue (unfiltered signal) to red (filtered signal) as illustrated in the Fig. 3. The blue bar

indicates the correlation between machining and noise signal whereas the correlation between filtered and noise signal was indicated by the red bar.

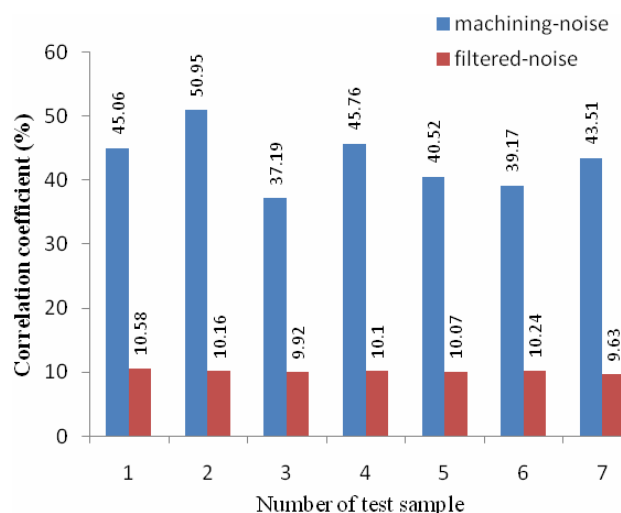


Fig. 3 Differences between correlation coefficient measured machining signal against noise and filtered signal against noise for each test sample.

Comparatively, the reliability of the Z-notch filter was quantified by the deviation between $R_{\text{machining-noise}}$ and $R_{\text{filtered-noise}}$. The deviation indicates the overall performance of the Z-notch filter because the percentage of the noise components that were still remained exhibits the ability of the Z-notch filter de-noising technique in removing noise components.

$$\begin{aligned} \text{Z-notch filter effectiveness} &= \frac{43.17 - 10.10}{43.17} \times 100\% \\ &= 76.6\% \end{aligned}$$

The value explains that the signal which has been filtered by the Z-notch filter technique in average has 76.6% less of noise content compared to the unfiltered signal. Therefore, further analysis for the diagnosis purpose will be more accurate due to the minimal amount of noise disturbance contained in the filtered signal.

B. I-kaz Method in Evaluating the Noise Content

I-kaz method has been reported [15] to be the most reliable method in evaluating a signal. Therefore, for that reason the I-kaz analysis was done for all test samples. An obvious consequence of the signal components reduction can be observed in the I-kaz three dimensional graphical representation. As shown in Fig. 4, it can be seen that the space of data scattering was obviously different for the filtered and the unfiltered signal. The data distribution of the I-kaz representation for the Z-notch filtered signal was shrunk compared to the unfiltered signal. As mention in the literature

section, the degree of data scattering was adequately corresponds to the I-kaz coefficient, Z° .

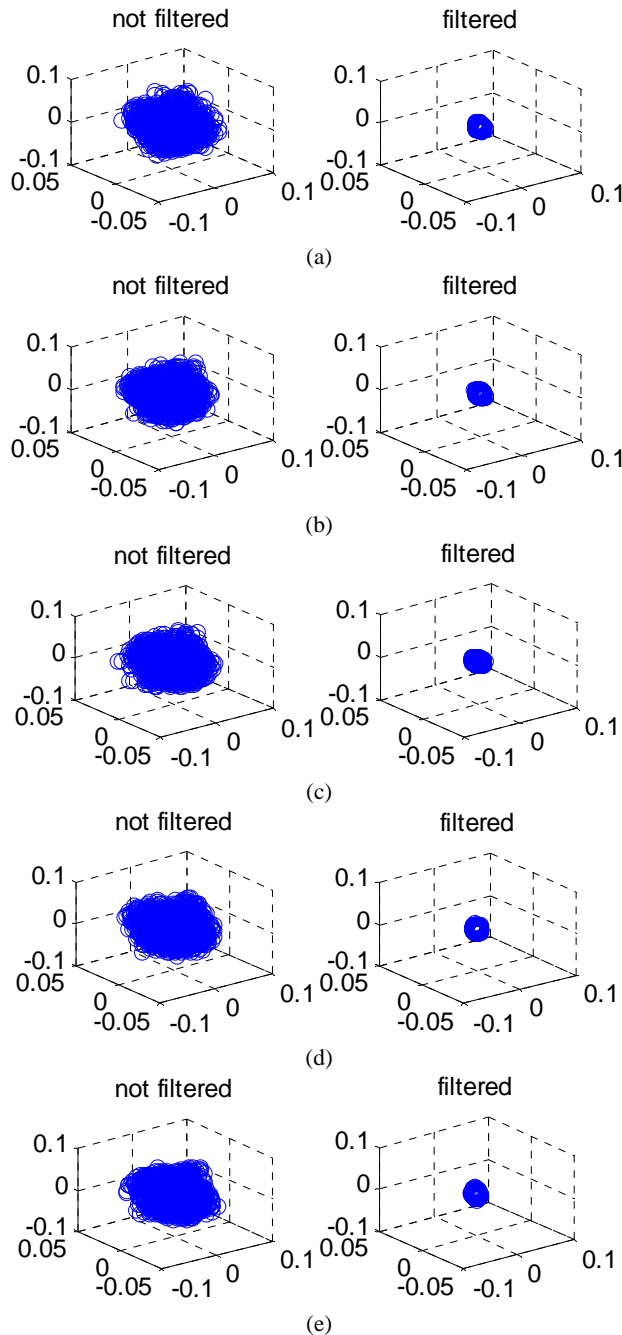


Fig. 4 Example of I-kaz representation for some test sample: (a) the 1st test sample, (b) the 2nd test sample, (c) the 3rd test sample, (d) the 4th test sample, (e) the 5th test sample.

Based on the Eq. (1), as the number of data was constant, the value of the Z° was decreased when the deviation of the data point and the mean value become smaller. In order to determine the functionality of the filtering technique, the value of Z° was compared between the filtered and unfiltered signal. Table II shows the value of Z° that calculated for all test

samples. The lower value of the I-kaz coefficient indicates that the degree of the data scattering has been reduced due to the Z-notch filter de-noising effect.

TABLE II
RESULT OF I-KAZ COEFFICIENT, Z° BETWEEN THE MEASURED MACHINING SIGNAL AND THE FILTERED SIGNAL

No. of test sample	I-kaz coefficient, Z°	
	Unfiltered signal	Filtered signal
1	6.59E-08	2.69E-09
2	6.11E-08	2.58E-09
3	6.10E-08	3.23E-09
4	6.47E-08	2.93E-09
5	5.78E-08	3.95E-09
6	6.50E-08	3.62E-09
7	7.97E-08	4.11E-09

Based on the table, the Z° value for the filtered signal was comparatively lower than the unfiltered signal. This trend of reduction was due to the elimination of noise components. As shown in Fig. 5, the value of Z° gained for a signal illustrates the noise contained in the signal. The high value of Z° exhibits the high noise content and otherwise. Therefore, the Z° value can be used as an effective indicator in determining the noise contained in a signal.

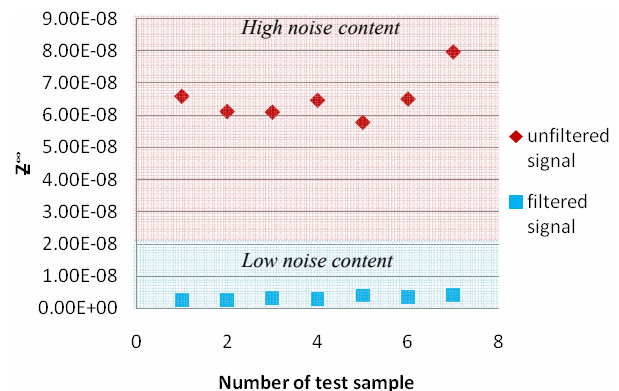


Fig. 5 Difference of noise contained in both filtered and unfiltered signal in terms of I-kaz coefficient.

IV. CONCLUSION

This paper discussed on the noise cancelling technique using Z-notch filter on machining signal. Since noise can be initially determined, the effect of the disturbance was proven could be removed from the measured signal by the Z-notch filter method. Although the mission frequency components were masked by the noise component, the Z-notch filter de-noising technique could segregate the unwanted noise. The applicability of the Z-notch filter as a de-noising technique

has been verified by the frequency domain representation where the noise frequency component was cancelled while the mission signal was simultaneously retained. In addition, the I-kaz display for the filtered signal was shrunk compared to the unfiltered signal. The value of the I-kaz coefficient was also decreased as the display shrunk. It could therefore be inferred that the frequency component has been reduced by the Z-filter, due to the de-noising effect. The Z-notch filter de-noising technique has gained 89.4% of signal which was not interrupted by the noise component. In quantifying the applicability of the Z-notch filter de-noising technique, it was proven that the Z-filtered signal was 76.5% more reliable compared to the unfiltered signal. Hence, the core of signal pre-processing i.e. to remove the noise and to highlight the signals interested was achieved. Thus, the tool condition monitoring using sound signal in noisy machining environment will be more practical.

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