Analysis of Cutter Wear Conditions in CNC Machine Tools with Wavelet Packet Transform

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Abstract

Cutter wear and breakages in CNC machines lead to financial losses ranging from 5% to 10% of annual revenue for companies. Especially in the production of automotive and defense ındustry products, there are high expectations for precision and uninterrupted production within the scope of ındustry 4.0. Therefore, minimizing cutter breakages and monitoring their conditions in CNC machines is of great importance. In recent years, research using smart methods to solve these problems has increased. In this study, the current of the servo motor operating in a CNC machine is measured during ıts operation. The obtained current signals are decomposed using the wavelet packet transform (WPT), and an attempt is made to determine the status of the cutter on the relevant axis. The use of WPT is proposed to ensure high noise immunity. The developed system aims to provide operators with real-time notifications about the condition of cutters, enabling rapid ıntervention. Thus, the goal is to reduce additional costs resulting from cutter breakages and minimize downtime that negatively affects production continuity. The results obtained using WPT are expected to make a significant contribution to ıncreasing efficiency and minimizing errors in the metalworking ındustry.

1. Introduction

Machining is one of the key sectors that ensures the continuity of the global manufacturing industry. Following the introduction of Industry 4.0 revolution in Germany in 2011, there has been a significant increase in the global market towards smart manufacturing, automation of machinery, and digitization. With the recent advancements in sensor technologies, embedded systems, machine learning, and cloud computing, the process of monitoring real-time data has become much smoother [1]. Alongside these technological advancements, research on CNC machines, which are indispensable in today's manufacturing sector, has also been increasing, particularly in industrial applications [2].

Studies on CNC machines have also addressed tool breakages as a current issue, representing a significant cost factor due to unplanned downtime for tool changes and reprocessing of damaged parts, which, in turn, affects machining quality and productivity. To reduce these additional costs, it is essential to monitor the tool's wear condition and intervene immediately. This monitoring can be either indirect or direct. Direct monitoring can be achieved with precision using optical, laser, or ultrasonic devices. However, reaching the tool wear area can be challenging due to situations like workpiece structure and coolant blockages, making real-time implementation quite difficult. Indirect methods, on the other hand, track in-process physical parameters such as force, vibration, acoustic emission, current, power, and temperature signals to assess wear conditions. Therefore, indirect methods are the most commonly used techniques for tool wear monitoring due to their ease of real-time execution and acceptable accuracy [3].

Numerous studies in the field of tool condition analysis, detection, and prediction have improved cutting tool performance and enabled the prediction of failure processes in advance. In one of these studies [4], forces were measured using a dynamometer, and classification was performed using the Adaptive Neuro-Fuzzy Inference System (ANFIS) method. In another study [5], drill sounds were used for fault detection, and the dataset was divided into normal and abnormal categories. To overcome the challenges of a small dataset, sound augmentation techniques were applied, features were extracted from log-Mel spectrograms, and a Convolutional Neural Network (CNN) combined with Long Short-Term Memory (LSTM) was employed to learn general representations of the two classes [5]. In another study focused on the detection and classification of poor welds using the sound and current signals of gas metal arc welding [6], data obtained from a microphone and current sensor were processed using principal component analysis (PCA). Artificial Neural Networks, Support Vector Machines, Decision Trees, and Nearest Neighbors methods are commonly employed for the classification of welding failures. In the machine learning-based approach discussed in Ref. [6], it was demonstrated that welding defects could be detected and classified using sound signals, highlighting the potential for rapid and concurrent quality control in welding. In another study aimed at predicting motor failures using a bearing test rig and laser-based techniques [7], features were extracted from vibration signals using the 1D- ternary patterns, and it was observed that these features improved classification performance. Different analyses yielded success rates of 91.25% at various speeds and 100% for different fault types and sizes. Another study aimed to monitor tool wear by developing an artificial vision system [8]. Flank wear of carbide cutting edges was detected using cameras and image processing. With the obtained data, tool wear width, area, and perimeter were calculated. The experimental results confirmed the effectiveness of the system, demonstrating that a reliable tool wear measurement system could be established. However, it's worth noting that artificial vision studies are generally limited due to the presence of heavy oil and dirt in the environment [12]. In studies related to this subject, the use of signal analysis and smart control methods has become increasingly common in recent years [9-11].

The choice to employ the WPT for the detection of cutting tool errors on CNC machines is grounded in its robust capabilities and distinct advantages in signal analysis. Unlike traditional methods, WPT excels in both time and frequency domain analysis, enabling a more comprehensive assessment of cutting tool conditions. Moreover, its ability to localize faults within the signal and extract relevant features is crucial for timely and accurate error detection. By harnessing the advantages of WPT, we aim to enhance the precision and efficiency of cutting tool error detection, ultimately reducing unplanned downtime, minimizing tool wear, and improving machining quality.

2. Theoretical Background of WPT

WPT is a signal processing technique used for the analysis of signals or data in the time-frequency domain. This method extends the wavelet transform to obtain more sub-bands, enabling more detailed and sharp analyses at higher frequencies. WPT is particularly useful for the analysis of non-stationary signals. The working principle of WPT involves decomposing the signal into sub-bands by applying wavelet transform separately to each sub-band. Then, the results obtained in these sub-bands can be used for further decomposition or different analysis methods. The decomposition process is done to both detail and approximation coefficients simultaneously at each level in the WPT method, in contrast to the discrete wavelet transform DWT, to improve frequency resolution. This method is highly flexible in capturing both low-frequency components and high-frequency details.

WPT is performed by dividing the signal into sub-bands and calculating the wavelet transform for each sub-band. Equation (1) provides the WPT.

$$WPT_j(n) = \{f, \varphi_{j,n}\} = \int_{-\infty}^{\infty} f(t)\, \varphi(t)\, dt \qquad (1)$$

where $WPT_j(n)$ is the n-th sub-band component at level j of the wavelet packet transform, $f(t)$ is the processed signal, and $\varphi(t)$ represents the wavelet function created for the n-th sub-band at the j-th level.

Fig. 1 shows the decomposition tree diagram resulting from the analysis performed with 3-levelWPT. The numbers in the box indicate the wavelet coefficients, while the numbers on the path correspond to the process applied to the signal. The number 0 indicates that the signal is passed through a low-pass filter; The number 1 indicates that the signal is passed through a high-pass filter. As can be seen in the figure, 2^n coefficients are obtained because of the decomposition for both detail and approximation coefficients at each level.

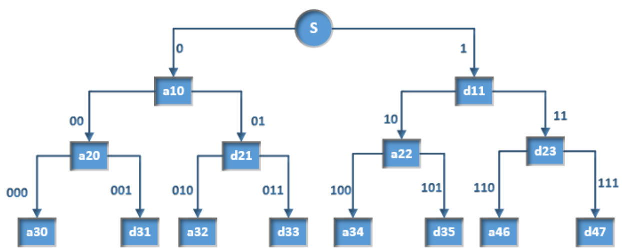


Fig. 1. Tree diagram for 3-level decomposition with WPT

Some advantages of WPT are as follows:

• Flexibility: It offers a wide range of applications due to its ability to analyze various levels of detail in various sub-bands.

• Detailed Analysis: It is particularly suitable for analyzing non-stationary signals because it can perform more detailed analyses in different frequency regions.

• Energy Density Representation: WPT provides energy density representations, showing the distribution of energy in the time-frequency domain of the signal.

• Data Compression: It can also be used in data compression applications, helping to identify important frequency components that represent the essence of the signal.

3.Developed WPT-based Method

This study used the current changes that occur during the processing of stainless steel on a CNC machine to apply the WPT-based approach to current signals to detect tool wear/breakage problems. Real-time current data related to the normal operation, processing, wear, and breakage conditions of the servo motor responsible for motion on the relevant axis were obtained. Subsequently, these data were interpreted using WPT to work towards detecting wear and breakage conditions. Fig. 2 provides a general template illustrating the acquisition of current data from the machine and the analysis process for detecting the tool's condition.

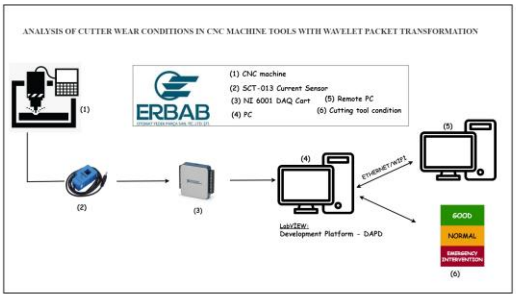


Fig. 2. The general schematic principle of the proposed method

3.1. Real-Time Acquisition of Current Data from CNC Machine

In this study, the primary reason for using current data is to provide accurate information about the cutting tool and to offer a cost-effective alternative to more expensive solutions such as dynamometers or vibration sensors. Current data can be used to monitor the performance of the cutting tool, detect wear and stress conditions, and assess the likelihood of failures. Furthermore, since the prices of current sensors are quite low, this method provides a cost-effective means of monitoring the status of the cutting tool. Thus, it is a suitable and effective solution for increasing efficiency in production processes and reducing maintenance costs.

Fig. 3 illustrates how current data obtained from the main transformer of the machine using a current reading kit is processed with the WPT method in the LabVIEW environment. Current data is obtained using an SCT-013 0-30A sensor and converted into a signal in the range of 0-1V. This signal is then transmitted directly to the data acquisition card (NI-6001). NI-6001 communicates directly with a PC with LabVIEW software installed via a USB cable. The results obtained can be monitored remotely and the LabVIEW program can be controlled.

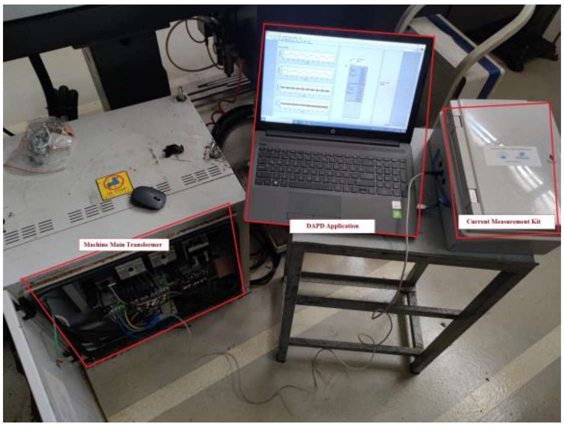


Fig. 3. Acquisition of current data a) Machine transformer b) Current measurement kit c) Application of WPT

In Fig. 4, the results of the Fast Fourier Transform (FFT) of data sampled at 10 kHz and collected with 0.2-second (2000-point) windows are presented. The input current to the driver exhibits high-level noise, especially with the 5th, 7th, 9th, and 11th harmonic components being prominent. This is attributed to the fact that servo drivers often use high-frequency control signals for fast and precise motion control, which can introduce harmonic components when entering the driver input.

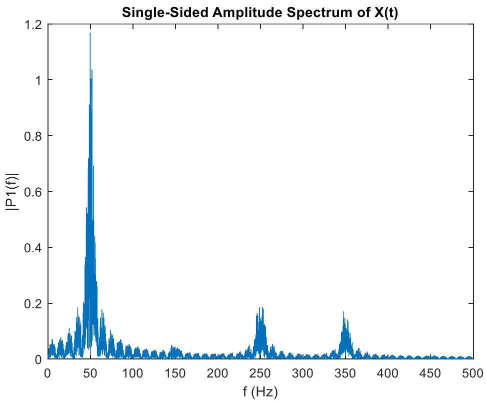


Fig. 4. Harmonic analysis of driver input current (a)

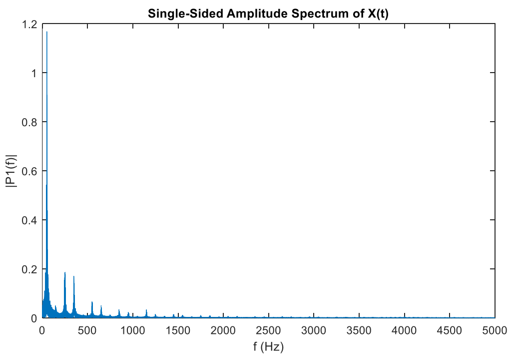


Fig. 5. Harmonic analysis of driver input current (b)

The selection of a CNC machine capable of operating stably for the intended work has been made for this study. The operational status of the servo motor operating in the Z-axis of the selected machine has been observed.

The current values drawn by the machine were obtained from the main transformer of the machine, taking into account the current variations that occurred during the operation of the motor. Current measurements were made using SCT013-0-30A and NI 6001 DAQ card to create a more organized data collection system. This hardware has been transformed into a special panel and kit to provide a more organized organization.

The obtained current data were analyzed using the WPT method in the LabVIEW software environment. Thanks to this method, current changes are examined in more detail, and detailed information about the condition of the cutting tool is obtained. This approach aims to detect factors such as tool wear, allowing for timely intervention and maintenance. This way, the efficiency of the machine and cutting tools can be increased, and processes can be managed more robustly and effectively.

At this stage, the data are collected from the main transformer. However, efforts to also obtain current information from the driver for a more accurate monitoring of the cutting tool's condition are ongoing. The goal is to monitor and understand the cutting tool more accurately. This development will enable the finer details of the machine's activities to be tracked and analyzed, leading to more solid and effective process management and optimization.

4. Results

In this study, WPT was applied to obtain meaningful information from the servo drive input current, which contains high noise and harmonics, and an attempt was made to detect tool wear and breakages based on threshold values determined for the denoised signal. Fig. 6 shows the original current signal, while the current waveform after the WPT process is shown in Fig. 7. The applied method consists of three steps: 1) First, based on the results obtained from the frequency spectrum analysis, it was determined which harmonic components are dominant and the overall harmonic content. 2) Using this information, filtering was applied to correct the data, smooth it, and remove unnecessary fluctuations. 3) Tool wear or breakage was estimated based on the determined threshold value.

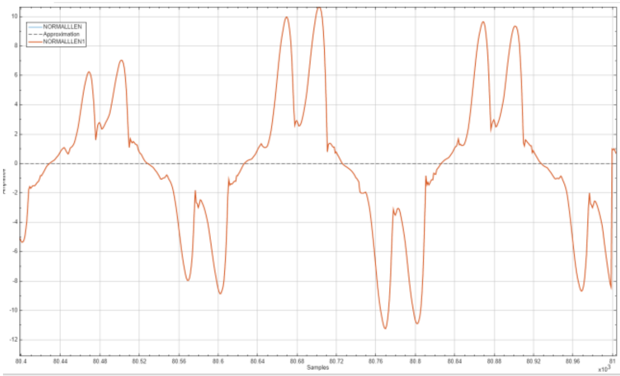


Fig. 6. Original current data

WPT allows for the analysis of a signal at different levels of resolution in both frequency and time domains. This feature enables its use for noise removal and signal smoothing. The selection of WPT parameters in this study was ensured through a combination of literature review and experimental tests. The db4 mother wavelet was chosen for the wavelet type, as it was found to be particularly sensitive to changes in current signals. A 5-level decomposition process was applied, which proved sufficient for obtaining appropriate frequency bands in the current signal sampled at 10 kHz. A fixed threshold method was used for eliminating low-energy or noise from the signal. Additionally, the Shannon entropy method was employed in WPT to detect irregularities. Soft thresholding was applied, and through amplitude tests, the global threshold value was determined to be 34.55.

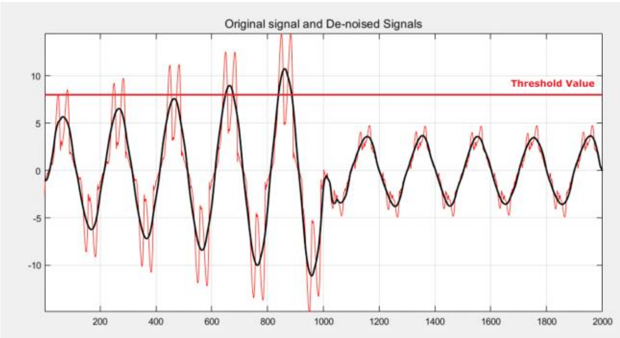
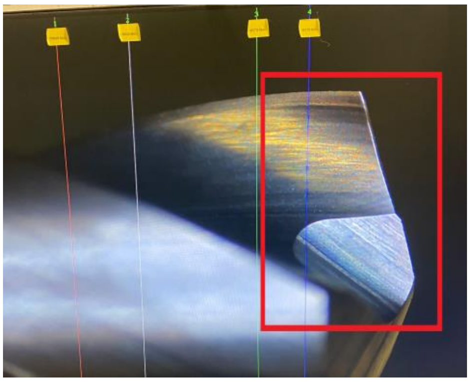
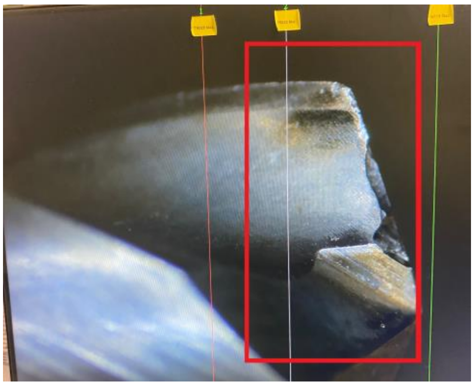


Fig. 7. Signal denoised and de-harmonized with WPT

Drill bit breakages can lead to significant issues in production processes and reduce production efficiency. Therefore, our study focuses on methods for detecting drill bit breakages in advance and automatically stopping our system to conserve economic resources. The initial condition of the drill used in this study is shown in Fig. 8(a), while its worn condition after producing 450 pieces is shown in Fig. 8(b).



(a)



(b)

Fig. 8. (a) initial condition of the drill, and (b) worn condition after producing 450 pieces

5. Conclusion

In this study, the usability of the WPT method for predicting tool wear in CNC machine tools using current data has been demonstrated. The experiments conducted successfully proved that the condition of the cutting tool can be detected by applying WPT to the current signals. The results show the significant potential of smart sensor technology for monitoring the condition of cutting tools and detecting problems such as wear and breakage. This can lead to minimizing the damages ranging from 5% to 10% of annual revenue in businesses and improving efficiency, especially in sectors like automotive and defense where high precision and uninterrupted production are expected. Furthermore, the developed feature extraction method based on WPT has made a significant contribution to ensuring high noise immunity, allowing the system to provide operators with accurate and reliable real-time information about the condition of the cutting tool.

The developed system can enable rapid intervention by operators, reducing the costs associated with tool breakages and minimizing the negative impact on other tools resulting from breakages. The combination of sensor technology and wavelet packet transformation methods to enhance efficiency and minimize errors in the metalworking industry can have significant implications for future industrial processes. This study aims to contribute to the field of tool monitoring and condition prediction.

6. Thanks

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7. References

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