MM Science Journal | www.mmscience.eu
ISSN 1803-1269 (Print) | ISSN 1805-0476 (Online)
Special Issue | HSM 2023
17th International Conference on High Speed Machining
October 25-28, 2023, Nanjing, China
DOI: 10.17973/MMSJ.2023_11_2023099

HSM2023-00003

CHATTER DETECTION IN VIBRATION SIGNALS USING TIME-FREQUENCY ANALYSIS

Dialoke Ejiofor Matthew [1,2], Jianghai Shi [1,2], Maxiao Hou [1,2], Hongrui Cao [1,2*]

[1]Xi'an Jiaotong University, National and Local Joint Engineering Research Center of Equipment Operation Safety and Intelligent Monitoring, Xi'an, 710049, P.R. China

[2]Xi'an Jiaotong University, School of Mechanical Engineering, Xi'an, 710049, P.R. China

*Corresponding author; e-mail: chr@mail.xjtu.edu.cn

Abstract

Chatter is a common state in the end milling, which has major influence on machining quality. Early chatter detection is a prerequisite for taking adequate measures to avoid chatter. Nevertheless, there are still numerous challenges and difficulties in the feature extraction of chatter detection. In this paper, effective chatter detection in the milling process of a vibration signal is investigated using time frequency analysis. Firstly, the measured vibration signal in the machining process was preprocessed by Wavelet Transform decomposition. Different sub-bands were obtained and the portion with high chatter information was reconstructed for further analysis. Since measured signals from sensors usually constitute of background noise and other disturbances, the wavelet decomposition serves as a preprocessor to denoise the measured signals and enhance the performance of the Wavelet Synchro Squeezing Transform (WSST) which was applied on the reconstructed signal for chatter Identification. The techniques were used to detect the chatter in different operating condition of the machining process. Finally, some milling tests were conducted and the experiment results prove that the proposed method indeed succeed in effectively chatter identification.

Keywords:

Milling, Time-frequency analysis, Chatter detection, Vibrational signals, High-speed spindle

1. INTRODUCTION

Chatter is a common adverse phenomenon in the process of **high-speed milling**[1]. It is a self -excited vibration between cutting force and vibration of tool-workpiece system. Among the diverse challenges in machining process, chatter has a significant detrimental effects on surface quality and tool life, and it is a major limitation factor in achieving higher material removal rate[2]. The occurrence of chatter has negative effects on poor surface quality, unacceptable inaccuracy and reduced material removal rate, tremendous destroying the cutting tools and shortening the life-time of machine tool. For these reasons and limitations mentioned above, early detection and identification of chatter occurrence is considered a key element in the milling process. Over several decades, some researchers reviewed about the chatter problems which includes chatter prediction, chatter detection, and chatter control strategies[3-5]. However, due to the complexity of the chatter mechanism and cutting conditions, the chatter prediction becomes a difficult task to carry out in industrial production, therefore chatter detection becomes crucial. Hence, in order to improve the accuracy and workpiece quality, effective chatter detection remains the key research contents. Timely detection of chatter will significantly avoid the unfavorable effect on the workpiece and the tools.

Over several decades, many chatter detection techniques have been developed for the purpose of monitoring the cutting status through monitoring a certain signal sensor such as accelerometer[6], current[7], AE sensor[8], microphone[9], dynamometer[10, 11], and multi-sensors[12, 13]. Regardless of the signal selected, the signal analysis method remains extremely important. The measured vibration signal during the manufacturing process usually constitutes with background noise, which hinders the detection and may not be directly used for chatter detection. It needs to be properly analyzed and extract the effective and sensitive features. Therefore, effective method of feature extraction and feature selection becomes inevitable for chatter detection through the signal processing. The advanced chatter detection method is developed mostly depending on frequency and Time-frequency analysis. The signal from the time domain is converted to frequency domain using the Fast Fourier transform (FFT) which can reflect the overall statistical characteristics of vibration signals. It only has a good resolution in the frequency domain, mask the time domain information and often used to detect cutting chatter[14]. However, the measured vibration signal in machining process is usually non-stationary and non-linear therefore the application of FFT becomes limited for detection of chatter. In the meanwhile, wavelet transforms have been developed as tools to study the dynamic characteristics of cutting processes. Wornell et al.[15] applied the maximum likelihood(ML) algorithm to estimation of fractal dimension using wavelets, which simplified the mathematical complexity of random processes and suggested a possible measure of randomness. Y Gao et al.[16, 17] adopted the synchro squeezing transform (SST) with aim to sharpen the Time-frequency representation. Gao considered (SST) based short-time Fourier transform with instantaneous frequency rate of change to non-stationary signal.

In this paper, Time-frequency analysis was adopted using wavelet transform based techniques for chatter detection.

The wavelet synchro squeezing transform (WSST) and wavelet transform as a processor is introduced to detect the chatter in the milling process. The method is validated with comprehensive experimental data under the various cutting conditions, (a) stable (b) slight chatter (c) severe chatter. Firstly, the vibration signal is preprocessed with Wavelet transform. The frequency band with high chatter information are selected and reconstructed. Then the reconstructed signal is used for the Time-frequency analysis and feature extraction. The experiment results show that the Time-frequency representation of the reconstructed signal were a promising approach to detect chatter in end milling. The remainder of the paper is organized as follows. The experimental setup is given in section 2. Section 3 present the chatter detection methodology. Section 4 present the results and discussion. Finally, the conclusion is given in section 5.

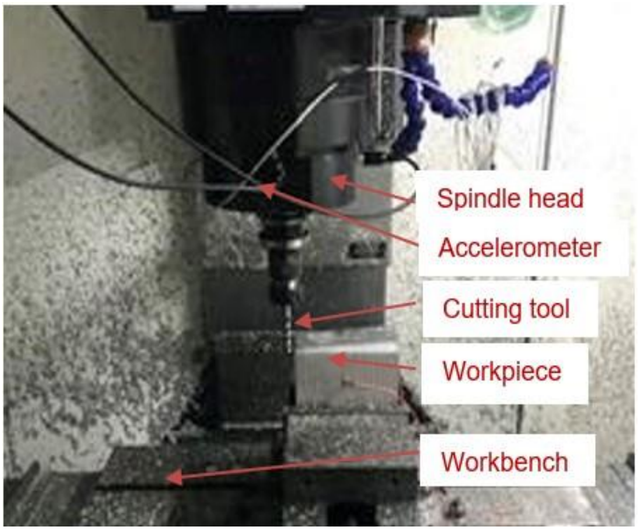


Fig.1: Experimental setup.

2. EXPERIMENTAL SETUP

As shown in Fig. 1, an experimental CNC three-axis milling machine is used for the validation of the proposed chatter detection methodology. The accelerometer was mounted on the spindle housing to collect the **vibration signal** during the milling process. The measurement was produced by a Cutpro-MalDAQ. The vibration signals were sampled by a data acquisition card, and then transmitted to a PC that was applied to save data and analyze signals. The signal sampling frequency is set to 6400Hz. Analysis was done using MATLAB R2023a.

Throughout the cutting test, a carbide end mill cutter with two flutes was applied to cut aluminum 7050. Since, it was well known that chatter can arise at certain combinations of axial depth of cut and spindle speed during a milling process[18]. Therefore, for the validation of the proposed method in this paper, the spindle speed and feed rate were 8500r/min and 1500mm/min, respectively and the depth of cut was increased from 1.0 to 3. 0mm until chatter occurs. All tests are conducted without coolant. The other cutting parameters in this experiment are shown in Tab. 1.

There are three states in the milling process, which are stable state, slight chatter state, and severe chatter state. The slight chatter case sometimes is regarded as transition state, it is seen that when chatter occurs, the amplitude of the vibration signal will increase drastically. At this moment, the surface quality and geometry of workpiece may have been tremendously damaged. When the stable state is transformed into the chatter state during the milling process, there is a transition state where the amplitude of vibration signal does not increase significantly, but it has been pregnant with chatter onset[19]

Tab. 1: Cutting conditions.

Cutting state	**Spindle speed(rpm)**	**Feed rate(mm/min)**	**Axial depth of Cut(mm)**	**Workpiece**
Stable	8500	1500	1	AL7050
Slight chatter			2	
Severe chatter			3	

Preliminary experiment has been conducted to examine the measured vibration signal and their FFT to check the chatter frequency. However, the chatter frequency is different since the chatter is influenced by the cutting parameters and the modal parameters of the machining system.

Fig. 2 shows the measured vibration signal and their FFT, where a, b, and c are corresponding to stable, slight and severe chatter respectively. From the figure, when chatter occurs during milling, the distribution of the frequency components has been changed. In Fig.2b and 2c, the chatter frequency has obviously emerged, which is about 1137Hz and 1314Hz respectively. Chatter is well known to be close to the natural frequency of the system.

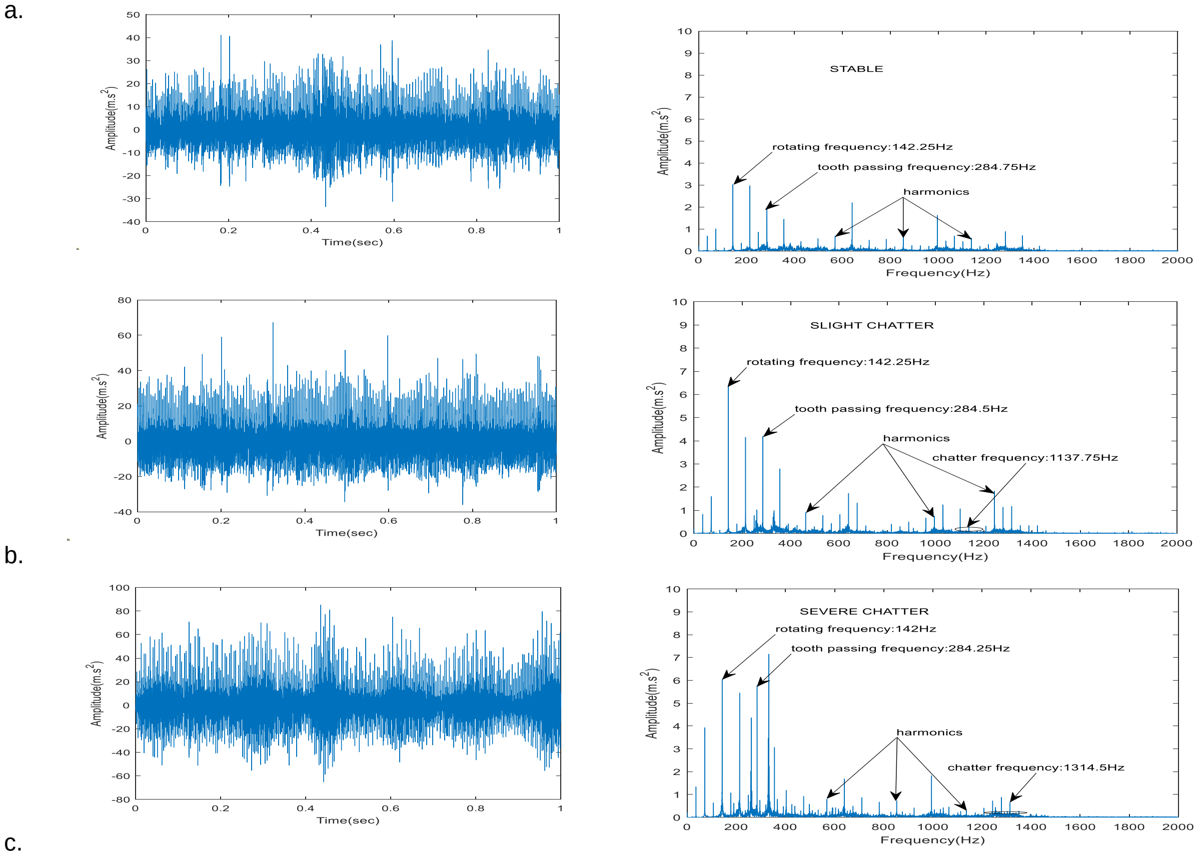


*Fig.2: The measured vibration signal and their FFT. (a**) stable state, (**b**) slight state, and (**c**) severe chatter state.*

3. METHODOLOGY OF THE PROPOSED CHATTER DETECTION

In signal processing, **Time-frequency analysis** comprises those techniques that study and analyze a signal in both the time and frequency domains simultaneously, using various Time-frequency representations. In order to enhance and improve the accuracy of chatter detection, the measured vibration signal is preprocessed by 2-level wavelet decomposition. The sub-band with rich chatter information is selected and reconstructed for effective detection since the task of chatter detection is to find out the chatter frequencies from the measured signals. The suppression or elimination of the background noise that usually contaminate the signal in machining process is critical and inevitable for the feature extraction of chatter. The main scheme of the detection is as shown in Fig.3.

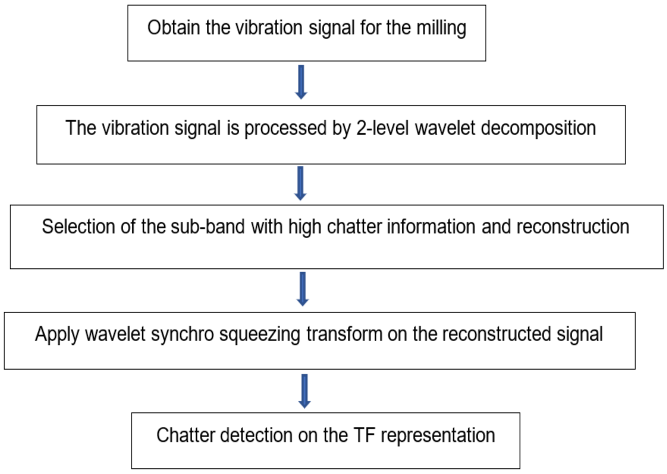


Fig.3: The overall workflow of the methodology.

Firstly, accelerometer sensors are used to measure and obtain the vibration signal in the machining process. The four main stages of chatter detection are then carried out. Secondly, the obtained vibration signal is now decomposed using 2-level wavelet decomposition in order to allocate the chatter signals into certain frequency band and the selected band of interest with chatter information reconstructed. Thirdly, WSST is deployed to analyze the reconstructed signal of interest, and the wavelet synchro squeezing transform presents the full Time-frequency representation of the signal. Finally, the slight chatter, severe chatter was identified and detected as shown in section 4. The standard deviation, peak value, root mean square and variance was calculated and compared between the three cutting conditions.

3.1 Wavelet synchro squeezing transform (WSST)

Most of the real-world signals with oscillating modes can be expressed as a sum of amplitude-modulated components. A general expression for these kinds of signals with summed components is

$$\sum_{k=1}^{k} A_k\,(t)\;Cos\;(2\pi\phi_k(t)) \qquad (1)$$

Where $A_k(t)$ is the slowly varying amplitude and $\phi_k(t)$ is the instantaneous phase.

One of the most basic forms of Time-frequency analysis is the short-time Fourier transform (STFT), but more sophisticated techniques have been developed, notably wavelet methods for unevenly spaced data.

The algorithm usually starts by obtaining the CWT of the input signal which must use an analytic wavelet to capture instantaneous frequency information. Using a phase transform, ω_f extract the instantaneous frequencies from the CWT output

$$\omega_f(s,u) = \frac{\partial t W_f(s,u)}{2\pi i W_f(s,u)} \qquad (2)$$

Where (s) is the scale and denotes as s = $\frac{f_x}{f}$ where f_x is the peak frequency and f is the frequency. To extract the instantaneous frequency, consider a simple sine wave $e^{i2\pi f_0 t}$

$$W_f(e^{i2\pi f_0 t}) = e^{i2\pi f_0 u}, \qquad (3)$$

Taking the partial derivatives of equation (2) above with respect to u,

$$\frac{\partial}{\partial u} W_f(e^{i2\pi f_0 t}) = i2\pi f_0 \hat{x}(f_x) e^{i2\pi f_0 u} \qquad (4)$$

The partial derivative is divided by the wavelet transform and i2π to obtain the instantaneous frequency f_0. The (WSST) as described uses the continuous wavelet transform and its first derivative with respect to translation.

Wavelet transforms are mathematical tools for processing and analyzing signal with varying features over different scales. Features can be frequencies varying over time, transients, or slowly trends. For this reason, it become suitable for the processing of the nonstationary signal The WT provides better resolution and noise filtering compared to an STFT[21, 22]. Tangjitsitcharoen et al.[23] identified that chatter frequencies can appear in different bands when using WT decomposition.

Synchro squeezing transform is one of the most effective Time-frequency analysis method that can decompose complex signal into time-varying oscillatory components. The application of this (WSST) for chatter detection proves that

obtained from the milling process for chatter detection. The wavelet transform (WT) converts the information into a group of wave-like signals, through which the original signal can be reassembled using the weighting coefficient of each signal (i.e., wavelet coefficients).

Yoon and Chin[20] showed that (WT) has the same reliability as FFT, and it can also act as a noise filter.

The well-known continuous wavelet transform is defined by

$$W_x(a,t) = \int_{-\infty}^{\infty} x(\tau) a^{\frac{-1}{2}} \psi^*\left(\frac{\tau - t}{a}\right) d\tau \qquad (5)$$

Where $\psi(t)$ is the mother wavelet chosen, ψ^* denotes the complex conjugate of ψ. The instantaneous frequency of $W_x(a,t)$ for signal x(t) can be derived by

$$W_x(a,t) = -i(W_x(a,t))^{-1} \frac{\partial}{\partial t} W_x(a,t) \qquad (6)$$

The synchro squeezed transform $T_x(w,t)$ can be determined only at the centers W_i of the successive bin $\left[W_i - \frac{1}{2}\Delta W, W_i + \frac{1}{2}\Delta W\right]$

Assuming $W_i - W_{i-1} = \Delta W$

Therefore, summation of different contributions gives

$$T_x(W_i,t) = (\Delta W)^{-1} \sum_{a_{k:|W(a_k,t) - W_i| \leq \frac{\Delta W}{2}}} W_x(a_k,t)^{-3/2} (\Delta a)_k$$

the Time-frequency representation is a good choice. Over the years, different researchers have adopted synchro squeezing transform (SST) in chatter detection task because it is a useful tool for vibration signal analysis due to its high Time-frequency (TF) concentration and reconstruction properties. However, existing (SST) requires much processing time for large-scale data.

4. RESULTS AND DISCUSSION

Wavelet synchro squeezing transform (WSST) Time-frequency domain analysis approach are reported to analyze frequency components of time-variant and nonlinear signals for mechanical diagnosis. This section investigates the properties of the measured signal under **stable, slight chatter and severe chatter state**. In most chatter applications, the first step is the decomposition of the signal into a group of new sub-signals, usually as a function of the dominant frequencies, specific frequency bands or just to minimize the noise effect. The difference between each method is the criteria and the mathematical manipulation to decompose and filter the original signal. The reconstructed signal for the three cases under study is illustrated in Fig. 4

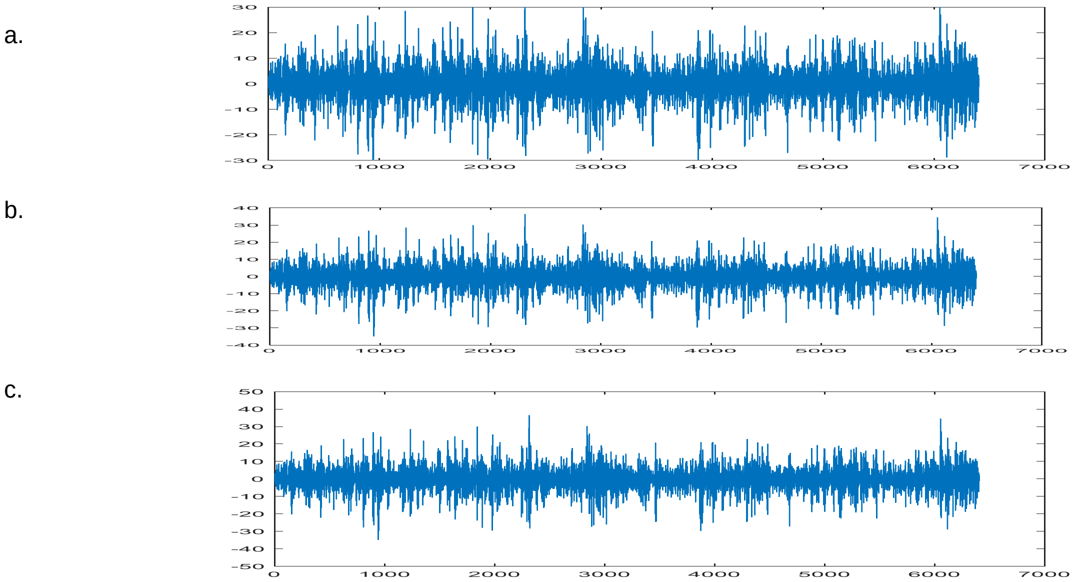


Fig. 4: The reconstructed signal of the three-cutting state (a) stable state (b) slight chatter state (c) severe chatter state.

The FFT result shown above has being the most employed methods in signal pre-processing, data labelling and determination of dominant frequencies is applied on the obtained signal. It is because chatter is characterized by a change in the frequency components and the energy distribution, rising uncertainty of the signal. However, it is common to use the frequency spectrum to compare machining conditions[24, 25]and signal analysis, identifying if the acquired signal corresponds to stable, slight or severe chatter cut as shown in Fig. 2. The result shows that when chatter happens, the vibration amplitude increases also leading to increase in standard deviation. In the three-cutting state, the standard deviation values are 6.369, 9.3288 and 15.1969 respectively. The peak value for the stable, slight and severe state is 40.8797, 67.1198 and 84.9900 respectively.

The result of the stable state shown in Fig. 5, reveal the absence of chatter and the cutting was stable as shown in the TF representation. The result also shows the grate difference between the pre-processed signal and the original signal without preprocessing. All other cutting conditions remains the same and the axial dept of cut is 1mm, 2mm and 3mm for stable, slight chatter and severe chatter respectively. The TFR of the three cutting condition is presented in Fig 5. The result of the slight and severe state shown in Fig. 5 reveal the presence of chatter on the TF representation. The analysis results confirms that the (WSST) Time-frequency spectrum can effectively capture the time-varying chatter components in the cutting process. This means that chatter state of the cutting process can be characterized by the Time-frequency spectrum of the vibration signal.

During the slight chatter state, the frequency peak value increased and also the time-domain illustration shows the increase in the signal amplitude. The slight chatter state is sometimes considered as the transition state and the detection of the slight chatter could also be said to be the detection of chatter onset. All the cutting is done without coolant, the spindle speed is 8500rpm and the feed rate is 1500mm/min and the axial dept of cut is 2mm. On the reconstructed signal, the frequency band of 1000 – 1500Hz which contains rich information of the chatter was processed and the slight chatter frequency was observed at 1137Hz. The frequency components appear quite clearer on the severe state and was observed at 1314Hz after analyzing the reconstructed frequency band of 1000 – 1500Hz. The severe chatter state result also reveals the increase in chatter intensity when chatter occurred and on time domain, causes transients and amplitude modulations by increasing degree of collision between the milling tool and workpiece as time went on. The TF representation also reveals that it clustered more closely during severe chatter, with higher intensity compared to the slight chatter state. Hence the (WSST) method fully and effectively presents the chatter frequency of the milling process in Time-frequency representation. The counterpart STFT result is presented in Fig .6 and comparation were made between the traditional STFT and the new proposed method (WSST).

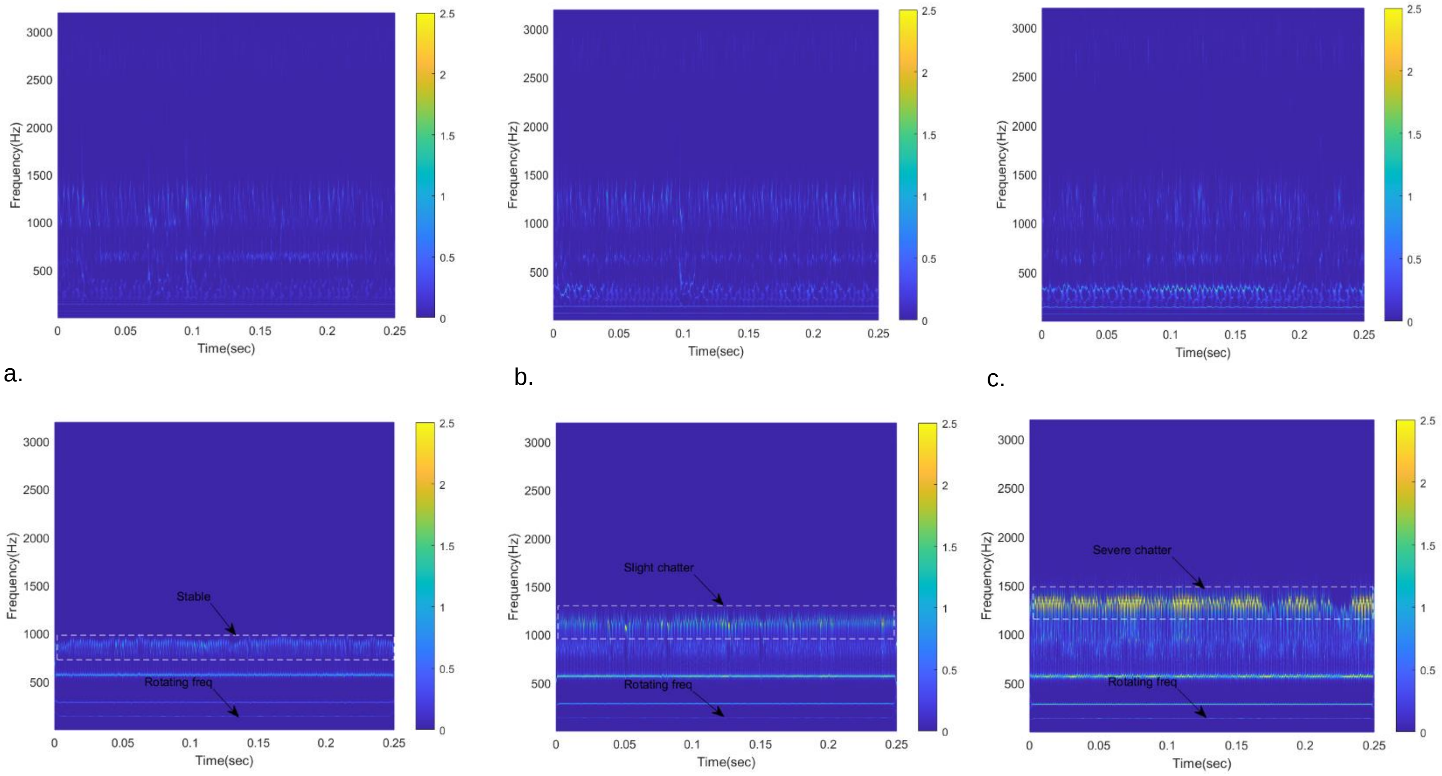


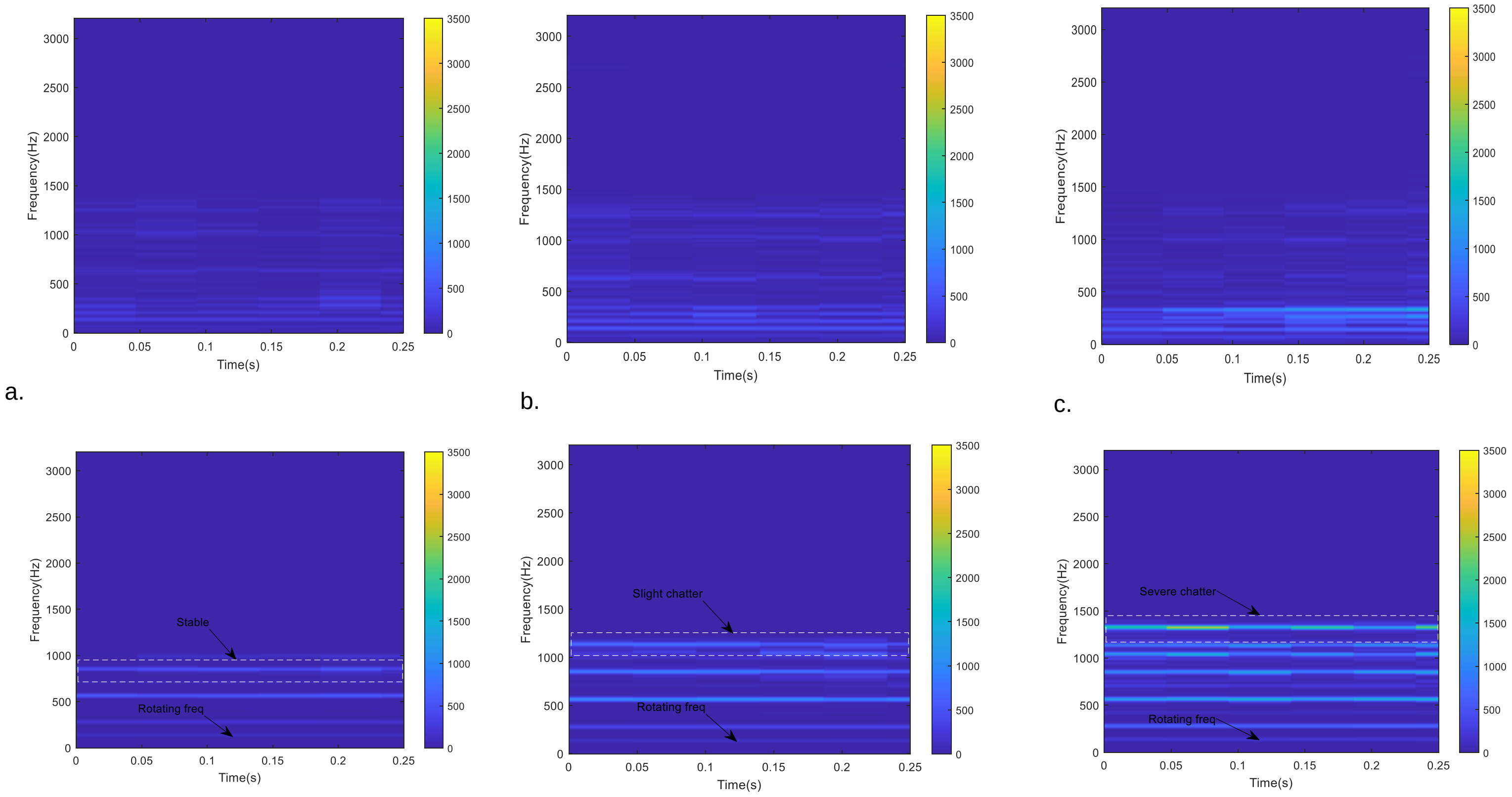
Fig.5: Wavelet synchro squeezing transform of the original and reconstructed signal. (a) stable case (b) slight chatter case (c) severe chatter case, (spindle speed 8500rpm, depth of cut 1mm).

4.1 Comparison between the traditional STFT and the proposed method

Time-frequency analysis has been a powerful tool used to analyze how the frequency contents of a nonstationary signal changes over time. In signal processing, Time-frequency analysis is a body of techniques and methods used for characterizing and manipulating signals whose statistics vary in time, such as transient signals. Considering the fact that the vibration signal obtained from machining process are nonstationary, that makes it suitable to analyze using Time-frequency analysis method. In this subsection, the Time-frequency representation (TFR) of the STFT and the (WSST) is compared based on the (TFR) resolution and the processing time. The both methods are used to analyze signal with varying characteristics which generate a Time-frequency representation result. With reference to Fig 5 and Fig 6, it shows that the new method (WSST) provides a superior (TFR) with high resolution better than the traditional STFT. The rotating frequency and its harmonics, chatter frequency is clearly indicated in the (TFR). The (WSST) also offers variable Time-frequency resolution and is particularly useful when precise localization in time and frequency domains is required, while (STFT) provides a fixed Time-frequency resolution suitable for many applications.

Considering the processing time, the actual processing time depends on various factors, such as the implementation, hardware resources, window parameters, number of decomposition levels and specific wavelet used in the WSST. Additionally, the number of wavelet scales used for the decomposition can impact the processing time. The (WSST) typically involves more computation time compared to the STFT due to the use of wavelet transforms. The processing time for the (STFT) generally scales linearly with the length of the input signal since each time frame needs to be processed. The STFT can be efficiently implemented using Fast Fourier Transform (FFT) algorithm, which allows for fast computations. Due to its simpler computations, the STFT often has faster processing time compared to the WSST. However, the actual processing time will depend on various factors as earlier mentioned and should be considered.

Fig 6: Short-time Fourier transform (STFT) of the original and reconstructed signal. (a) stable case (b) slight chatter case (c) severe chatter case, (spindle speed 8500rpm, depth of cut 1mm).



Tab.2, present the statistical features of the three state and the increasing values of the peak value from stable, slight and severe chatter state is an indication that the occurrence of chatter causes increment of the vibration amplitude. Chatter is clearly seen to be related with the tremendous increase of the cutting amplitude and dominate with a high intensity over time.

Tab.2: Statistical features.

Cutting state	Standard deviation	Peak value	Root mean square	Variance
Stable	6.3696	40.8797	6.3695	40.5715
Slight chatter	9.3288	67.1198	9.3286	87.0258
Severe chatter	15.1969	84.9900	15.1969	230.9456

5. CONCLUSION

This paper presents a Time-frequency (TF) analysis method suitable for chatter detection based on wavelet transform in milling processes. The proposed method characterizes the significant transition from stable, slight chatter to severe chatter in the cutting process. Considering the nonstationary signal and the background noise associated with the signal of the machining process, a wavelet-based decomposition has been employed. Based on these techniques, a chatter detection (TF) representation has been generated, and the comparison between WSST and STFT results indicates that the WSST outperforms the STFT in various aspects. The WSST provides superior Time-frequency localization, reduced frequency smearing, improved energy concentration and minimized cross-term interference. Due to its notable **accuracy and speed**, this proposed method is appropriate for chatter detection and extensive tests on actual cutting data obtained from milling processes demonstrated the validity of the method.

6. ACKNOWLEDGEMENT

The authors would like to acknowledge the support of the National Natural Science Foundation of China (Nos. 52205125) and XJTU-Xi'an City Government Belt and Road scholarship (710000).

7. REFERENCES

1. Chen, G.S. and Q.Z. Zheng, *Online chatter detection of the end milling based on wavelet packet transform and support vector machine recursive feature elimination.* The International Journal of Advanced Manufacturing Technology, 2018. **95**(1): p. 775-784.
2. Navarro-Devia, J.H., et al., *Chatter detection in milling processes—a review on signal processing and condition classification.* The International Journal of Advanced Manufacturing Technology, 2023. **125**(9): p. 3943-3980.
3. Quintana, G. and J. Ciurana, *Chatter in machining processes: A review.* International Journal of Machine Tools and Manufacture, 2011. **51**(5): p. 363-376.
4. Altintas, Y. and M. Weck, *Chatter Stability of Metal Cutting and Grinding.* CIRP Annals, 2004. **53**(2): p. 619-642.
5. Siddhpura, M. and R. Paurobally, *A review of chatter vibration research in turning.* International Journal of Machine Tools and Manufacture, 2012. **61**: p. 27-47.
6. Li, X.Q., Y.S. Wong, and A.Y.C. Nee, *Tool wear and chatter detection using the coherence function of two crossed accelerations.* International Journal of Machine Tools and Manufacture, 1997. **37**(4): p. 425-435.
7. Soliman, E. and F. Ismail, *Chatter detection by monitoring spindle drive current.* The International Journal of Advanced Manufacturing Technology, 1997. **13**(1): p. 27-34.
8. Hutton, D.V. and F. Hu, *Acoustic Emission Monitoring of Tool Wear in End-Milling Using Time-Domain Averaging.* Journal of Manufacturing Science and Engineering, 1999. **121**(1): p. 8-12.
9. Quintana, G., J. Ciurana, and D. Teixidor, *A new experimental methodology for identification of stability lobes diagram in milling operations.* International Journal of Machine Tools and Manufacture, 2008. **48**(15): p. 1637-1645.
10. Tangjitsitcharoen, S., T. Saksri, and S. Ratanakuakangwan, *Advance in chatter detection in ball end milling process by utilizing wavelet transform.* Journal of Intelligent Manufacturing, 2015. **26**(3): p. 485-499.
11. Lamraoui, M., et al., *Indicators for monitoring chatter in milling based on instantaneous angular speeds.* Mechanical Systems and Signal Processing, 2014. **44**(1): p. 72-85.
12. Kuljanic, E., M. Sortino, and G. Totis, *Multisensor approaches for chatter detection in milling.* Journal of Sound and Vibration, 2008. **312**(4): p. 672-693.
13. Kuljanić, E., M. Sortino, and G. Totis, *Multisensor approaches for chatter detection in milling.* Journal of Sound and Vibration, 2008. **312**: p. 672-693.
14. Tangjitsitcharoen, S. and N. Pongsathornwiwat, *Development of chatter detection in milling processes.* The International Journal of Advanced Manufacturing Technology, 2013. **65**(5): p. 919-927.
15. Wornell, G.W. and A.V. Oppenheim, *Estimation of fractal signals from noisy measurements using wavelets.* IEEE Transactions on Signal Processing, 1992. **40**(3): p. 611-623.
16. Gao, Y., et al. *Adaptive synchrosqueezing transform based instantaneous frequency rate estimation*. in *Twelfth International Conference on Signal Processing Systems*. 2021. SPIE.
17. Cheng, X., et al., *An enhanced version of second-order synchrosqueezing transform combined with Time-frequency image texture features to detect faults in bearings.* Shock and Vibration, 2021. **2021**: p. 1-20.
18. Altintaş, Y. and E. Budak, *Analytical prediction of stability lobes in milling.* CIRP annals, 1995. **44**(1): p. 357-362.
19. Yao, Z., D. Mei, and Z. Chen, *On-line chatter detection and identification based on wavelet and support vector machine.* Journal of Materials Processing Technology, 2010. **210**(5): p. 713-719.
20. Yoon, M. and D. Chin, *Cutting force monitoring in the endmilling operation for chatter detection.* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2005. **219**(6): p. 455-465.
21. Tran, M. and M. Liu. *Chatter Identification in End Milling Process Based on Cutting Force Signal Processing*. in *IOP Conference Series: Materials Science and Engineering*. 2019. IOP Publishing.
22. Gao, J., Q. Song, and Z. Liu, *Chatter detection and stability region acquisition in thin-walled workpiece milling based on CMWT.* The International Journal of Advanced Manufacturing Technology, 2018. **98**: p. 699-713.
23. Tangjitsitcharoen, S., T. Saksri, and S. Ratanakuakangwan, *Advance in chatter detection in ball end milling process by utilizing wavelet transform.* Journal of Intelligent Manufacturing, 2015. **26**: p. 485-499.
24. Shimana, K., et al., *Fast detection of chatter in end-milling using pseudo auto-correlation function.* International Journal of Automation Technology, 2012. **6**(6): p. 728-735.
25. Chen, D., et al., *Development of a novel online chatter monitoring system for flexible milling process.* Mechanical Systems and Signal Processing, 2021. **159**: p. 107799.