

# Prediction of Tool Wear in the Turning Process Using the Spectral Center of Gravity

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**Abstract** The recent increase in machining productivity is closely related to longer tool life and good surface quality. In the present study, an experimental technique is proposed to evaluate the performance of a cemented carbide inset during the machining of AISI D3 steel. The aim of this technique is to find a relationship between the vibratory state of the cutting tool and the corresponding wear during machining in order to detect the beginning of the transition period to excessive wear. A spectral indicator named spectral center of gravity, SCG, is proposed to highlight the three phases of tool wear using the spectra of the accelerations measured. Very promising results are obtained which can be used to underpin an industrial monitoring system capable of detecting the onset of transition to excessive wear and

alerting the user of the end of the tool's life. The purpose of this study is to review the vibration analysis techniques and to explore their contributions, advantages and drawbacks in monitoring of tool wear.

**Keywords** Vibration signatures · AISI D3 steel · Cutting tools · SCG · Wear · Scalar indicators

## List of symbols

$V_c$	Cutting speed (m/min)
$f$	Feed rate (mm/rev)
$a_p$	Depth of cut (mm)
RMS	Root mean square
VB	Flank wear (mm)
$R_a$	Arithmetic average of absolute roughness ( $\mu\text{m}$ )
$R_t$	Maximum height of the profile ( $\mu\text{m}$ )
$R_z$	Average maximum height of the profile ( $\mu\text{m}$ )
SCG	Spectral center of gravity
OL	Overall level
WMRA	Wavelet multi-resolution analysis
$f_s$	Sampling frequency
$L_i$	Value of the autospectrum at the sampling frequency
$\gamma$	Rake angle ( $^\circ$ )
$\lambda$	Inclination angle ( $^\circ$ )
$\chi_r$	Major cutting edge angle ( $^\circ$ )

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## Introduction

Machining with cutting tools is the most important manufacturing process in industry. However, limiting tool wear is one of the main factors capable of guaranteeing greater productivity associated with better quality products. Indeed,

the evolution of wear influences the quality of machined surfaces, the geometrical tolerances imposed and tool life, leading to high cutting forces. Tool wear monitoring techniques are generally classified into two categories: direct and indirect. Direct methods can be applied when cutting tools are not in contact with the workpiece. Indirect methods use relationships between cutting conditions and the response of the machining system, which is a measurable quantity through sensor output. Many types of sensors have been used for tool wear monitoring, such as vibration, force, acoustic emission and power sensors [1–4].

In the literature, Xiaozhi and Beizhi [5] proposed the use of wavelet analysis for the treatment of acoustic emission signals. The results showed that standard wavelet coefficients can be used as a criterion for cutting tool monitoring.

Jemielniak and Otman [6] employed a statistical algorithm using several indicators, such as the root mean square (RMS), skew and kurtosis of acoustic emission signals to detect damage to cutting tools. The results showed that skew and kurtosis are better indicators of sudden tool failure than the RMS.

Weihong et al. [7] designed a fast algorithm of the wavelet transform based on a pair of quadrature mirror filters. They noted two main frequencies: The first mode is related to the tool's natural frequency in the axial direction, and the second mode is related to the tool's torsion. The results showed a correlation between the variations of the wavelet coefficients and progressive tool wear under various cutting depths and cutting speeds.

Cemal and Yahya [8, 9] used cutting force measurements to calculate the exit value indicating tool wear with a warning system. The results proved that variations of cutting force decrease uniformly when the tool breaks.

Zhou et al. [10] monitored the constraints acting on the tool edge during the machining process in order to predict sudden rupture. By assessing the risk factor, defined as being the relationship between the instantaneous constraints, the authors concluded that it is possible to predict the sudden rupture of cutting tools.

In previous works [11, 12], we proposed a monitoring method based on both the time- and frequency-domain analysis of measured signals to identify tool wear. The results obtained showed the effectiveness of these approaches in turning operations.

In a recent study, Rmili et al. [13] developed a signal processing strategy using vibratory signals in order to extract a large number of indicators of cutting tool states. One of the innovative results was the tracking of tool wear by variance and coherence estimation, and the application of this general idea leads to the conclusion that it is necessary to monitor the cutting process.

The approach suggested in this work consists in using an experimental methodology based on the use of SCG,

making it possible to estimate the transition zone between stable and accelerated wear. The purpose of this study is to review this technique and explore their advantages and disadvantage in the tool wear monitoring.

The paper is organized as follows: “[Lifespan Theory of the Cutting Tools](#)” section presents theoretical tool wear. “[Experimental Setup and Data Acquisition](#)” section presents the various technological means used for the realization of the experiments as well as the experimental step. “[Experimental Results and Discussion](#)” section concludes our contributions and gives some of our additional remarks. Finally, “[A Comparative Study with Frequency Indicator](#)” section comparative study with spectral indicator.

### **Lifespan Theory of the Cutting Tools**

The lifespan represents the actual productive time during which the cutting edge is directly related to wear in order to provide acceptable results taking into account the specific parameters of roughness and dimensional accuracy. The wear manifests itself on the cutting tool in several forms dependent of the cutting conditions, the material being machined, the material of the cutting tool and its geometry.

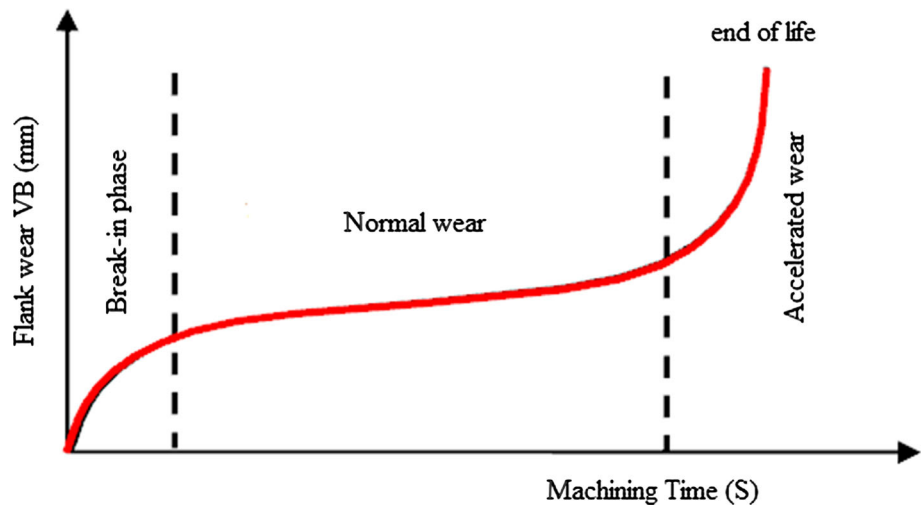
Several researchers allowed establishing mathematical models allowing the calculation of the lifespan of the cutting tools. Taylor was the first researcher who proposed in 1907 a mathematical model connecting the effective duration of cutting tools. This model, considered to be sufficiently representative, is usually employed to evaluate the lifespan of the cutting tools [14]. In 1950, Gilbert proposed the generalization of the model of Taylor by taking account of the geometry of the cutting tool, the feed rate and depth of cut. Koning-Deperieux, in 1969, proposed a model of the exponential type which allows a correct representation of the law of wear in agreement with the experimental curves.

In practice, and also theoretically, the flank wear (VB) is the means more used to evaluate the lifespan of the cutting tool. Its evolution according to machining time passes by three phases: break-in phase, wear stabilization and accelerated wear, see Fig. 1. The device of cutting tool monitoring allows the measurement of a representative signal of the tool state, the treatment of this signal and the detection of possible anomaly. The extraction of useful information built-in in these measured signals is carried out by analysis; this allows identification or prediction of the tool life transition.

### **Experimental Setup and Data Acquisition**

Cutting experiments were conducted using an SN40C universal lathe with a spindle power of 6.6 kW. The

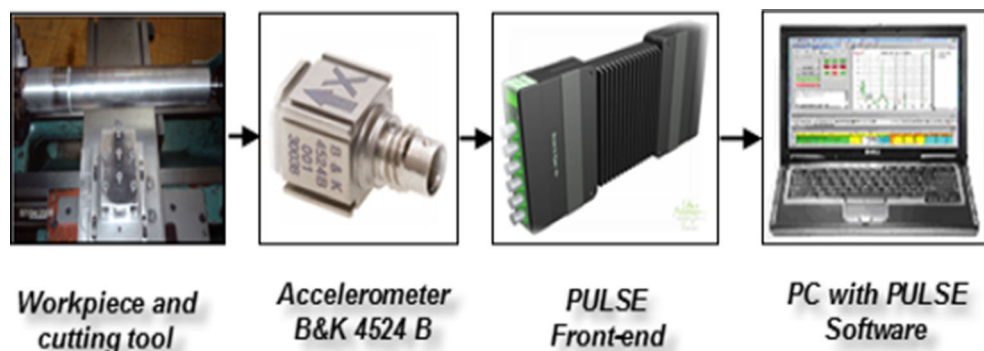
**Fig. 1** Theoretical tool wear



**Table 1** Characteristics of AISI D3 steel

Elements	Cr	C	Mn	Si
Composition (%)	11.5	2	0.30	0.25
Physical properties	Elastic modulus		Density	
	211000 MPa		7.7 g/cm <sup>3</sup>	
				Thermal conductivity
				20 W/m °C

**Fig. 2** Experimental setup and data acquisition system



chemical composition and the physical properties of the workpiece material AISI D3 are given in Table 1. This steel is especially recommended for the manufacture of matrices, punches, blanking, stamping, drawing dies, roller profilers, wood tools and combs for net rolling.

The square cutting insert with eight cutting edges, designated SNMG 432-MF 2015, was coated with TiCN/Al<sub>2</sub>O<sub>3</sub>/TiN. The insert was mounted on a toolholder designated PSDNN 25 × 25 M12 with a geometry described by the cutting edge angle  $\chi_r = 75^\circ$ , the cutting edge inclination angle  $\lambda = -6^\circ$  and the rake angle  $\gamma = -6^\circ$  [15].

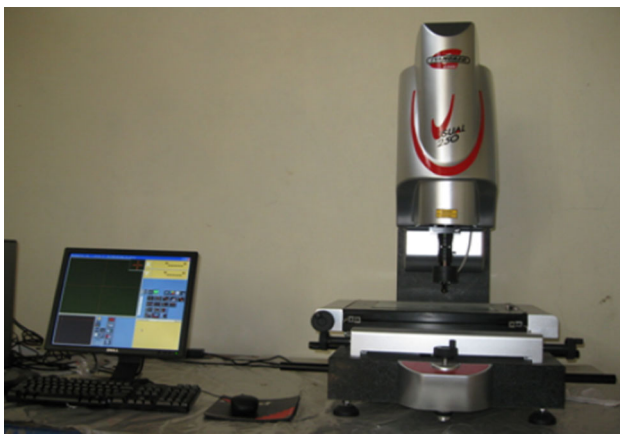
The cutting operations were conducted without applying cutting fluid at cutting speed  $V_c = 120$  m/min, feed rate

$f = 0.12$  mm/rev and depth of cut  $a_p = 0.2$  mm. A Brüel & Kjaer 4524B triaxial accelerometer, placed on the tool near the cutting area zone, was used to collect the vibratory signals. This generated a large number of features which was helpful for acquiring a maximum amount of information on the state of tool wear. The signals measured were acquired at the end of each operation for a duration of 2 s in the frequency band (0–12,800 Hz), where each signal contained 16,384 samples. The collected data were stored directly on the PC hard drive by the Pulse LabShop software (Fig. 2).

Instantaneous roughness components ( $R_a$ ,  $R_t$  and  $R_z$ ) for each cutting condition were measured using a Mitutoyo SurfTest 301 roughness meter. The length examined

was 4.0 mm with a basic span of 0.8 mm. The measurement range of the  $R_a$  roughness was between 0.05 and 40  $\mu\text{m}$ , while for  $R_t$  and  $R_z$  was extended between 0.3 and 160  $\mu\text{m}$ . The measurements were repeated three times for the three lines equally positioned at  $120^\circ$ , and the result considered was the average of these values for a given machining test. After each test, the cutting insert was removed from the toolholder, cleaned and placed on the table of the Standard 250 visual microscope to measure the flank wear (Fig. 3). The microscope had the following characteristics: measuring range ( $x/y$ ) = 250  $\times$  150 mm,  $z$  displacement = 200 mm, calibration at 10 mm.

The device used for cutting tool monitoring allowed the measurement of a representative signal of the tool state, the



**Fig. 3** Standard gage—Visual 250

**Table 2** Experimental results

Test no.	Time (s) $t$	Flank wear (mm) VB	Roughness ( $\mu\text{m}$ )		
			$R_a$	$R_t$	$R_z$
1	240	0.041	0.50	5.15	4.87
2	480	0.090	0.66	5.66	5.42
3	720	0.118	0.87	5.67	5.33
4	1200	0.154	1.08	6.66	5.67
5	1440	0.180	1.25	6.35	5.87
6	1680	0.202	1.56	6.79	6.70
7	1920	0.215	1.87	9.14	8.73
8	2400	0.257	2.20	11.38	10.34
9	2640	0.280	2.27	10.48	10.04
10	2880	0.292	2.55	11.16	10.62
11	3360	0.323	2.97	14.18	13.62
12	3600	0.345	2.99	15.09	14.59
13	3840	0.360	3.20	15.40	14.61
14	4080	0.377	3.26	16.09	14.67
15	4320	0.396	3.51	16.81	16.12
16	4560	0.403	3.62	17.01	16.15

processing of this signal and the detection of possible faults. It is essential to make the right choice of data measurement and processing device for an online monitoring system.

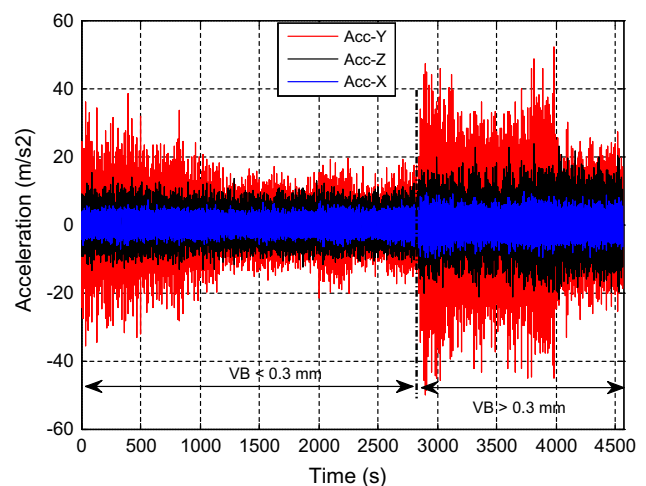
## Experimental Results and Discussion

### Evolution of Flank Wear and Roughness

Table 2 summarizes the measurement of flank wear and roughness for 16 tests. According to the cutting conditions, tool life was approximately 48 min, corresponding to the criterion of stopping the machining tests when the width of flank wear reached the value of 0.3 mm [13]. This was the wear value at which the cutting tool was assumed to be in the phase corresponding to the critical zone of machining quality. The roughness values increased during machining as a function of cutting time, which is directly related to tool wear evolution. After cutting for 2880 s, the  $R_a$  roughness did not exceed 2.55  $\mu\text{m}$  corresponding to a wear of 0.292 mm which was assumed to be acceptable. However, the thermo-mechanical solicitations increased with cutting time, and after 4560 s of machining, the wear reached 0.403 mm with a corresponding roughness of 3.62  $\mu\text{m}$ .

### Acceleration Signal Analysis

The vibratory signals acquired during machining must be used to estimate and monitor the variation of the cutting tool wear, starting from the evolution of various relevant parameters. These signals were recorded for 2 s at the end of each machining test. Figure 4 shows the concatenation of vibratory acceleration signals acquired throughout tool



**Fig. 4** Concatenation of vibratory signals of the cutting tool

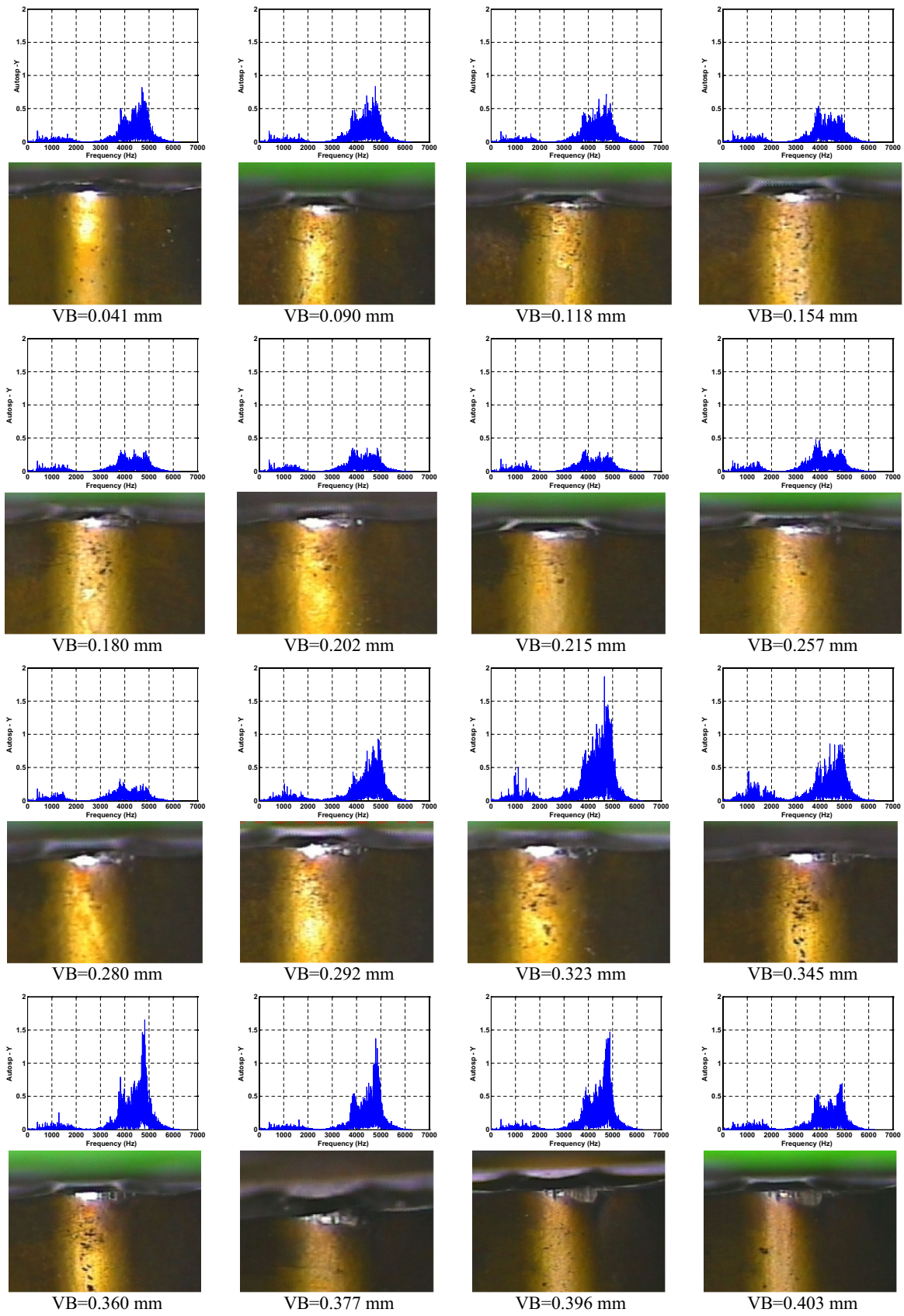


Fig. 5 Autospectrum of measured signals for different wear



life in three directions. According to this presentation, three main phases of cutting tool life can be observed: break-in period, stabilization and accelerated wear.

The transition to the accelerated wear phase is more pronounced and is readily detectable in the radial direction. This observation is confirmed by cutting force measurement in hard turning [16]. The analysis proposed allows the detection of the transition point from the stabilization phase to the accelerated wear phase because it is intrinsically linked to the onset of tool degradation.

### Wear Morphological Analysis

The microscopic observations served to monitor the flank and crater wear morphology as a function of time for various cutting speeds. Figure 5 shows 2-D measurements of typical wear generated during this cutting process where the cutting edge damage increases with time. Flank wear remains below 0.3 mm in test 10 after 2880 s. In the last test, the wear caused by the thermo-mechanical stress leads to a catastrophic failure ( $VB = 0.403$  mm) and machining in these conditions becomes unstable due to the increase in vibrations, confirmed by the surface roughness presented in Table 2. The corresponding autospectrum of different stages of wear (Fig. 5) contains two characteristic frequency bands.

The first one (1000–2000 Hz) describes the natural frequencies of the Kistler device, and the second one (3500–5500 Hz) describes the natural frequencies of the cutting tool. These results were confirmed by modal tests of the tool mounted on the Kistler device, as shown in Fig. 6a, b. According to these measures, it can be seen that the two natural frequencies of the Kistler device appear at 1500 and 1800 Hz. However, two bending modes of the tool appear at 4000 and 5032 Hz in the axial and tangential directions, respectively, and the torsion mode appears at 4760 Hz in the axial and tangential directions.

The variation of the amplitudes of the tool's natural frequency band depends directly on the tool wear evolution where the three-phase wear is clearly distinguished. In the break-in period, where the contact between the tool and the workpiece is very small, the tool is in free configuration causing high vibration amplitudes. In the wear stabilization phase, the tool workpiece contact increases progressively and becomes regular. In this case, tool vibration is damped and decreases the tool's natural frequency amplitudes. In the third phase, corresponding to accelerated wear, contact surface irregularity once again increases the tool's natural frequency amplitudes.

To optimize cutting tool life, a system for wear monitoring based on the analysis of its natural frequency amplitudes can be developed. To make this process simpler for industrial application, we propose the use of SCG as a

scalar indicator calculated from the autospectrum of the acceleration signals measured to highlight the transition to the accelerated wear phase.

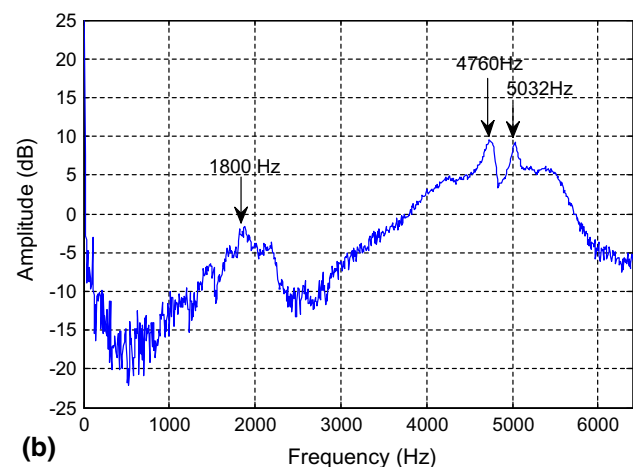
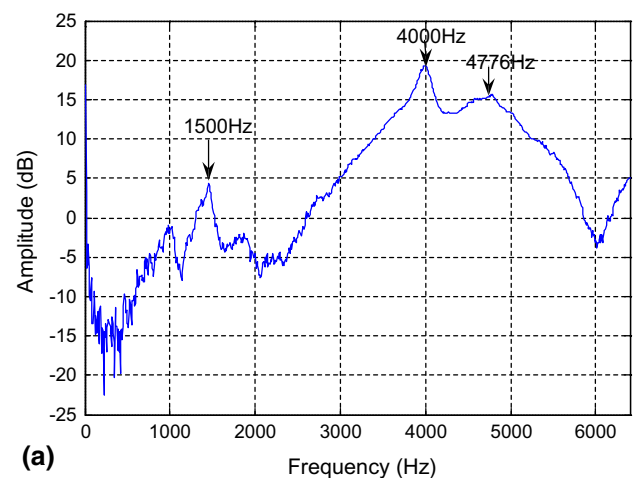
### Prediction of Tool Wear Using the Spectral Center of Gravity

The spectral center of gravity is widely used to reveal a perspective dimension of the sound in the stamping of components used in musical instruments, as well as for the analysis of sounds of vehicles and traffic noise. It is regarded as the most reliable factor for judging the dissimilarity between two sounds of a corpus, corresponding to two defects of different gravities.

The expression of the spectral center of gravity is given by the following expression [17]:

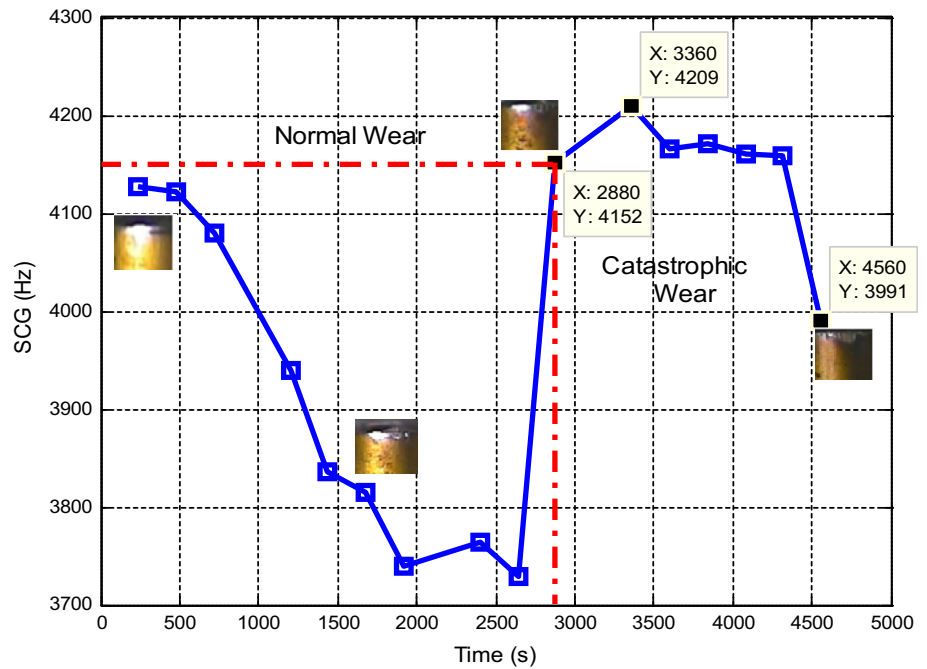
$$SCG = \frac{\sum_{i=1}^N f_i L_i}{\sum_{i=1}^N L_i}, \quad (\text{Eq } 1)$$

where

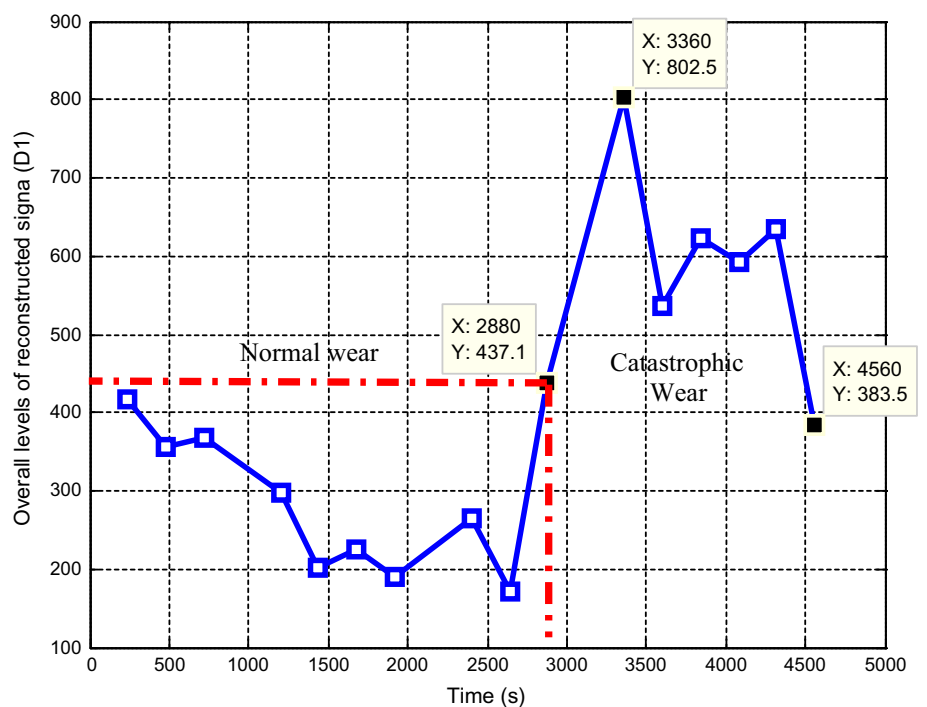


**Fig. 6** Modal test of the tool mounted on the Kistler device: (a) axial direction; (b) tangential direction

**Fig. 7** SCG of the autospectrum of Fig. 4



**Fig. 8** Overall level of reconstructed signal over the tool life



$$f_i = i \times f_s / 2N \tag{Eq 2}$$

with  $1 \leq i \leq 8182$ ,  $f_i$  is the instantaneous frequency at each line.

For gear defects, Kenzari and Younes et al. [18, 19] showed that the value of the SCG decreases with the aggravation of the defect, which explains the judgments of dissimilarity for gear sounds in the case of a simulated and real defect.

In this work, a new method for cutting tool wear monitoring based on SCG was proposed. SCG is a scalar indicator calculated from the autospectrum of the signals measured during the machining operation. It is directly related to the presence of the most dominant natural frequencies of the mechanical system. In our study, SCG depends mainly on the natural frequencies of the cutting tool. Therefore, the change in the amplitudes of the tool's

**Table 3** Comparative study of the two indicators

Indicators	Techniques used	Advantages	Drawbacks	Contributions
Spectral indicator Spectral center of gravity (SCG)	Calculated starting from the autospectrums of accelerations (autospectrum)	Simplicity Lifespan of tool wear can be predicted	SCG decreases with the aggravation of the defect	The use of the SCG can be an effective mean which makes it possible to detect the phase of accelerated wear leading to the stop of machining at the suitable time
Frequency indicator Overall level (OL)	WMRA Choice of the optimal decomposition signal Tool's natural frequency band	Able to provide the moment of the transition to accelerated wear	Too much of calculations How to select the appropriate mother wavelet How to select the decomposition level	The great contribution of overall level showed its capacity to visualize the transition toward the phase accelerated from the cutting tools wear around the characteristic frequencies

natural frequencies can be monitored by calculating SCG to find a relationship between this indicator and wear. The occurrence of serious vibrations leads to an increase in vibratory energy which results in a disturbance of the spectral balance.

As shown in Fig. 7, the SCG values are in the frequency band (3700–4200 Hz), which is situated in the band of the tool's natural frequencies mentioned above. The decrease in the SCG results in the disturbance of the spectral balance due to the occurrence of vibrations generated by the evolution of wear. Once over the VB threshold value, the SCG increases quickly, indicating the onset of the catastrophic wear phase. During the wear stabilization phase, the SCG decreases significantly, reaching a minimum value of 3729 Hz at a time of 2640 s corresponding to  $VB = 0.28$  mm. Then, the SCG starts to increase to a value of 4152 Hz at a time of 2880 s, corresponding to  $VB = 0.292$  mm, and reaches a maximum of 4209 Hz at a time of 3360 s, corresponding to  $VB = 0.323$  mm.

### A Comparative Study with Frequency Indicator

To return the method of monitoring of the wear of the simpler cutting tools for its industrial application, we propose to start modifications on an indicator called overall level, usually to use for rolling bearing fault detection [19] to make it applicable in the case of the forecast of the lifespan of the cutting tool.

Considering vibratory energy is concentrated around the band where the natural frequencies exist, this indicator is calculated starting from the spectrum of the reconstructed signals (D1) in the frequency band covering the tool natural frequency, by the following expression:

$$OL = \sqrt{\frac{2}{3} \sum_{F_{\min}}^{F_{\max}} (N_i)^2}, \quad (\text{Eq 3})$$

where  $F_{\min}$  and  $F_{\max}$  are the limits of the tool's natural frequency band and  $N_i$  the number of spectrum lines in the same band.

The wavelet multi-resolution analysis is applied on the acceleration signals measured in radial direction using the Daubechies 5 (db 5) wavelet. The choice of the WMRA parameters is very important in signal processing; it depends of the analysis type and its regularity (see references [2] and [12] for more details).

Figure 8 represents the evolution of the proposed frequency indicator over the entire tool life. The variation of this indicator is marked by two main phases. The overall level (OL) of the phase of stabilization of wear varies between 170 and 417 ( $VB \approx 0.3$  mm). Catastrophic wear is characterized by an overall level which quickly believes worms of the significant values with a peak in 802 for  $VB = 0.323$  mm. The normal tools wear phase until approximately 2800 s of machining and the catastrophic wear phase characterized by an abrupt increase in the overall level values.

The comparative study of the two indicators which can be used to evaluate the lifespan of the cutting tool is enumerated in Table 3.

### Conclusion

This paper described an indirect technique based on the measurement of the acceleration signals during the turning operation of AISI D3 steel. Contrary to the direct



measurement of tool wear by microscopy, this approach is very interesting as monitoring can be performed without stopping the machining process. The natural frequencies of the machining system can be identified and analyzed from the signals measured and the corresponding autospectrums. The spectral center of gravity is applied to quantify the changes of the amplitudes of the tool natural frequencies that result from the evolution of tool wear. SCG is an efficient tool for wear monitoring that can be easily used to detect the accelerated wear phase making it possible to stop machining at the appropriate moment. The results obtained are very promising for application in industry with the development of an online tool wear monitoring system.

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