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Procedia Engineering 132 (2015) 405 – 412

Procedia Engineering

www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2015

Design of a TCM system based on vibration signal for metal turning processes

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Abstract

This paper presents a study about the identification of cutting tool wear state by means of vibration signal analysis in steel dry turning operations. Analyzing the RMS value evolution and FFT frequency spectra of signal an on-line tool condition monitoring system has been developed. The main purpose is to determine the instant from which tool condition is considered unacceptable affecting machining process quality. After the analysis was carried out, the main conclusion is that both the RMS and frequency amplitude ranges of certain spectrum bands are related to tool wear.

Peer-review under responsibility of the Scientific Committee of MESIC 2015

Keywords: turning; turning; TCM; vibration; monitoring; tool wear

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1. Introduction

The present work is focused on the development of an efficient Tool Conditioning Monitoring system (TCM) for supervising steel turning operations. The proposed system estimates tool flank wear by means of the analysis of vibration signals. An optimized system provides good surface finish, adequate tolerances and minimum downtime

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Peer-review under responsibility of the Scientific Committee of MESIC 2015
doi:10.1016/j.proeng.2015.12.512

due to insert substitutions. Because of its importance, it has drawn the attention of many authors in recent years. Bhuiyan et al. [1] presented a monitoring system based on Acoustic Emission and vibration signals on ASSAB-70 turning processes, highlighting the incidence of cutting parameters on signal, its wear related evolution and interest frequencies. Salgado et al. [2] conducted a study using Singular Spectrum Analysis (SSA) processing and Root Mean Square (RMS) values of vibration signals obtained during turning process, concluding that it is a useful methodology for TCM, since high frequency signal amplitudes provides information about tool condition. Bonifácio and Diniz [3] work on turning ASIS 4340 steels, proved that RMS evolution of the feed and cutting direction signals become good tool condition monitoring parameters, especially in certain frequency bands. The system developed in this work gets the signal data during machining process using triaxial accelerometers. Signals are recorded by means of data acquisition software and processed using Fast Fourier Transform (FFT) algorithm. An adequate sampling rate allows this technique to obtain the frequency spectrum of vibration signals. The RMS of vibration signals is also evaluated in order to correlate its value with tool flank wear. After the analysis was carried out, the main conclusion is that both the RMS and frequency amplitude ranges of certain spectrum bands are related to tool wear.

Nomenclature

a_p	depth of cut
FFT	Fast Fourier Transform
f_n	feed rate
L	length of cut
RMS	Root Mean Square
TCM	Tool Condition Monitoring
VB_b	Flank wear measurement (b zone)
V_c	Cutting speed

2. Methodology and experimental procedure

2.1. Instrumentation and equipment

In this work, test have been performed on a Pinacho 594 C/225 lathe provided with Fagor CNC 800T. Machined material was F1140 steel. Cutting parameters remain constant in each dry cylindrical turning pass (cutting speed Vc=200 m/min, feed rate fn=0.2 mm/rev, depth of cut ap=1 mm and length of cut L=100 mm). The specific tests are listed in Table 1, indicating which ones have been carried out under the same diameter, with the purpose of comparing several statistical procedures afterwards. The processing and comparison of sets of signals related to the same diameter avoids diameter-effect on cutting forces and, therefore, on vibration, as Fernández-Abia et al. [4] pointed out.

Inserts used during experiments were Sandvik Coromant CNMG 12 05 08-PM. Signals were acquired by a Kistler K-Shear 8793A triaxial accelerometer, connected to Kistler 5108A low impedance sensor couplers. An IOtech DBK-40 digitalizes the analogical signal, which is processed in a 1.79 GHz 256 MB RAM PC featuring an IOtech Daq 2000 data acquisition card. Devices arrangement scheme is shown in Fig. 1. The most suitable sample rate for the frequencies of interest is 30 kHz [5]. Although the initial sample rate setting was lower in accordance to frequencies studied by other authors [2], early trials showed significant amplitude values at higher frequencies (between 5 Hz and 15 kHz), so sampling rate must be set to at least twice the higher frequency observed in order to get a fair spectrum analysis. From recorded signals several 16384 block length vectors were generated for FFT processing. RMS axial values ('x' feed direction, 'y' radial direction, 'z' tangential direction) were also calculated and stored. A Pullnix PE2015 B/W 1/3¨ CCD camera was used to capture 768x756 pixels tool flank wear pictures (noise ratio 50 dB). Image digitalization ran by Matrox Meteor II card, measuring VBb tool wear [6] by means of a developed Matlab application.

Table 1. List of machining tests.

Diameter (mm)	#Test	Diameter (mm)	#Test
67	36	47	7, 26, 46
65	17, 37	45	8, 27, 47
63	18, 38	43	9, 28, 48
61	19, 39	41	10, 29, 49
59	1, 20, 40	39	11, 30, 50
57	2, 21, 41	37	12, 31, 51
55	3, 22, 42	35	13, 32, 42
53	4, 23, 43	33	14, 33, 43
51	5, 24, 44	31	15, 34, 44
49	6, 25, 45	29	16, 35, 55

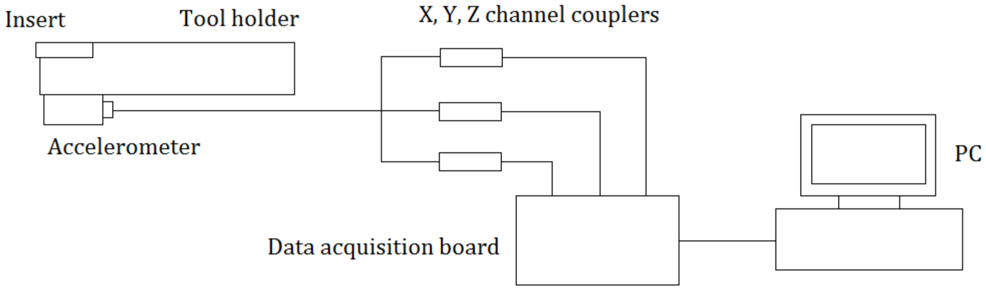

Fig. 1. Scheme of experimental devices arrangement.

2.2. FFT and RMS processing

Fifty signals were captured in a total cutting time of 22.09 minutes, machining three different F1140 steel workpieces. Since vibration signal levels where strongly workpiece diameter dependent (descending with lower diameters), we proceeded to perform a statistical signal treatment for the same diameter passes, so it was possible to compare similar gathered data at different tool wear stages. Looking at the results of machining the three workpieces, three differentiable tool wear condition patterns were clearly detected: (i) workpiece related to low tool wear signals (LW), (ii) workpiece related to intermediate tool wear signals (IW) and (iii) workpiece related to high wear signals (HW). The purpose is to determine the instant from which the tool condition becomes unacceptable, affecting the machining quality and resulting in a poor surface finish. Fig. 2 depicts tool flank wear evolution that has been measured after each pass. Tool is considered worn if VBb value is between 0.2-0.3 mm [6], depending on the process nature (rough or finish).

Signal recording and processing were carried out by means of DASYLab 8.0 software (Fig. 3). The design of the circuit is set by a high pass-filter (5 Hz) and a low-pass filter (15 kHz). Data window module forces signal conversion to periodic within the time record avoiding leakage phenomenon [7]. Windowing process employed Hanning window, overlap and amplitude correction features, obtaining an output vector of the same length as the input. Signal sampling time was set to 10 seconds considering the possible existence of transient events. The three types of used signal analyzing methods are presented below: a) Frequency spectra, b) Frequency amplitude evolution and c) RMS value.

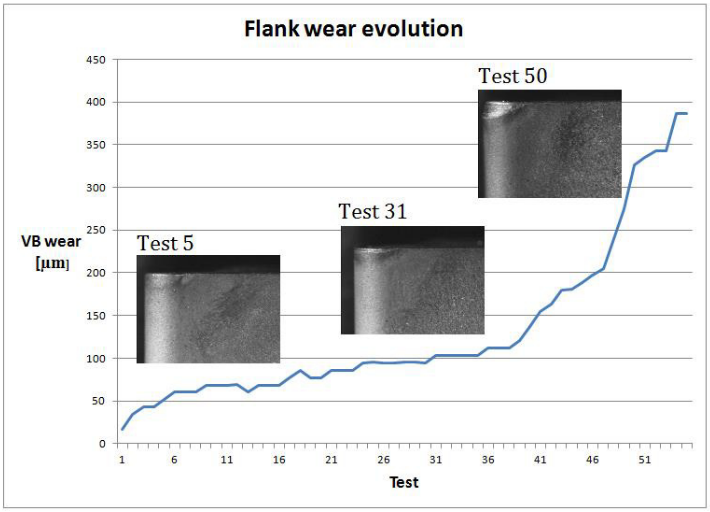

Fig. 2. Tool wear evolution along different trials.

2.3. Frequency spectra

The gathered data were arranged in vectors of 16384 elements (input block length), so after FFT algorithm processing, the output block length was 8192. By means of FFT processing of each test, 19 vectors were collected (the number of output vectors is sample time related), so the same number of frequency spectra can be plotted for each signal, showing the acceleration amplitude at each frequency characterizing each pass. From FFT spectra gathered data, average and median amplitude values are calculated at each frequency. This procedure enables the determination of interest frequencies and their amplitude during cutting process.

2.4. Frequency amplitude evolution

Another analysis also performed by means of FFT spectrum vectors, consisted on the study of the change of maximum amplitude values within four band frequencies: band 1 (0-3786 Hz), band 2 (3798-7574 Hz), band 3 (7575-11362 Hz), band 4 (11363-15151 Hz). This procedure is applied to x, y and z axis, the last being the most representative (tangential axis).

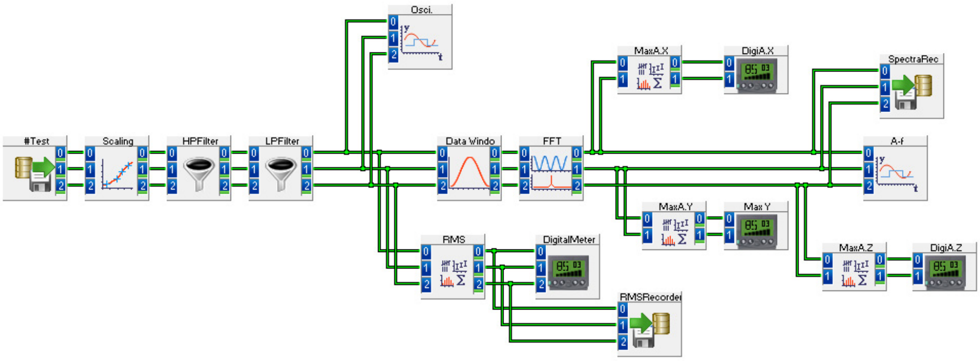

Fig. 3. DASYLab circuit scheme.

2.5. RMS value

Signal RMS value of each axis was also stored during time record, obtaining 18 element vectors that contain RMS values of each sampled block calculated each 500 ms (the number of output vectors is input block length dependent). Analysis was performed for the same diameter trials in order to identify tendency and contrast between different tool condition stages. Results obtained for each of the aforementioned analysis procedures are described and discussed below.

3. Results and discussion

3.1. Frequency spectra

As an example of the same diameter passes signal processing, the tangential axes frequency spectra of test 7, 26 and 46 (Ø=47 mm) are shown in Fig. 4. With regard to changes in frequency spectra along the performed tests, maximum acceleration level seems to increase with tool wear. It also seems that worn insert produces an increment of amplitude over the entire frequency spectrum. Frequencies with peak amplitude were located between 5 and 8 kHz. Besides, the larger the diameter the higher the change in amplitude. The acceleration levels descend with workpiece diameter. In addition, a remarkable variation of spectra distribution was evident, with a peak frequency shift along the frequencies 5-8 kHz. Frequency shift phenomena specially occurred at high tool wear passes, in which amplitude values below 4 kHz rose sharply.

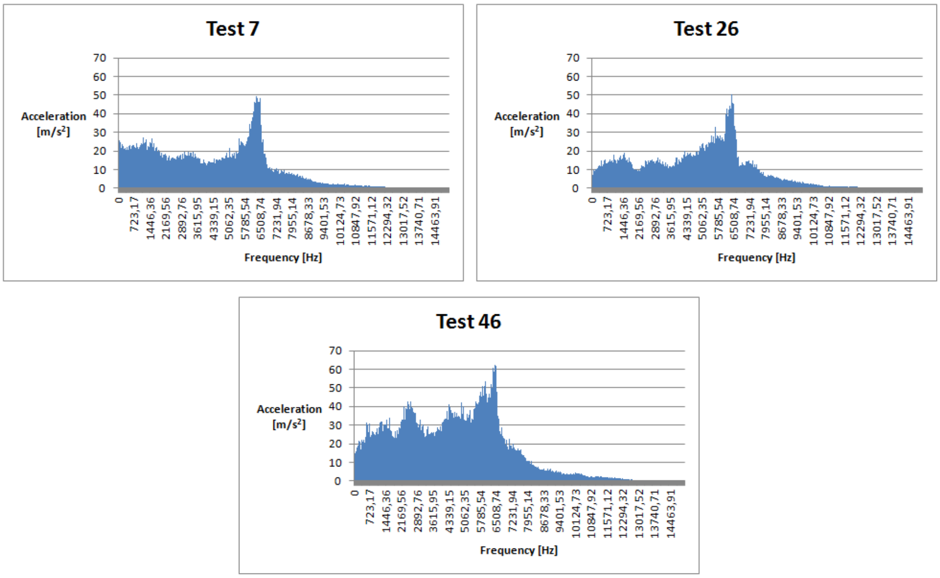

Fig. 4. Typical frequency spectra change (z axis) for tests 7, 26, 46 (diameter 47 mm).

3.2. Frequency amplitude evolution

Based on amplitude frequency median value of each machining pass spectra, four peak acceleration values were obtained, each one for a frequency band (bands were divided as indicated in section 2.4.). The comparative graph shown in Fig. 5 corresponds with test 7, 26 and 46 with 47 mm diameter, showing the regular behavior presented for identical cutting condition passes at different tool wear stages: initial (LW), intermediate (IW) and final (HW). This kind of analysis made possible to obtain the percentage increase of maximum acceleration in each band, taking low wear pass maximum amplitude as reference value in each set. Hence the purpose of this procedure is to set a percentage of increase value in each band, from which the tool can be discarded due to its wear. The maximum peak amplitude difference was reduced between LW and IW passes of each set, even being higher at LW pass, in which tool condition is supposed to be optimal. In all the cases HW passes present higher maximum acceleration levels with respect to LW and IW passes.

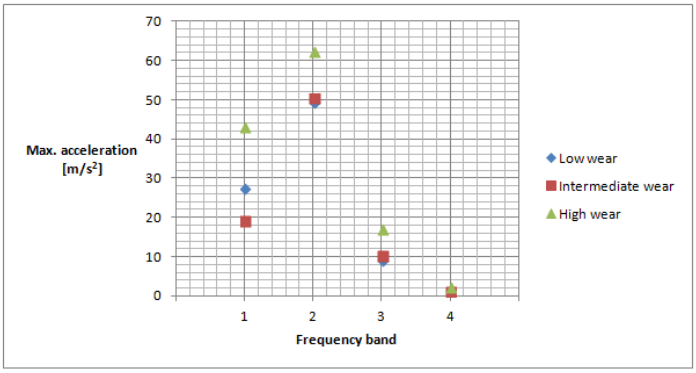

Fig. 5. Maximum acceleration values in each band frequency for test 7, 26, 46 (diameter 47 mm).

3.3. RMS value

RMS signal value processing provides useful information for its implementation in monitoring tasks. RMS value of each signal block and axis is depicted as shown in Fig. 6 (test 12). This plot provides information about RMS value trend along each pass, which can be compared quantitatively and qualitatively at different tool stages. RMS value during time record presents a constant trend in most cases, with slight fluctuations regarding its mean value. Furthermore RMS signal pattern is similar in the three axis, but with different amplitude levels. One of the procedures followed for analyzing value changes is to calculate the difference between passes carried out at the same diameter but at different tool wear stages. LW and IW passes presented similar RMS values and trend along each time record.

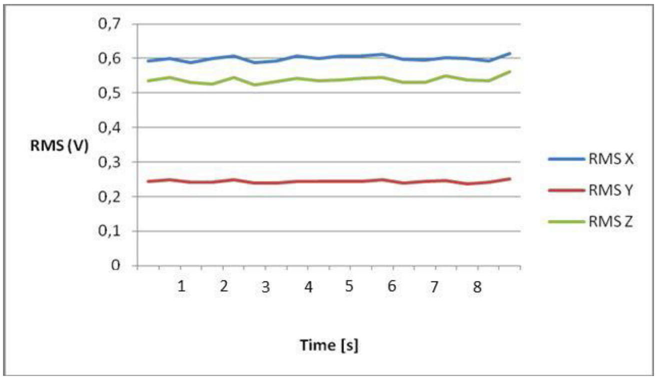

Fig. 6. RMS typical trend and values during time record (test 12)

In the same way that FFT spectra analysis, the z axis is the most representative for tool wear state correlation. An example is shown in Fig. 7, which depicts the differences between initial and intermediate passes (11-30) and between initial and final passes (11-50) of turning tests conducted with 39 mm diameter. Furthermore, since the

RMS signal value had a stable trend, median values along time record of each pass were obtained. By means of the RMS median value of each signal, the difference between initial, intermediate and final passes is calculated, setting down with this information the percentage increase of RMS median value between passes. RMS median value of initial pass was taken as reference since it stands for lower tool wear level.

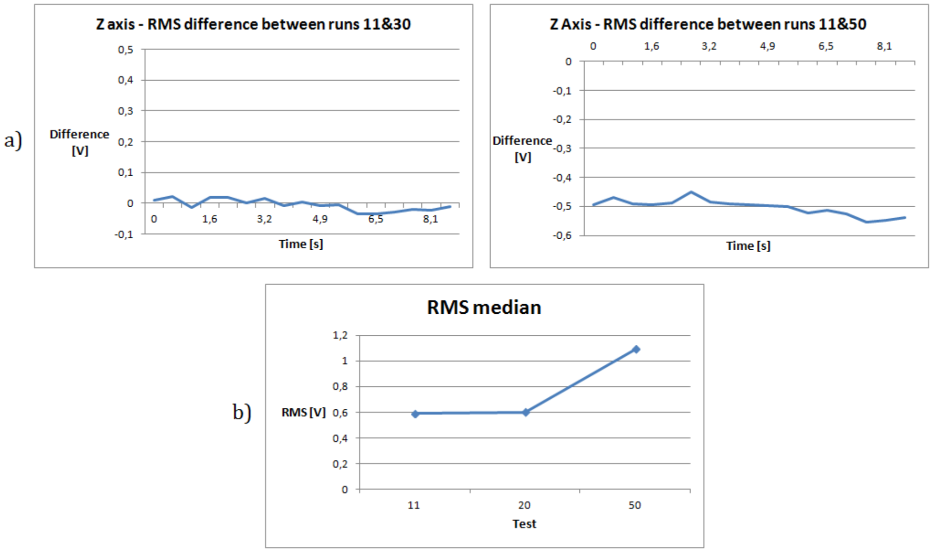

Fig. 7. (a) RMS difference between passes along time record; (b) RMS median evolution. (For tests conducted at 39 mm diameter)

The information gathered by means of this method is expressed in Table 2, which contains diameters, RMS median of low, intermediate and high wear tests (LWT, IWT and HWT respectively), and percentage of increase between performed passes. A clear tool deterioration and wear trend change was observed from 59 mm diameter tests (Fig. 2). Since RMS median percentage increase between low and high wear were above 50% in most cases (except for test 49), it could be considered that tool presents an unacceptable flank wear exceeding this value. Hence an insert replacement becomes necessary to ensure the turning process quality.

Table 2. Percentage of increase of RMS median between passes.

Diameter (mm)	LWT RMS	IWT RMS	HWT RMS	%Δ(LW-IW)	%Δ(LW-HW)
59	0.69	0.71	1.06	2.36	53.32
57	0.71	0.61	1.22	-14.29	71.43
55	0.73	0.80	1.13	9.21	55.09
53	0.66	0.70	1.13	6.82	71.16
51	0.74	0.65	1.20	-12.76	60.91
49	0.81	0.66	1.17	-17.78	44.51
47	0.74	0.68	1.12	-8.17	52.08
45	0.64	0.62	1.12	-3.97	73.65
43	0.70	0.71	1.12	1.16	59.83
41	0.63	0.67	1.15	6.79	81.91
39	0.59	0.60	1.09	1.72	84.51
37	0.54	0.61	0.94	13.88	74.71

35	-	-	-	-	-
33	0.55	0.61	1.02	9.19	83.09
31	0.50	0.54	0.83	7.68	65.25
29	0.45	0.55	-	22.35	-

4. Conclusions

After performing a large number of tests at different insert wear conditions, several tool wear related phenomena has been determined through RMS and FFT spectral analysis. Described experimental procedures led to the following conclusions:

- Frequencies which present higher amplitude values have been clearly identified through spectral analysis. Interest frequency levels and transitions are tool wear related. Through Fast Fourier Transform (FFT) analysis it was determined that acceleration level at some frequencies increases with tool flank wear. Moreover amplitude level increase will occur for the most frequencies along the spectra, being more evident for 0-4 kHz and 5-8 kHz frequency bands.
- Signal amplitude level is strongly influenced by workpiece diameter. Keeping constant cutting parameters (feed rate, speed, depth and length of cut), acceleration amplitude levels in the whole frequency spectra decreased with smaller diameters.
- FFT spectra shape varies as tool undergoes increasing wear levels.
- RMS signal value increases with tool wear. Initial and intermediate wear passes present approximately equal RMS value while high wear passes present a remarkably greater value. Hence tool wear conditioning monitoring in turning operations through RMS statistical procedures becomes feasible.

Future analysis will be focused on characterizing sample distribution statistically, e.g., by means of kurtosis or skewness, trying to evidence wear related characteristic behaviors.

Acknowledgements

We gratefully acknowledge the support provided by the Spanish Ministry of Economy and Competitiveness through project DPI2012-36166.

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