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COMPARISON OF SIGNAL FEATURES FROM TIME AND FREQUENCY DOMAIN FOR CHATTER DETECTION

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Abstract: *This paper presents the results of the research into the applicability of the features derived by statistical analysis of signals from the machining process in the recognition of occurrence and evolving of chatter vibration. Selected set of statistical features were discussed, 3 of them in the time domain, an one in the frequency domain. Effects of these signal features were discussed through analysis of the results of two experiments with machining. It was shown that standard deviation and the skewness of the force or acceleration signal have some desirable properties in recognition of the moment when chatter vibrations occur.*

Keywords: *chatter vibrations, signal processing, feature extraction*

1. INTRODUCTION

In early days of theory of machining processes significance of chatter vibrations was recognized, with all types of degradation of process outputs, referred to this phenomenon. From pioneer works by Tlusty, Tobias and Meritt, until present time, during more than seven decades, chatter is permanently in focus of different research projects.

The main directions of these researches are aimed at predicting of chatter vibrations, online identification of chatter occurrence and techniques for its suppression. In the prediction of chattering, models based on the interaction of the cutting process model and experimentally identified dynamic parameters of the machine structure, tool, and workpiece are used [1]. More reliable results in form of stability lobes were achieved through extension of such model with process damping [2]. Finally, the most accurate stability lobes can be created using more complex experimental identification procedure [3].

For applications for machining process monitoring there were presented a number of procedures, based on various types of sensors, and especially numerous algorithms for signal parameter classification in order to recognition of occurrence of chatter vibrations [4]. Most of them are based on fast Fourier transform, wavelet transform and Huang-Hilbert transform. One systematic overview of research achievements aimed for developing techniques for chatter suppression, as a specific kind of adaptive control of machining processes is given in [5].

This paper is related to the domain of on-line identification of chatter occurrence during machining process. The aim was to examine potential use of statistic features of signals, acquired in process, in recognition of the moment in which the chatter vibrations start to evolve. These features derived from time series, of course, cannot be substitute for algorithms based on frequency content of the signal.

A potential benefit is reflected in the possibility that the monitoring system can be of a dual nature. The processing of signal segments in the time domain, as less demanding in terms of processing time, would serve to act as a trigger for signal processing procedures in the frequency domain based on such classified parameters.

This paper primarily is considering the applicability of selected set of statistical features derived from signal in time domain. It is also considered one of the statistical features of the signal in frequency domain. Definitions of these features is given in Section 2. Nature of these features are illustrated on 2 examples with machining, in Section 3. Results obtained from experiments, and potential use of these signal features is discussed in Section 4.

2. STATISTICAL FEATURES OF THE SIGNAL

In Literature source [6], specific sets of statistical features from both the time and frequency domains of a signal as a candidate for parameter classification with specific values that strongly correlate with certain changes in process. In the following, the correlation of some of these features with the stability of the machining process will be discussed using concrete examples. A selected set of these features is shown in Table 1. The first of them refers to the signal transformed into the frequency domain, and the remaining to the signal in the time domain.

Real-time applications imply that processing is performed not for the entire record, but in successive time windows of finite width and certain overlap. The power spectrum of a signal indicates the relative magnitudes of the frequency components composing the signal, identifies the frequencies that carry the highest signal energy. The Mean Square Frequency (MSF) represents the energy of the vibration signal in the frequency domain, where f_j (j=1, 2, L, …, m) is the *j*-th frequency of the power spectrum [7].

Table 1. Statistical features from frequency and time domain

Formulation	Statistical featutes	Domain
$MSF = \dfrac{\sum_{j=1}^{m} f_j^2 S(f_j)}{\sum_{j=1}^{m} S(f_j)}$	Mean square frequency	Frequency domain
$x_m = \dfrac{1}{n}\sum_{i=1}^{n} x_i$	Mean value	Time domain
$x_{std} = \sqrt{\dfrac{1}{n-1}\sum_{i=1}^{n}(x_i - x_m)^2}$	Standard deviation	
$x_p = \max(\lvert x_i \rvert)$	Pick	
$x_{ske} = \dfrac{\sum_{i=1}^{n}(x_i - x_m)^3}{(n-1)\cdot x_{std}^3}$	Skewness	
$x_{kur} = \dfrac{\sum_{i=1}^{n}(x_i - x_m)^4}{(n-1)\cdot x_{std}^4}$	Kurtosis	

The 'Peak' feature represents the maximum value of the signal, while 'Mean' signifies the mean value of the signal, with $\boldsymbol{x_i}$ representing the current value of the signal. These values serve as a basis for calculating other features listed in Table 1. Skewness is a statistical measure assessing the asymmetry of a probability distribution, quantifying the extent to which the data is skewed or shifted to one side. Positive skewness indicates a longer tail on the right side of the distribution, while negative skewness indicates a longer tail on the left side. Kurtosis is a statistical parameter used to characterize a signal, offering a measure of the "peakedness" of a random signal. This feature is widely used in systems for monitoring of assemblies with rolling bearings. Signals with higher kurtosis values have more peaks greater than three standard deviations. The standard deviation measures the extent of signal distortion from the mean value.

3. EXPERIMENTAL EXAMPLES

The specific processing of the signals from the machining process is illustrated by two examples. The first refers to the internal turning with a linearly variable depth of cut. In the experiment, a time record of the acceleration is formed from the accelerometer placed on the tool shank. In the second experiment an internal planar contour was machined with flat end mill with variable axial and radial depth of cut. Recorded signal was referred to the one force component in the XY plane, using a dynamometer on which the workpiece is placed. The dynamometer, in this case, represents a substructure of maximum compliance.

3.1 EXP1: Internal turning

The first case refers to internal turning with a linearly variable cutting depth, as in Fig. 1. In such setting of the experiment, cutting tool was the element with dominant compliance in the whole mechanical structure. Internal turning is particularly interesting from the point of view of chatter vibrations, because the usual logic contained in stability lobes does not apply in this case.

That is the reason for development of special tool holders for such operations [7]. An unstable process is expected in the zone of small depths and especially in cases with small feeds.

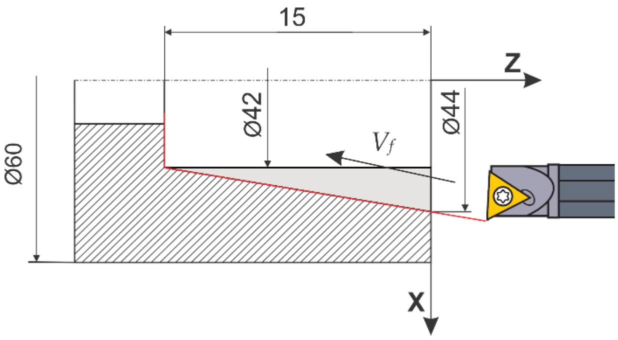

Figure 1. Cutting area in machining test

For this tool setup, an experimental modal analysis was performed, along with a dynamic analysis in Ansys software. Dominant modes have following frequencies: 372.5Hz for X direction, and 409.27Hz for Y direction. (Fig. 2).

During machining tests, the workpiece material was 42CrMo4 steel. Machine: Echo-Eng TCN410 - 2 axis CNC lathe. Tool: R S36.8 - 25-16 with TPMR 160312 4C40 P40 TiN coated carbide insert. Cutting speed 90m/min.

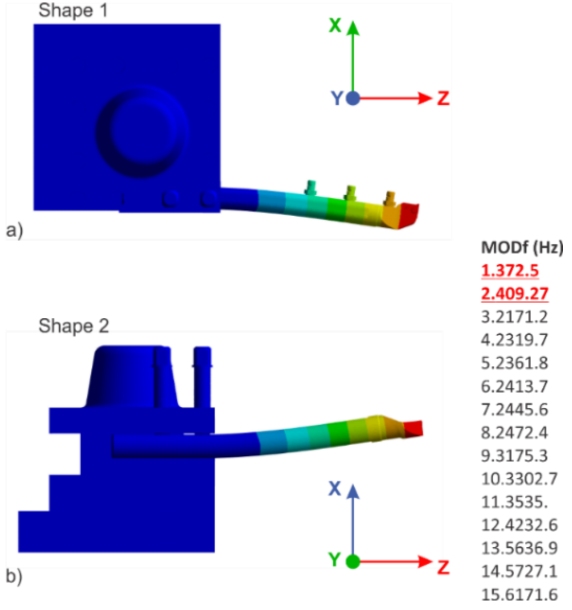

Figure 2. Results of dynamic analysis for tool shank and tool holder (ANSYS)

Set of 3 experiments was performed with different value of feed: 0.15, 0.16, and 0.18 mm/rev. An accelerometer, the PCB Piezotronics 352C03, was affixed to the tool shank. The cDAQ NI 9174, with S/V Input Module NI9234, driven by NI-LabView, were used for data acquisition. Sampling frequency was set on 1024 S/s. Acquired acceleration signal for example with 0.16 mm/rev is shown in Fig. 3.

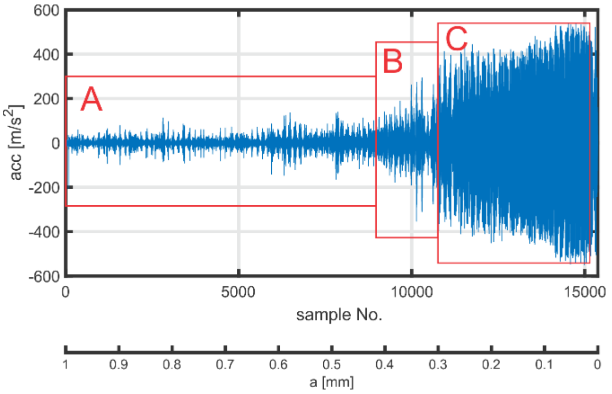

Figure 3. EXP1: Acceleration along X axis of the tool shank

Three zones can be observed in Fig. 3. Area A represents a stable process. The transition region is marked with B, while the chatter region is marked by C. Acceleration signal processing is performed in a sliding window (here called buffers). The width of the window is 450 samples, and the overlapping factor is 0.5 (225 samples).

Figure 3 shows the spectrogram (amplitude spectrum in successive buffers), calculated using FFT. The dominant frequency in all buffers is 372.5 Hz, which is also the frequency of the first mode, determined by the modal analysis of the tool holder. A sudden increase in amplitude at this frequency over time is not noticeable. This can be interpreted as a consequence of the slightly changing process damping.

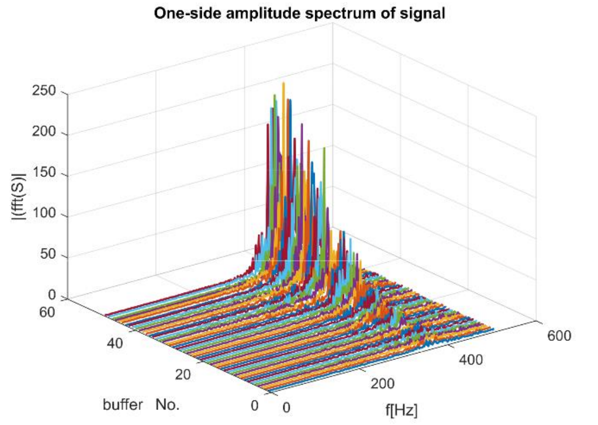

Figure 4. EXP1: Amplitude spectrum in successive buffers

Mean square frequency, defined as in table 1, for this case is shown by the diagram in Fig. 5.

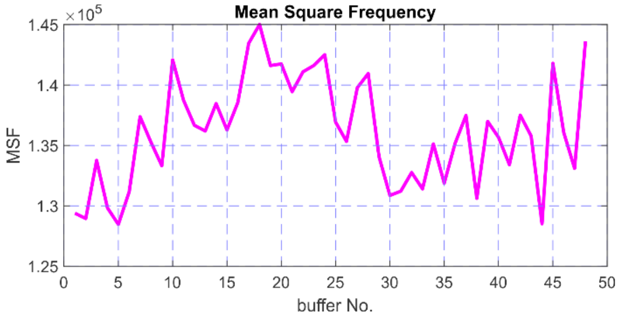

Figure 5. EXP1: Mean square frequency in successive buffers

Figure 6 presents three selected statistics features derived from acceleration signal in time domain.

Here, some conclusions can be made, observing original signal and its different presentation, shown in figures 4-6. In the amplitude spectrum, the dominant frequency is the natural frequency of the structure during whole time.

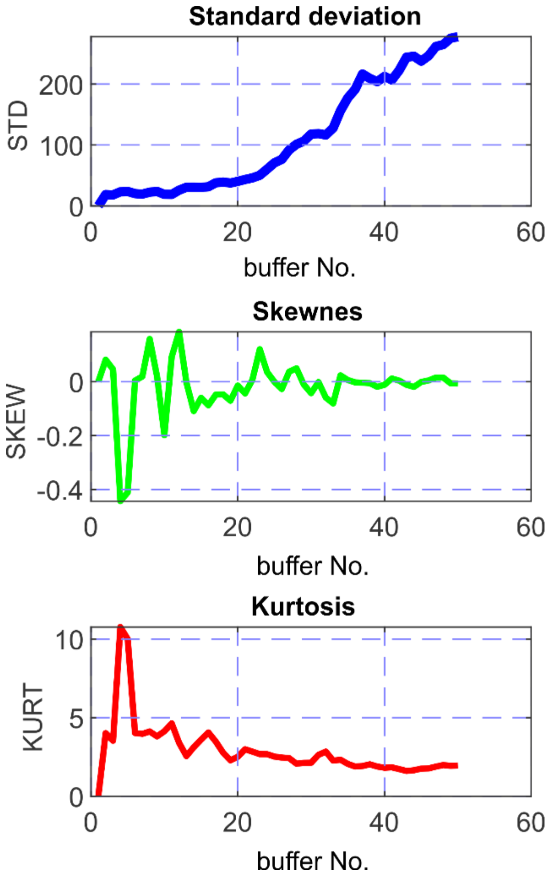

Figure 6. EXP1: Statistical features (time domain) of acceleration signal

In the first part, the amplitudes are smaller, which is explained by higher process damping. It is not possible to clearly identify the moment of chattering. Mean square frequency (MSF, figure 5) has a profile that cannot be clearly correlated with moment of chatter occurrence. The same can be conclude for the profile of kurtosis (KURT). It should be noticed that, in the graph of skewness (SKEW), evolving of chatter vibrations is related with SKEW value near to the zero.

3.2 EXP2: End milling

In This example is referred to milling operation. Measurements was a part from an earlier research project [8]. Figure 7 shows a signal recorded during the milling process (closed internal contour in XY plane), where variations were made through variable axial (0-8mm) and radial (0-16mm) depth of cut along the tool path. Feed rates along tool path was variable, according to results of the algorithm for federate scheduling. In this experiment one pre-machined part made of ENAW 7019 alloy was milled on horizontal machining center (LOLA HMC500). Tool was an HSSE end mill ø16, with 4 flutes. Dynamometer was 4-component, with strain gauges. Workpiece was fixed to the plate of the dynamometer. Force signal (y direction of the dynamometer) was recorded with sampling rate of 2000 S/s.

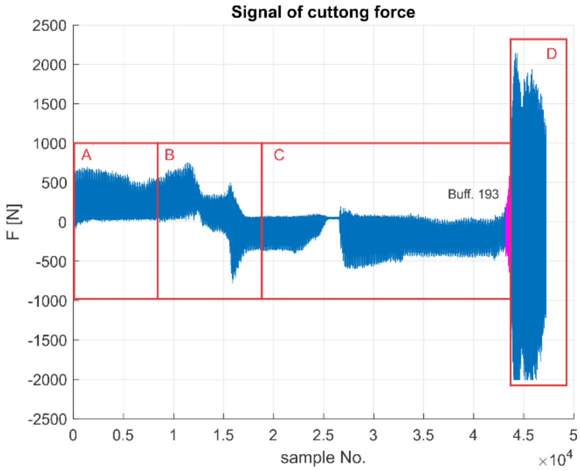

Figure 7. EXP2: Force signal during test with end milling

Time series of measured force contains several zones, regarding chatter vibrations. With A and C there are marked zones of stable cutting process. Specific zone is marked with B, and it was referred to early stage of chatter evolving. Further amplitude rise was suppressed with change in subsequent cutting parameters. Finally, zone B represents true chatter vibrations. Such flow of considered milling operation has clear explanation in spectrogram, shown in Fig. 8.

In the stages of the stable process, the frequency of the mill teeth entering (39Hz) is dominant. Unstable phases of the process have spectrum with dominant frequency equal to the one of the natural frequencies of the dynamometer (280Hz).

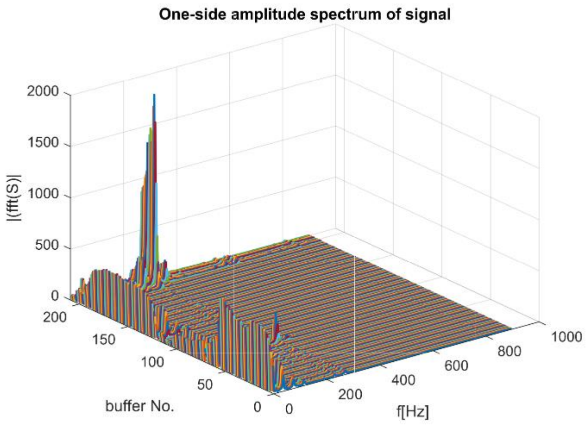

Figure 8 EXP2: Amplitude spectrum in successive buffers

Figure 9 presents the mean square frequency of the signal from this example.

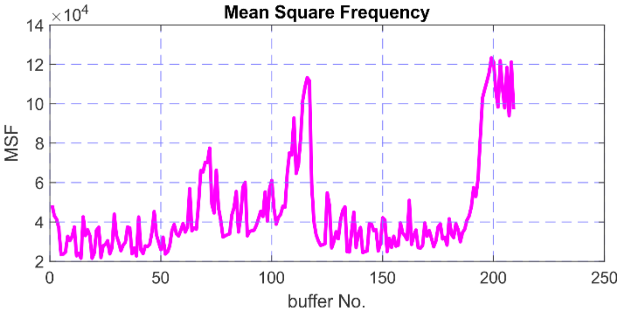

Figure 9. EXP2: Mean square frequency

Figure 10 presents three selected statistics features derived from force signal in time domain.

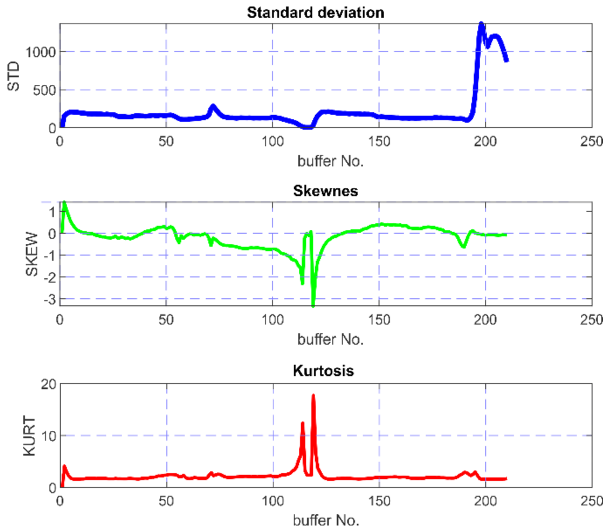

Figure 10. EXP2: Statistical features (time domain) of force signal

Some conclusions can be made, observing original signal and its different presentation, shown in Figs. 7-10. In the amplitude spectrum, evolving of chatter vibrations can be recognized in two zones of original force signal. These situations are followed by changing in frequency of dominant component in amplitude spectrum of considered buffer, shifting this frequency to the natural frequency of the structure (transition from forced to self-exciting vibrations). Evolving of the first occurrence of chatter was broken by change of cutting parameters along tool path. In the second case this evolving is not damped and the sudden rise and high amplitudes of measured force was notable.

These phenomena cannot be recognized by MSF profile (Fig.9) or by kurtosis (KURT, Fig.10). The standard deviation STD, of the force signal (Fig.10) has sudden rise in the zone where chatter occurs. These moments in force signal also corelated with zero values of the skewness (SKEW, Fig.10).

4. CONCLUSION

The paper illustrates the potential of standard deviation and skewness of the signals from machining process in the detection of the occurrence of chatter vibrations. They cannot replace identification algorithms based on fast Fourier transform and wavelet transform, but they can be an additional criterion in the procedures for monitoring the stability of the machining process. This limitation stems from the fact that chattering is accompanied by a marked increase in amplitude (force, acceleration), but that the recognition of high amplitudes in the signal does not mean the occurrence of chattering. In the further work, it is planned to formulate additional derived quantities, for which it is possible to clearly define the threshold, and with the aim of more precisely identifying the moment when chattering occurs.

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