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Time localization of abrupt changes in cutting process using Hilbert Huang Transform

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Cutting process is extremely dynamical process influenced by different phenomena such as chip formation, dynamical responses and condition of machining system elements. Different phenomena in cutting zone have signatures in different frequency bands in signal acquired during process monitoring. The localization of signal's frequency content in time is extremely important in machining operations studying and monitoring. An emerging technique for simultaneous analysis of the signal in the time and frequency domain that can be used for time localization of certain frequencies is Hilbert Huang Transform (HHT). It is based on empirical mode decomposition (EMD) of the signal into intrinsic mode functions (IMFs) as simple oscillatory modes. IMFs can be processed using Hilbert Transform and instantaneous frequency of the signal can be computed.

This paper gives a methodology for time localization of cutting process stop during intermittent turning. Cutting process stop leads to abrupt changes in acquired signal correlated to certain frequency band. This frequency band is localized in time using HHT. To address the problem of low-frequency pseudo components an improvement to HHT is introduced in this paper. The proposed methodology is experimentally verified. The potentials and limitations of HHT application in machining process monitoring are shown.

Keywords: Cutting process monitoring, Hilber-Huang Transform, time localization of signal

0 INTRODUCTION

Sensor based monitoring of cutting process gives valuable information that can be used for process and quality control. In situ monitoring systems are usually based on measurements of cutting force, acceleration, acoustic emission or audible sound close to the cutting zone. All these methods are suitable for practical online application. A comparison of frequency contents of the signal that can be obtained using different sensors is given in Fig. 1.

Cutting process is extremely dynamical process. Besides phenomena related to the chip formation itself, cutting process dynamics is influenced by the dynamical responses and condition of machining system elements (machine, tool, workpiece). Different stages of material removal process: shearing, ploughing, plastic deformation are correlated to the different frequency contents of the signal [1]. As shown in the Fig. 1, interaction of the tool tip with the workpiece microstructural features: voids, inclusions, grain boundaries also leads to different spectral components [2, 3]. Besides, tool condition (wear or breakage) can be identified in signal. Using signal processing techniques, different frequencies carrying information on various phenomena can be extracted from signal.

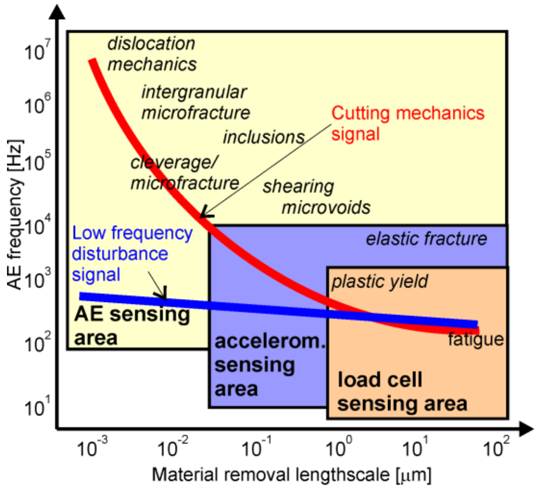

Fig. 1. *Sources of AE in material removal [1]*

The information from sensory system is useful for process and quality control only if it is available in due time. In order to detect tool condition or to detect or link the surface finish or material microstructure to the chip formation mechanism e.g., it is not enough to identify the presence of corresponding frequency in signal. The frequency should be localized in time/space.

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In machining operations monitoring different signal processing methods can be used for simultaneous analysis in time and frequency domain [4]. Short time Fourier Transform (STFT) and specially Wavelet transform (WT) have obtained significant attention. WT was extensively applied in methods for tool condition monitoring [4], or in studying of phenomena related to the chip formation [3] e.g. Nevertheless, in STFT the time and the frequency resolutions are fixed in the whole spectrum. The shortcoming of WT is the poor frequency resolution at high frequency range.

An emerging technique for simultaneous analysis of the signal in time and frequency that gives good resolution in both domains is Hilbert Huang Transform (HHT) [5]. There have been some applications of HHT in general machine health monitoring [6]. Tool condition monitoring methods based on HHT were also researched. In [7] an approach to flute breakage detection in end milling based on HHT is proposed. A tool wear correlation to HHT during end-milling is explored in [8], were the marginal Hilbert spectrum was considered and the changes were not localized in time.

The most dramatic phenomena in cutting process are perceived as abrupt changes during short time interval in acquired signal. Two characteristic conflict situations that lead to abrupt changes are catastrophic tool failure and collision of tool with workpiece, fixture or machine. The third class of phenomena inherently containing abrupt changes is intermittent cutting, while turning splined shaft e.g. This situation does not have conflict contents, it is regular, but delicate state of cutting process. The detection of cutting process start and stop in intermittent cutting is especially important in micromachining. Generally, the exact time localization of abrupt changes in signal is of the most importance.

This paper gives a methodology for time localization of cutting process stop during intermittent turning. Cutting process stop leads to abrupt changes in acquired signal correlated to certain frequency band. The frequency band related to abrupt changes is localized in time using HHT. This approach is different from approach given in [7] since only the energy in frequency band of interest is considered rather than the energy of the whole spectrum.

1 HILBERT HUANG TRANSFORM

In the traditional Fourier analysis the notion of frequency is connected to the sine and cosine functions' wavelength. In order to determine certain frequency using Fourier Transform (FT), one needs data for at least full wave. FT is created for linear, stationary data. Nevertheless, the most of the natural systems are nonlinear and data are usually non-stationary, but for the lack of alternatives, FT is still applied. The typical example is cutting process. In non-stationary data, frequency is changed in each instant, and time localization of frequency is very important. For definition of instantaneous frequency of the signal, Hilbert Transform (HT) can be used. For time series $x(t)$, it is defined by:

$$y(t)=\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(\tau)}{t-\tau}d\tau . \qquad (1)$$

where $x(t)$ and $y(t)$ represent complex conjugate pair and define an analytic signal $z(t)$:

$$z(t)=x(t)+jy(t). \qquad (2)$$

which can be represented in polar coordinate system as:

$$z(t)=a(t)e^{j\theta(t)}. \qquad (3)$$

with

$$\begin{aligned} a(t)&=\sqrt{x(t)^2+y(t)^2} \\ \theta(t)&=arctg(y(t)/x(t)) \end{aligned}. \qquad (4)$$

where $a(t)$ and $\theta(t)$ represent instantaneous amplitude and phase of the analytic signal. They give the best local fit of an amplitude and phase varying trigonometric function to $x(t)$. From instantaneous phase, an instantaneous frequency can be derived as:

$$\omega(t)=\frac{d\theta(t)}{dt}=\frac{\dot{y}(t)x(t)-y(t)\dot{x}(t)}{x^2(t)+y^2(t)} . \qquad (5)$$

As shown in [5] the instantaneous frequency $\omega(t)$ will have the physical meaning only if $\theta(t)$ is monocomponent function. Since θ(t) is derived from $x(t)$, $x(t)$ should be monocomponent signal. This means that $x(t)$ has to wave around, that is to be symmetrical with respect to the zero mean level, without riding waves (purely oscillatory function).

The most of the real world data and specially nonlinear and non-stationary data do not meet given prerequisites. In order to prepare this kind of signals for Hilbert Transform, Empirical Mode Decomposition (EMD) method is introduced [5]. EMD starts from assumption that each signal represents a superposition of simple purely oscillatory functions. These functions are called Intrinsic Mode Functions (IMFs) and represent the counterpart of harmonic functions in FT. IMFs should satisfy the following conditions: 1) the number of extrema and number of zero crossings in the whole data set must be either equal, or differ at most by one, 2) the mean value of the envelopes defined by local maxima and local minima at any point should equal to zero.

EMD decomposes signal into IMFs using sifting process as follows. First, the local maxima and minima are identified and upper and lower envelop are created by connecting local maxima and minima, respectively using cubic splines. The mean of envelopes m_1 is subtracted from signal $x(t)$ and the first component h_1 is obtained:

$$h_1 = x(t) - m_1 . \quad (3)$$

Ideally, h_1 is IMF, but usually this is not fulfilled. In order to create IMF sifting process is repeated more times. In sifting process, h_1 is treated as data and then:

$$h_{11} = h_1 - m_{11} \quad (6)$$

and procedure is repeated k times:

$$h_{1k} = h_{1(k-1)} - m_{1k} \quad (7)$$

until IMF is obtained.

A criterion for sifting process stop is given by setting the standard deviation between two consecutive sifting results:

$$SD = \sum_{t=0}^{T} \left[\frac{\left(h_{1(k-1)}(t) - h_{1k}(t) \right)^2}{h_{1(k-1)}^2(t)} \right]. \quad (8)$$

to 0.2-0.3. The first IMF component is defined as:

$$c_1 = h_{1k} . \quad (9)$$

c_1 is then separated from the rest of the signal by:

$$x(t) - c_1 = r_1 . \quad (10)$$

The residue r_1 still contains information about lower frequency components, and it is treated as a new signal and the same sifting process is applied to it, c_2 is obtained, etc:

$$r_2 - c_1 = r_1, \ldots, r_{n-1} - c_n = r_n . \quad (11)$$

The procedure is repeated n times, until one of the following criteria is fulfilled: 1) c_n or r_n have very small values, 2) r_n is monotonic function.

Sifting process eliminates the riding waves and makes the wave profiles more symmetric. The signal is represented by:

$$x(t) = \sum_{i=1}^{n} c_i + r_n . \quad (12)$$

After IMFs are obtained, Hilbert Transform is applied to each IMF and instantaneous frequencies are computed using eq. (5). Since the starting signal $x(t)$ is multicomponent, it has more than one instantaneous frequency. Applying given procedure signal is represented as:

$$x(t) = \mathrm{Re}\left(\sum_{i=1}^{n} a_i(t) \exp\left(j \int \omega_i(t) dt \right) \right). \quad (13)$$

with time dependant amplitude and frequency.

The signal representation given by (13) represents its HHT. FT representation of the same signal is given by:

$$x(t) = \mathrm{Re}\left(\sum_{i=1}^{\infty} a_i(t) \exp\left(j\omega_i t \right) \right). \quad (14)$$

with a_i and ω_i constant.

Equation (13) enables the representation of the signal in time-frequency-amplitude (energy) 3D space. This representation (in which the amplitude axis can be in the form of colour e.g.) is called the Hilbert spectrum. In Hilbert spectrum the existence of energy at certain frequency means that there is high likelihood that such a wave has appeared locally at that time instant.

As an example, IMFs and Hilbert spectrum in parallel with Fourier spectrum of a synthetized signal are given in Figure 2. A time localization of frequences (20, 30 and 15 Hz) and amplitudes (10, 5 and 7) can be percieved.

One of the shortcomings of EMD is that it generates undesirable IMFs at low frequencies. This is ilustrated in HHT presented in Fig. 2 where the frequencies near 0 Hz which do not exist in the signal are detected. This can lead to missinterpretation of the results.

The low frequencies in HHT come from the low frequency IMFs that do not represent the real components of the signal [9]. In order to addres given problem, the cross corelation of the IMFi with the original signal - μ_i should be checked. Only those IMFs whose cross corelation μ_i crosses predefined treshold λ, should be considered as real IMFs. The IMFs whose μ_i does not cross λ should be treated as pseudo-components and added to the residue.

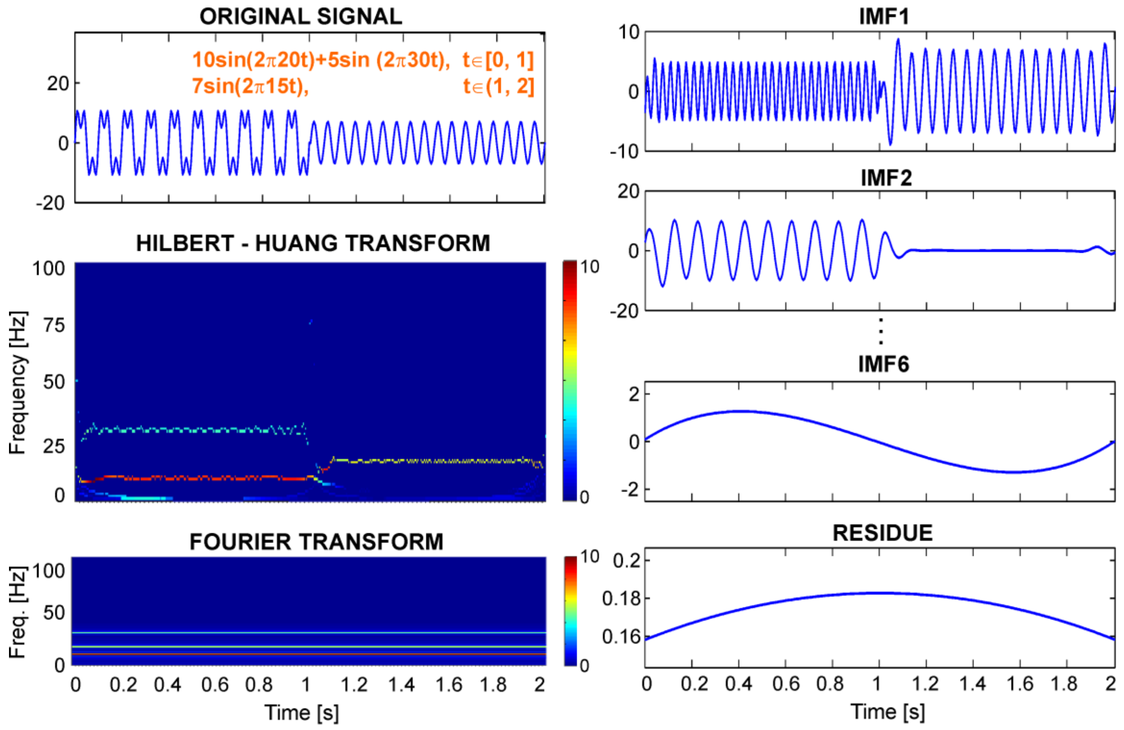

Fig. 2. *Synthesized signal: a.)signal, b) Hilbert spectrum of the signal, c) Fourier transform of the signal, d) IMF components obtained using original EMD*

2 TIME LOCALIZATION OF ABRUPT CHANGES IN CUTTING PROCESS

HHT with introduced improvement is exploited for detection of cutting process stop during intermittent turning.

The kind of intermittent turning applied in this study was chosen because it can be used for simulation of tool breakage [10]. Experiments have shown [11] that tangential force (as well as induced vibrations) at tool breakage increases suddenly when a broken tool part jams between the tool and workpiece and then drops to zero when gap is formed. When tool approaches the workpiece again, forces increase beyond their original value.

Although it seams that the cutting process stop can be clearly recognized, it is not so straightforward. It is covered by free vibrations of entire machining system. The interruption of cutting process is strong energy impulse and it is followed by dynamical response of mechanical system. After the stop, the transients with huge vibrations occur. Besides, there are some other phenomena, like cutting process start, or chip breakage that lead to the similar change in signal.

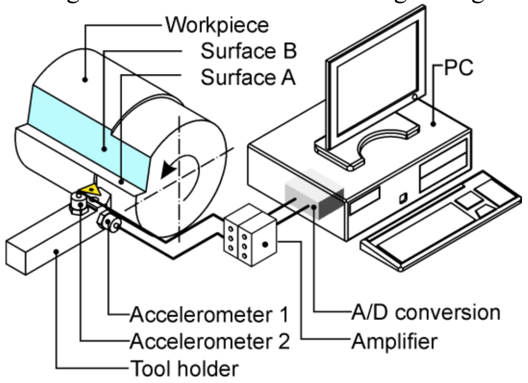

Fig. 3. *Experimental setup*

The experimental setup is shown in Fig. 3. Workpiece is grooved and has two mutually perpendicular flat surfaces of interest. In this way intermittent turning is performed. Surface A provides an extremely sharp decrease (step excitation), while surface B is inclined, thus providing relatively gradual increase of cutting force (ramp excitation). The vibrations caused by cutting process are measured. Experimental setup is shown in Fig. 4. Experiments are carried out on Hasse & Wrede lathe. During experiments speed (118–950 rpm) and feed (0.05–0.2 mm/r) were varied. Two types of P25 tool inserts (TNMM 220408 and TNMM 220424) were used. For measurement purposes, a pair of accelerometers (Kistler 8002) was fixed on tool holder at two perpendicular axes. Signal is acquired using 10 kHz sampling rate.

A signal from one accelerometer acquired during an experiment (n=475rpm, s=0.05mm/r, tool insert TNMM 220408-4025) is shown in Fig. 4. EMD of given signal revealed a total of 13 IMFs. The cross correlation of the first 8 IMFs with original signal was greater than 0.05. These IMFs (Fig. 4) are taken as real IMFs. The remaining 5 IMFs are added to the residue.

The 2d and 3d views of Hilbert spectrum of the signal are given in Fig. 4. Thorough analysis of given spectrum shows that cutting process stop is correlated to high energy in the spectrum at frequencies from 1.8 to 2.3 kHz. The marginal spectrum for this frequency band is shown in Fig. 4. At these frequencies cutting process stop is clearly extracted from all other phenomena with similar signature in signal (transients after process stop, cutting process start, chip breakage, etc.).

The proposed procedure gave the same results for all the experiments.

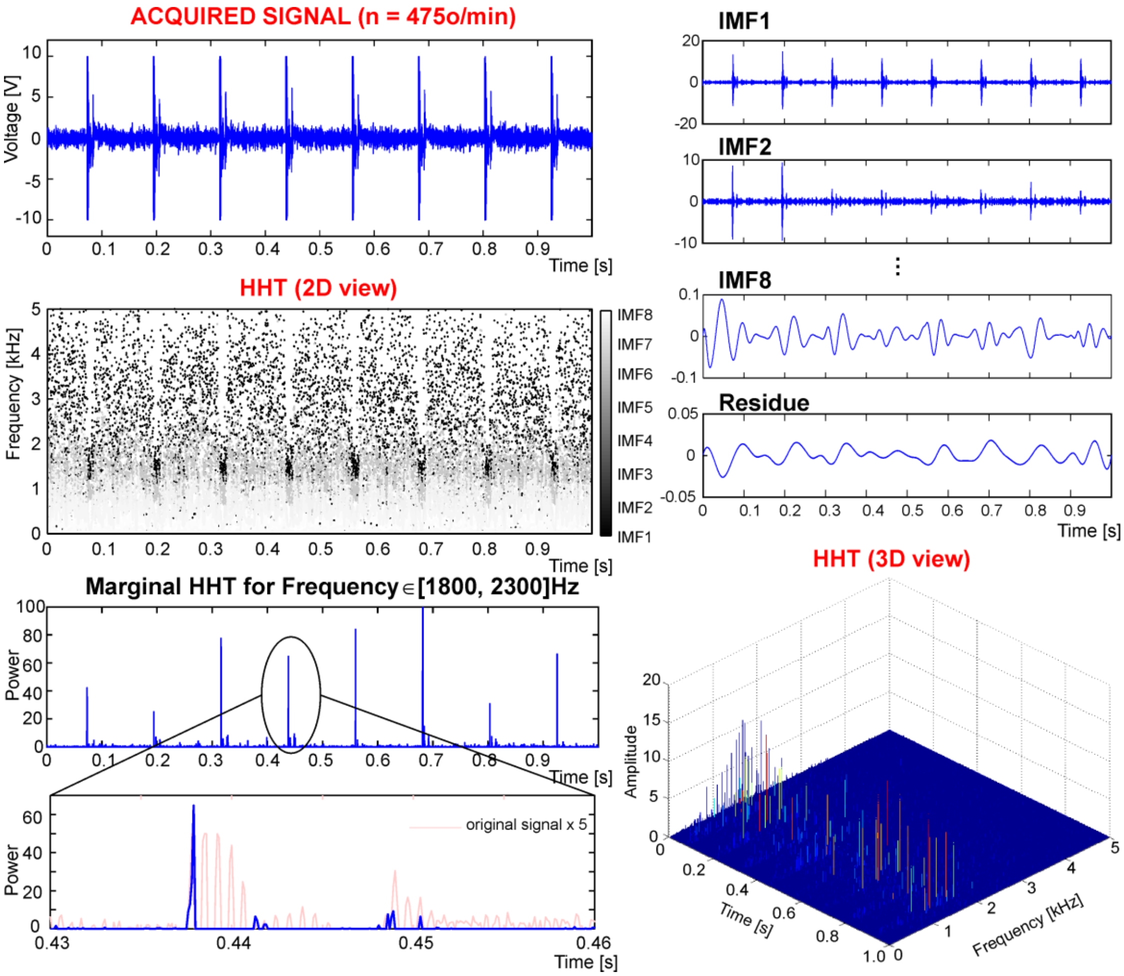

Fig. 4. *Experimentally obtained signal: a.) acquired signal, b) Hilbert spectrum of the signal – 2D presentation, c) Marginal Hilbert spectrum for the frequencies 1800-2300Hz, d) IMF components obtained using improved EMD, e) 3d view of Hilbert spectrum*

3 CONCLUSION

In the monitoring, as well as in the studying of machining operations, time localization of certain frequency bands represents an important issue. The time-frequency analysis technique used in this paper, HHT, gives much sharper resolution in frequency and a more precise location in time when compared to STFT and WT. In HHT the resolutions in both domains can be as high as sampling rate allows. HHT is intuitive, direct, a posteriori and adaptive. The decomposition into IMFs is obtained from the data, while harmonic functions and wavelets are chosen a priori. IMFs represent complete, adaptive and almost orthogonal representation of the analyzed signal.

Nevertheless, HHT has some shortcomings: 1) EMD generates undesirable IMFs at the low frequency region that may cause misinterpretation of the result; 2) In order to make instantaneous frequency physically meaningful, IMFS should be in narrow frequency band; depending on the analysed signal, the first IMF may cover too wide frequency range, so that the property of monocomponent can not be achieved; 3) the EMD can not separate signals that contain low-energy components.

The first shortcoming was addressed in this paper. The pseudo IMFs are excluded from decomposition using cross correlation with original signal as a criterion. In this way the number of IMFs that should be computed online is reduced, and real-time applicability of the method is improved.

The cutting process stop in intermittent turning studied in this paper is correlated to the certain frequency band in Hilbert spectrum. It is shown that the HHT can be used as a powerful tool for exact time localization of cutting process stop.

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