Monitoring of drilling conditions using the Hilbert-Huang transformation

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Abstract. The article presents the results of design and monitoring the drilling process. Vibroacoustic sensors were used to observe spindle vibrations. These signals were subjected to a Huang decomposition and a Fourier transform. Results for various conditions were studied and classified with help of Fourier spectra and the envelope curves. Using the additional results of numerical simulations sources of vibration were identified. We considered four different types of drilling which were diversified in terms of geometrical parameters of blades. The application of Hilbert transform enable to find nonlinear characteristics via the deflection profile of resonance backbone curves.

1 Introduction

The recent development of materials and new technologies used in the construction of machines require improvements of tools used for machining [1]. The improvement consists of applying wear resistant coatings and adjusting the geometry of cutting tools but also certain machining parameters and identification of dynamical system response [2, 3]. This trend can be seen in aerospace and automotive industries, where the use of ultra-light and durable materials are important in construction [4].

In many industrial areas, the desire to reduce manufacturing cost, shorten manufacturing time, or even the time for implementing the production of a new type of material, e.g. composite material, Inconel and stainless steel, is important [4–6]. Modern computer tools for simulating the operations of machining tools and measuring paths with various sensors are applied to this end [3, 7]. Numerical methods and research tools applied in laboratories are being increasingly applied in tool-rooms. Computer technologies allow new methods and algorithms to control and evaluate of machining tools' operation.

In this note, we apply empirical mode decomposition in accordance with Huang [9] and Hilbert [8] algorithms designed for the assessment of machining tools' operation. As a result of Hilbert-Huang decomposition, information on the amplitude and frequency of integral signals composing the analysed signal in current time is obtained [12]. The evaluated empirical modes characterize phenomena emerging during aggressive machining, which induces vibrations in the machine-material-tool system (m-m-t system). Isolation of integral systems with regards to their frequency and amplitude enables information on the tool's vibrations while the individual cutting edges penetrate the material to be obtained. Such information allows for machining parameters to be selected and optimized, the tool's working conditions, including cooling, lubrication and wear, to be monitored.

The heat generated during the cutting process is less well evacuated because the drill is always surrounded by workpiece material. There are no entering phases of cutting edge into the material (for shallow holes, without breaking the chip).

Modeling of the cutting process takes into account the types of materials and geometries of workpiece and tool, and cutting speeds and chip load. Cutting coefficients are determined during experimental cutting or using mechanistic models. These coefficients are used to predict cutting forces, torque, power and limits of the chatter stability. In order to estimate the stress, strain and temperature distribution in the tool and chip is used micro mechanics of metal cutting. Beyond material properties like elastic modulus, yield stress and fracture toughness, the friction can also be important[13, 14].

An analysis of the slip line field with numerical modeling can provide detailed information about the cutting zones. However, due to the deformation, rates of strain and temperature these numerical modeling of cutting process is complicated and complex. For the prediction of reaction in parts and tools depend on cutting conditions developed an Arbitrary Lagrangian-Eulerian Finite Element (ALE-FE) [13, 15].

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Among the significant size of the cut affecting the service life of tools can mentioned the flow stress and average forces per tooth. The finite element (FE) model used in this study is based on the commercial FE software “Thirdwave AdvantEdge!”. This software conducts calculations based on six-nodded quadratic triangular elements. The tool drills through the workpiece at a constant speed and constant feed rate. Simulations were started in a state after entering the blade into the material [16, 17].

2 Materials and apparatus

Example signals were collected during extensive studies conducted in cooperation with a producer of special cutting tools. The studies pertained to the adaptation of tools’ geometry and working parameters to the type of the machined material, and requirements associated with tools’ durability and manufacturing capacity they were intended for.

The object of the study were 6 mm-diameter drills tested on steel. In the course of the study, vibrations of the drilling machine’s spindle caused by forces impacting the tool’s cutting edges in the machining process were recorded and analysed. The signal of the tool vibration during drilling process recorded by means of Hansford Sensor HS-102 measuring system with the range of 16 kHZ and sensitivity of 100 mV/g. Vibroacoustic sensors provide the acceleration signal, which is then filtered by means of Buttherworth’s high-pass filter to eliminate signal’s drift and obtain an average value of zero. The sensors were attached to the spindle perpendicularly to the tool’s axis by means of magnets (X and Y directions). Signals were recorded by means of National Instruments data acquisition card type NI USB6341 equipped with a 16-bit converter of 500 kS/s update rate. The recorded acceleration signal underwent consecutive integration operations in order for characteristics of speed and sensors’ shift to be determined. Such characteristics provide information on forces influencing the spindle. Due to the ambiguity of signals’ interpretation obtained from the vibroacoustic sensors, the study was comparative in character. Drills of various materials, types of coatings and geometry of teeth were compared in twos. Studies were commissioned by the producer of special cutting tools (adapted to the requirements of manufacturing process of the ordering party) in order to evaluate advantages of changes introduced in improved tools.

Example characteristics analysed further in the paper were recorded in the course of 6mm drills’ work, which were intended to cut series of holes with depth of 15mm.

We use decomposition methods of empirical algorithms developed by Hilbert and Huang to assess the working conditions of cutting tools. As a result of Huang decomposition, and Hilbert transform information about the amplitude and frequency of the signal components forming the analyzed signal is obtained. As a consequence, signal components are extracted and information about the amplitude and frequency is obtained. The resulting components (modes) characterize phenomena occurring during an aggressive type of machining, during which induced vibration is a complex tooling system (machine, grip, object, tool). Separation of the component signals, because of their frequency and amplitude information can be confirmed on the tool vibrates during insertion of the material of the panels. This information allows the selection of cutting parameters, and their optimize and monitor the con-

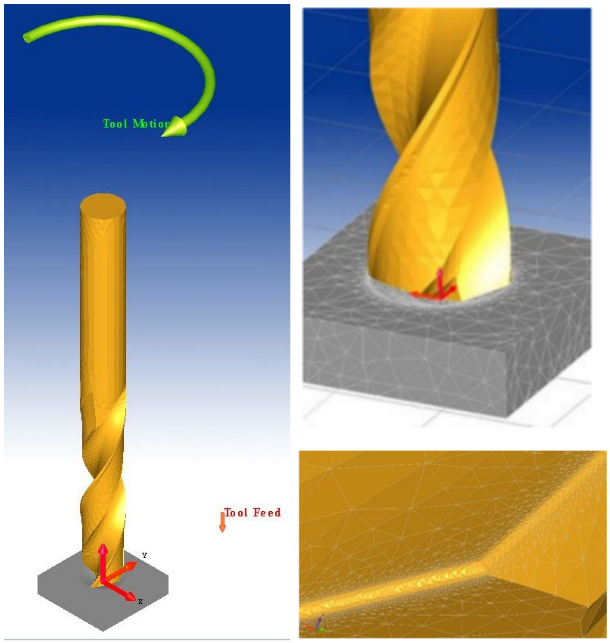

Figure 1. 3D simulation: solid model of drilling (a), mesh (b) and zoom of cutting edge with roundness (c).

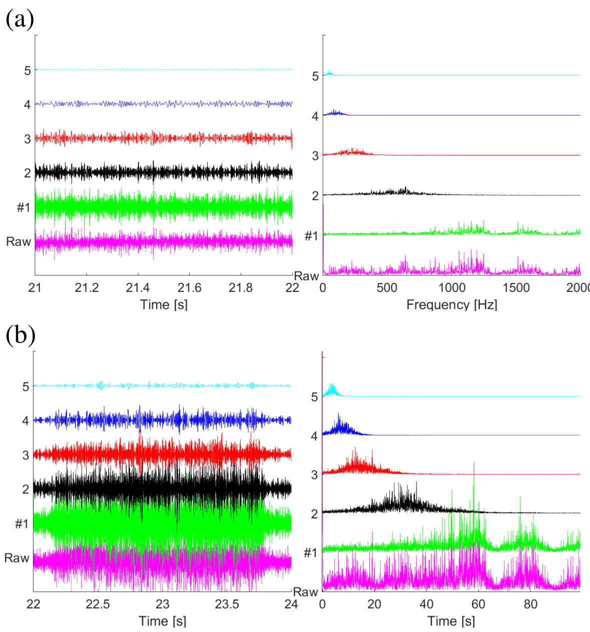

Figure 2. Huang’s empirical mode decomposition of the vibration signal recorded during (a) positioning passes without machining (channel 1, command G0, time=1 s) and (b) drilling work pass (channel 1, command G1, time=2 s) into modes (left side) and FFT spectra of mod Huang (right side).

ditions of work tools, including cooling, lubrication and wear of tools [3, 4, 10, 11].

In the analysis by Hilbert-Huang one performs the so-called signal decomposition into empirical modes (Huang decomposition): $F_x^1(t)$, $F_x^2(t)$, ..., $F_x^m(t)$ [4]:

$$F_x(t) = \sum_{j=1}^{m} F_x^j(t) + r_m \tag{1}$$

where r_m is a truncation error after estimation of successive m modes. Each next empirical j mode is defined after subtracting average of maximum and minimum values interpolated by cubic splines of the local envelope $F_x^{j-1}(t)$. Note that the first mode $F_x^1(t)$ is obtained from the original signal $F_x(t) = F_x^0(t)$ and the Huang decomposition procedure [9]. The Hilbert transform is obtained from the original signal $g(t) = F_x^j(t)$ as follows:

$$\hat{g}(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{g(\tau)}{t - \tau} d\tau. \tag{2}$$

Finally, a new complex function z(t):

$$z(t) = g(t) + i\hat{g}(t), \tag{3}$$

provide information about the instantaneous amplitude, A, phase, Θ, and frequency $f = 2\pi(d\Theta/dt)$.

3 Results and Discussion

The simulation encompassed the sliding motion pass of two cutting edge through the material. The material has shape of cone of a cone matching the cutting edge of drill. The analysis of phenomena occurring in machining zone encompasses tools' FEM simulations. Figure 1 presents an example of geometrical and working condition choosing including different radius of cutting edge rounding. Consequently, the 3D simulations encompassed the sliding motion pass of one cutting edge into the material.

On the basis of 3D machining models, force characteristics impacting the tool were determined. Results of simulations are presented in Tab. 1. Low values of maximum force and standard deviations (values in parentheses) in X, Y and Z directions should increase tool life. The lowest values of maximum force and standard deviations characterized drill with R =10 μm.

After approval of changes to the credit card's credentials, there are a series of prototype tools that are subjected to testing at a nearby position in the vibration sensors. Comparative tests have been carried out, monitoring the working conditions of cutters divided into groups differing in the rounding radius of the blade. Five tools were prepared in both groups. During testing at the Manufacturer's Factory, stainless steel material. The drilling depth was 15mm. The treatment was carried out at spindle rotation S =2000 rpm.

Experimental results are presented in Fig. 2. Namely, the comparison of decomposition of the signal recorded during tools' passes (command G1), when the tool cuts the material with positioning passes (command G0), when the spindle spins and moves without the contact between the tool and material. The isolation of signal's components (vibrations) associated with the drive system of the machine allows them to be isolated from the registered signal in the course of the tool's work, and the analysis of only these components which were induced by phenomena resulting from machining itself. Furthermore, Fig. 2a presents an example characteristic of a signal recorded without drilling (Fig. 2b, plot labeled "raw"). The recorded interval was of 1 second, with sampling frequency of 4kHz. The left side plots outline the recorded signal and consecutive modes obtained by Huang's decomposition algorithm. On the right side, the corresponding spectra obtained by Fast Fourier Transform are collected. Finally, Fig. 2a features clear cut frequency intervals characterizing individual Huang's modes (components of the tool's vibration signal). High spectra were recorded to higher frequencies and outlined in modes 1 and 2. These frequencies result from phenomena occurring in machining zone including: the way the material is cut by the edges, head's vibrations (tools of small diameter), change of drilling depth in individual passes through the material in circular motion. Due to the was the Fast Fourier Transform (FFT) is estimated, component signals induced by one type of the phenomena may induce peaks in the spectrum in various locations. However, the featured characteristics demonstrate the utility of Huang's decomposition in monitoring the conditions of machining. It is also worth to notice that the truncation error r_m (Eq. 1) was negligibly small after first 5 modes. Fig. 2 show that the Huang modes from 1 to 5 decrease considerably.

Hilbert-Huang empirical mode decomposition is based on isolating composing signals on the basis of their frequency and amplitudes. Values of the amplitudes characterising the component signals enables the sources of the generated signals to be determined and the analysis of their root causes to be conducted [3, 4]. In case of FFT, the selection of signals is based upon frequencies. An additional difficulty in interpretation is associated with intervals of composite signals which were identified as being multiple from the original frequency, and which form a separate concentration on the spectrum chart. FFT analysis revolves around the quantitative analysis with regards to frequency, while Hilbert-Huang decomposition enables values of amplitudes and frequency in time to be established. Such a feature is of particular utility in the evaluation of machining in real time in industrial conditions.

Figure 3 presents example of 1.75 s interval for tool's passes (record of spindle's vibrations) in the course of a single operation during the tool's pass (a) and 1s interval for a positioning pass without cutting (b). They underwent Huang empirical mode decomposition, and subsequently Hilbert spectral analysis. Values of instantaneous frequencies (vertical axis) and amplitudes (colour of the point) in 6 initial Hilbert-Huang's modes were presented by means of points. Due to the overlap of results on the chart the point's numerical force are invisible in frequency (time) plane. Therefore, their force in individual areas may be assessed by evaluating neighbouring concentrations' results.

The intervals featured in 3 are significantly different with regards to Huang modes' amplitudes of higher fre-

Table 1. Maximum values (and standard deviations) of FEM results analysis of tools with the corner radius R =(0, 10, 20, 30 [μm])

Corner radius [μm]	0	10	20	30
Force X [N]	579(199)	522(137)	1556(421)	5638(1943)
Force Y [N]	640(169)	412(102)	595(151)	8091(1877)
Force Z [N]	1574(177)	1468(195)	2052(255)	2382(456)
Power [W]	3827(701)	4563(929)	4062(907)	10834(2395)
Torque [Nm]	9(1.6)	10(2.1)	9(2.1)	24.63(5.44)
Temperature [C]	1224(42)	935(42)	1277(47)	1347(61)
Tool Stress [MPa]	3727(117)	1566(98)	1596(89)	1626(122)
Contact Pressure [MPa]	5745(258)	8069(383)	10205(504)	9996(662)
Contact Shear [MPa]	2804(207)	2432(156)	2468(164)	2417(180)
Deflection X [mm]	0.044(0.007)	0.022(6.5e-3)	0.018(0.016)	2.59e-5(7.9e-3)
Deflection Y [mm]	0.014(4e-3)	0.015(4.8e-3)	0.009(4.2e-3)	4.42e-6(8.27e-3)
Deflection Z [mm]	0.002(6e-4)	0.002(5e-4)	0.004(5e-4)	3.06e-5(1.05e-3)

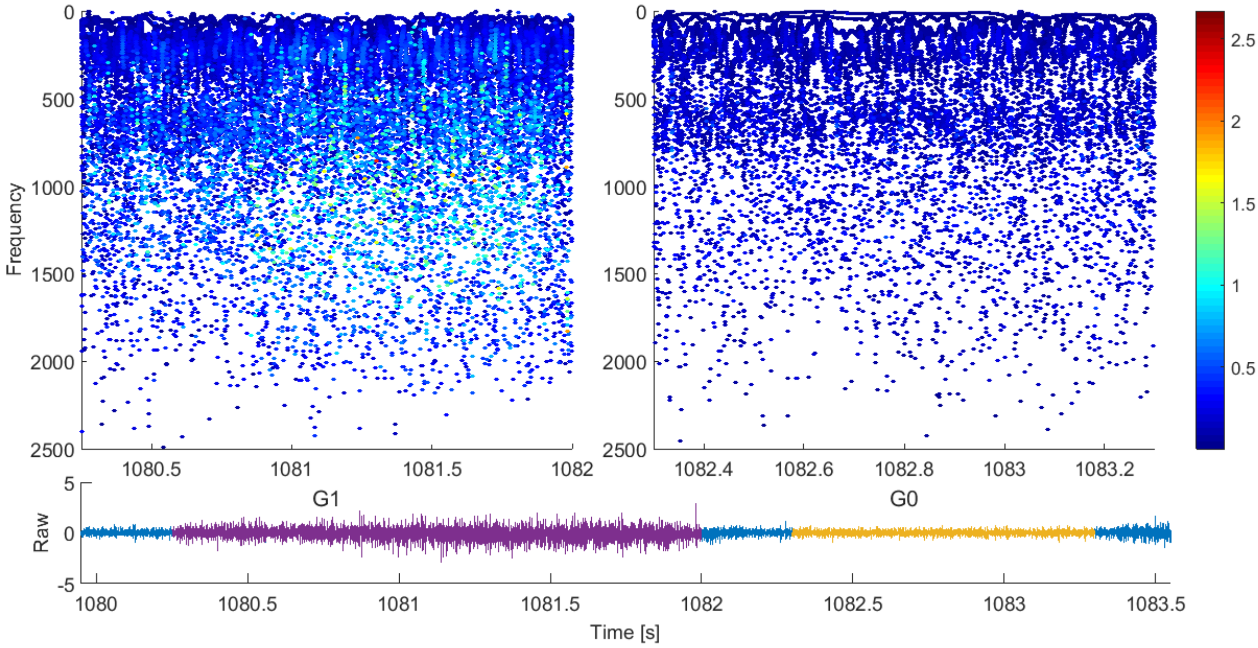

Figure 3. Sequence of frequencies from Hilbert-Huang's transform of example passes of tool No. 8 (group of tools with rounding edge of the blade R = 10 μm) in the course of a) drilling (command G1, left drawing) and positioning pass (command G0, right drawing), featured in the bottom channel. The color scale in the upper channel denotes the amplitude size.

quencies, over 1100Hz. An increase in the amplitude in the course of a tool's pass (Fig. 3a) in relation to vibrations originating from the machine (ranging from 50 to 1500Hz) may also be noticed. Such an analysis enables vibrations induced by the machine's drive system to be distinguished from vibrations generated by the cutting tool.

Fig. 4 presents the Magnitude (Frequency) of Hilbert-Huang's instantaneous decompositions in the course of the end mill's pass and spindle's positioning pass. Such a projection enables differences between passes to be determined. Vibrations' areas presented in Fig. 4b are characterize the machine's work in the course of positioning passes, above the machined material, in the same direction the tool's pass was made (Fig. 4a). The area visible in fig. (b) has two higher(elevated) areas with maximums in 400 and 1400 Hz. Similar concentrations are visible in chart (a). However, the amplitudes increased approximately 1,5-fold for frequencies 400HZ and 3-fold for wide area around 100Hz by forces originating from the tool's work. The remaining points present in fig. 4a result from the material being cut by cutting edges.

Initial evaluation of machining quality comes down to the observation of the points' concentration above the limit line of approx. 0.06 on the amplitude axis of accelerations registers by means of vibroacoustic sensors and decomposed by Hilbert-Huang's decomposition. High amplitude values characterize values of forces impacting the tool's edges. When selecting machining parameters, reduction of amplitudes is desirable.

Fig. 5 presents the analysis of vibrations' sources included in Huang's individual modes, conducted on the basis of frequency spectra. It may be conducted on the basis

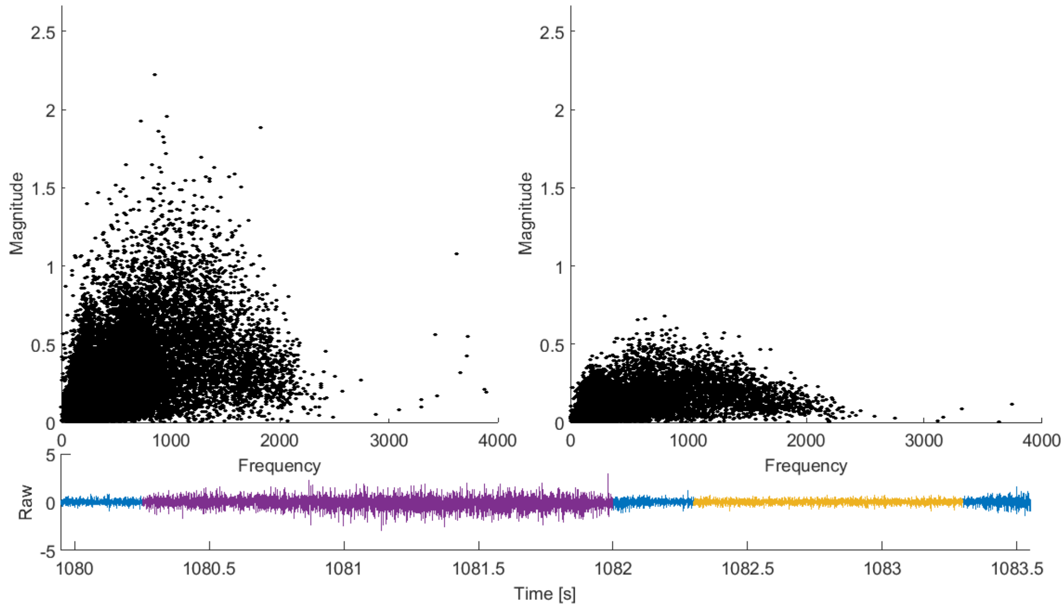

Figure 4. Magnitude versus frequency plot of Hilbert-Huang's instantaneous decompositions results for example passes of tool No. 8 (group of tools with rounding edge of the blade $R = 10\ \mu$m) in the course of drilling (command G1, left drawing) and positioning pass (command G0, right drawing).

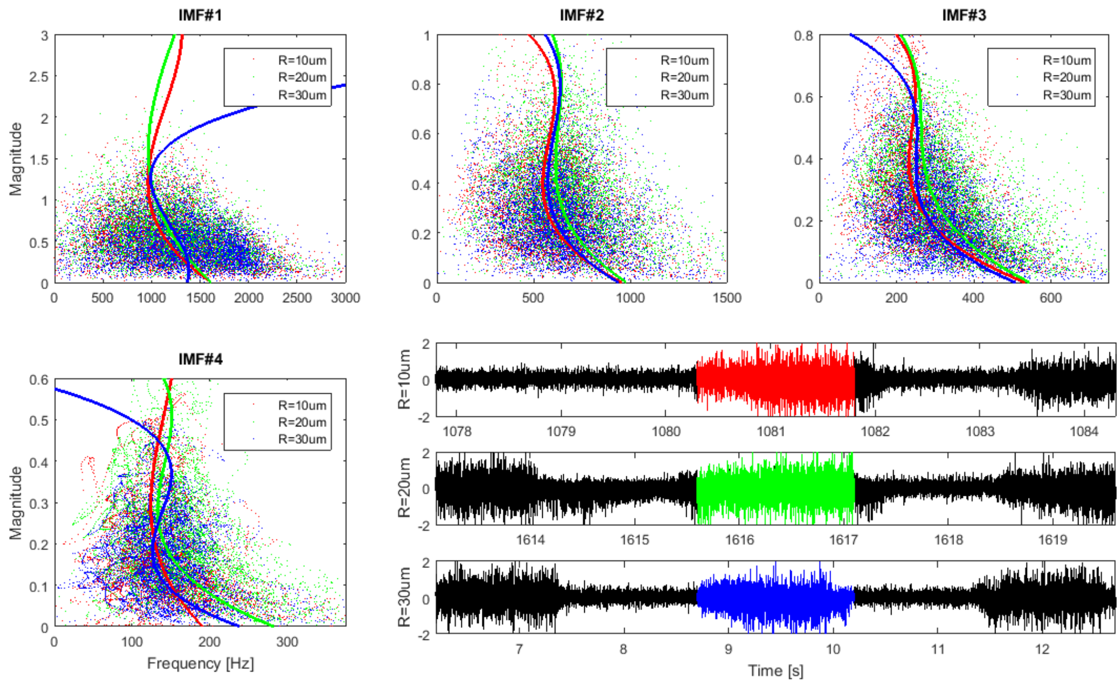

Figure 5. Relationship of amplitude and frequency of Hilbert-Huang empirical mode decomposition in example passes of three types of drills (with various parameters R of the tool corner radius, indicated). The deflection of the backbone of the modal (first four modes: INF#1-4) resonance curves. The fitting polynomial backbone lines are plotted exceeding the estimated clouds of estimated points in purpose to show the differences in nonlinear responses. Note, the system nonlinearities are signalled as backbone deflections in the particular modes.

of Amplitude (Frequency) charts. Relationship of amplitude and frequency of Hilbert-Huang empirical mode decomposition in example passes of three types of drills with different radius of corners, adequately 10, 20 and 30 [μm]. The backbones of the resonances obtained from the analysis indicate the nonlinearities in the physical process. Interestingly, both of nonlinearities are present in the empirical mode characteristics: hardening and softening. The most transparent are first three modes. Additionally, the backbones of the first and third modes are sensitive to the parameter, R, representing the type of drills, while the second mode seems to be independent.

4 Summary

When monitoring machining conditions with vibration sensors, recorded signals are distorted by components generated by the drive system and machine tool's mechanisms. The application of Hilbert-Huang empirical mode decomposition enables the extraction of vibrations' signals with regards to their amplitude and frequency.

An example decomposition of signals recorded by means of vibroacoustic sensors was made during drilling. FTT spectral analysis of Huang's modes was employed in order to establish frequencies characterizing known vibration sources such as: spindle's rotational speed, number of teeth on the cutting tool, and tool's vibration frequency determined during numerical simulations. Component signals generated in machining zone were isolated on Hilbert-Huang modes Amplitude (frequency) chart.

Hilbert-Huang decomposition enables amplitudę and frequency values to be determined in time. Such a feature is of particular significance for evaluating machining conditions in real time. The Huang's lower modes contained components of higher frequencies can be used during the real-time monitoring of the cutting.

The backbone shapes in the frequency-amplitude distribution specify uniformity of tool working. A vertical shape of backbone is characterized for oscillations with a lower content of nonlinear components. Nonlinear components are related to the cutting process dynamics and reflect larger amplitude chatter oscillations. They are most frequently undesirable, so we indicate such a tool with lower durability.

Note that the results of signal decomposition for different tools are very close to each other. The shapes of mode resonance backbones for all of them have similar shapes. This is expected phenomenon because the tools were nearly identical (same number of teeth, values of angles and other outside the rounded edge). Huang decomposition allows to detect subtle differences in the work of geometrically improved tools. It is also possible to observe the effects of such phenomena like slip-stick motion and contact losses.

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