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Experimental Analysis and FEM Modelling of a Cutting Tool Vibrations

***Aco ANTIĆ*[1], *Milan ZELJKOVIĆ*[1]**
***Petar B. PETROVIĆ*[2],**
***Aleksandar ŽIVKOVIĆ*[1] and**
***Janko HODOLIČ*[1]**

1) Fakultet tehničkih nauka, Univerzitet u Novom Sadu (Faculty of Technical Sciences, University of Novi Sad),
Trg Dositeja Obradovića 6,
21000 Novi Sad, **Republic of Serbia**

2) Mašinski fakultet, Univerzitet u Beogradu (Faculty of Mechanical Engineering, University of Belgrade), Kraljice Marije16,
11120 Beograd, **Republic of Serbia**

antica@uns.ac.rs

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Presented in this paper is a comparative analysis of vibrations, measured during machining process and modelled by FEM. Moreover, microscopic structure of chip cross section was analyzed in order to establish the frequency of lamellae generation and its influence on the total level of vibrations of the cutting tool. Based on the results thus obtained, a method was proposed which allows determination of tool wear degree through separation of reliable indicators from the high-frequency spectrum of the measured vibration signals. This investigation showed that the change of chip segmentation frequency significantly influences the output vibration signal within the high-frequency spectrum, and is a function of tool wear degree.

Eksperimentalna analiza i MKE modeliranje vibracija reznog alata

Izvornoznanstveni članak

U radu je prikazan usporedni pregled vibracija reznog alata izmjerenih u procesu obrade i modeliranih primjenom metode konačnih elemenata (MKE). Također, analizirana je mikroskopska struktura poprečnog presjeka odvojenih čestica sa ciljem utvrđivanja frekvencije stvaranja lamela i njihovog utjecaja na ukupnu razinu vibracija alata za obradu. Prikazom dobivenih rezultata postavljene su osnove za verifikaciju predložene metode određivanja stanja istrošenosti alata izdvajanjem pouzdanih pokazatelja iz visokofrekventnog dijela spektra signala izmjerenih vibracija. Provedeno istraživanje pokazalo je evidentan utjecaj promjene frekvencije segmentacije odvojenih čestica na odziv signala vibracija u visoko-frekventnom dijelu spektara, te ovisnost o promjeni stupnja istrošenosti reznog alata.

1. Introduction

The sources of vibrations appearing on a tool are of diverse origin, while their causes can be classified into deterministic and non-deterministic. Among the deterministic ones are: material deformation, friction of the tool and workpiece and chip separation. Their main feature is the inherent nonlinearity, having as a consequence the appearance of self-induced vibrations in the cutting process [1] and [2].

The increased loads lead to the reaching the material elastic limits, rise into the plastic deformation zone and material failure. In the process, the accumulated energy that appears impulsively each time the lamella shearing process occurs i.e. a chip is being formed, is released. This can be explained by the fact that in the material that has the crystal structure, the micro crack occurs during the crystal breaking and it rapidly moves creating the material failure i.e. breaking the inter-crystal connections and releasing the energy. These short-term individual events induce the elastic-viscous behavior of the workpiece system that generates vibrations in a wide frequency range. The friction on the contact areas between the tool and the workpiece creates the "stick-slip" effect. This effect introduces the vibrations into the workpiece system, which, same as in the case of the formation of chip segmentation can be observed as a set of discrete energy impulses inducing the elements of the workpiece system in the wide frequency range as well.

Chip morphology significantly influences thermo-mechanical characteristics in the tool/workpiece system, which directly impacts tool life. In order to increase productivity and tool life, simulations of influence of machinability, chip forming mechanism, and chip segmentation type on tool life have been performed [3] and [4].

Symbols/Oznake

a_p	- cutting depth, mm - dubina rezanja	p_{sb}	- saw-tooth height, mm - širina nazubljenog dijela segmenta
d_c	- shear band spacing, mm - širina formirane lamele odvojenih čestica	v_{ch}	- chip speed, m · min^{-1} - brzina odvojenih čestica
$_{seg}$	- chip segmentation frequency, Hz - frekvencija segmentacije odvojenih čestica	v_c	- cutting speed, m · min^{-1} - brzina rezanja
f	- feed, mm - posmak	δ_{sb}	- shearing zone band, mm - širina zone smicanja
$_h$	- average height of the deformed chip part, mm - srednja vrijednost visina deformiranog dijela odvojenih čestica	γ	- rake angle, ^{o} - kut rezanja
h'	- chip height of continuous portion, mm - visina neprekinutog dijela odvojenih čestica	λ_h	- chip compression ratio - deformacija odvojenih čestica
h'_{ch}	- height of the chip part, mm - visina odvojenih čestica	Φ	- shear angle, ^{o} - kut smicanja
p_c	- segments formation steps, mm - korak formiranja lamela odvojenih čestica		

Morehead et al. [5] investigated the influence of various machining parameters on the shape of the generated chip in hard materials. Included in their analysis was the change of tool wear degree. They established that chip dimensions and frequency of lamellae generation depend on machining parameters and tool wear degree, while the lamellae shear angle is approximately constant.

From the available literature it is obvious that FEM analysis is commonly used in modeling of chip forming mechanisms and tool wear. Yang and Li [6] used FEM modeling to simulate chip forming in cast iron milling. Key elements which were used to enhance accuracy of FEM model were the constitutive material model, friction model, chip forming criteria, chip breaking criterion, as well as the heat propagation and transfer. The results of this research show that the serrated chip formation is accompanied by maximum cutting temperature. In addition, the serrated chip is formed by a double action of thermoplastic and plastic instability. Li and Shih [7] simulated "chip curl" forming mechanism in FEM, comparing the simulation results with experimental ones. They considered the influence of: machining speed, material type, friction type, as well as the influence of tool tip radius on force magnitudes and temperatures at which particular chip forms are generated. Analysis of obtained results leads to recommendations for geometry improvement of tools for titanium alloy machining. Umbrello et al. [8] used FEM modeling to predict type of chip segmentation, orthogonal cutting forces, and their relationship with tool wear. The authors concluded that FEM simulation performed satisfactorily, suggesting further investigation to be directed towards prediction of temperature and force influence on tool wear. Authors used FEM to simulate the influence of tool tip radius on the shape of deformation and the size of continuous chip portion in micromachining. They considered the degree of conformity of the modeled chip forming process with several theoretical laws and experimental results.

2. Geometrical analysis of the Chip segmentation

Segmented appearance of chip lamellas comprises of two phases in which the workpiece material is plastically deformed in front of the tool causing the material convexes on the free chip surface. The result of the material deformation in the process of chip segmentation occurrence is composed of the moderately deformed chip segments separated by detached narrow band with the intensive material deformation [9]. The described model of chip segmentation is presented in Fig. 1.

One of the induction mechanisms causing the vibrations in the machining process is the creation of chip lamellae. Generation of internal stresses within material structure due to material shear and lamellae generation excites complete system into dynamic oscillations at the frequency which corresponds to lamellae generation frequency. In their research, Cotterell and Byrne [10] have determined the frequency of the occurrence of a lamella f_{seg} by analyzing the video material with chip formation. The frequency of chip segmentation formation linearly increases with the increase of the cutting speed, and decreases with the increase in depth.

Chip frequency can occur in the range from 3.8 kHz to 250 kHz in hard material turning, leading to great variations in the frequency of forces in a tool [11]. The influence of chip segmentation onto the tool wear and processed surface quality has not yet been explained in detail, although it has been determined that it influences the intensity of force in the cutting process and the tool condition [5]. Flank wear and Crater wear the primary processes in tool wear with the cutting speed in the range between 80-800 m/min [12] and [13].

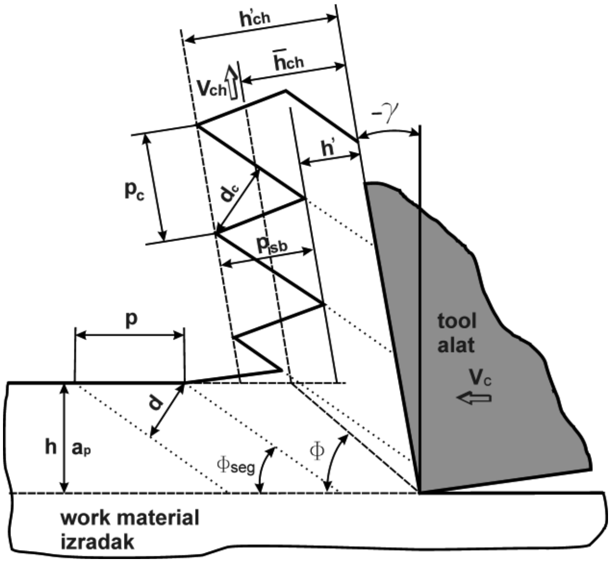

Figure 1. Chip formation model and geometry

Slika 1. Model i geometrija formiranja odvojenih čestica

The chip compression ratio from the [8]:

$$\lambda_h = \frac{h}{\bar{h}_{ch}} = \frac{p_c}{p} = \frac{d_c}{d} \cdot \frac{\sin \Phi_{seg}}{\cos(\Phi - \gamma)} \tag{1}$$

This cutting ratio can be further used to determine the segmentation frequency f_{seg}. Lamella formation in the cutting process is characterized by their occurrence frequency. The chip segmentation frequency can be calculated on the basis of the lamella formation steps p_c, cutting depth $a_p = h$, average height of the deformed chip part $\bar{h}_{ch}$ and cutting speed v_c, applying the expression:

$$f_{seg} = \frac{v_{ch} \cdot \bar{h}_{ch}}{h \cdot p_c} = \frac{v_{ch}}{\lambda_h \cdot p_c} \tag{2}$$

Based on the expression (2), one can observe that the increase of the cutting depth leads to the decrease in the chip formation frequency which is directly observed in the decrease of the chip deformation coefficient.

$$f_{seg} = \frac{v_c \cdot f \cdot \sin \gamma}{h'_{ch} \cdot p_c} \tag{3}$$

The relation (3) comprises parameters linked to the tool cutting geometry and technological parameters speed, feed and depth of cutting. On that basis, it can be concluded that the lamella formation frequency is directly proportional to the machining speed and feed, and indirectly proportional to the depth. The increase in the cutting speed directly influences the chip segmentation formation frequency, the increase in the energy that is reflected in the intensified heat release and the decrease in lamella steps; in a word, the overall wear dynamics is being increased. In the performed experimental research with the plate made of hard metal and the cutting speed range between 200 and 250 m/min, the frequencies of the chip segmentation were around 8 kHz - 100 kHz. Cutting ratio can be further used to determine the segmentation frequency f_{seg}, which is a ratio between cutting speed and segmentation spacing in machining as follows [5]:

$$f_{seg} = \frac{v_{ch}}{p_c} = \frac{v_c}{p_{sb}} \tag{4}$$

The area of the lamella formation frequencies, based on the mathematical calculations equations (3) and (4), approximates the measured frequencies of the tool holder oscillations, i.e. its natural frequencies, between 30 kHz and 120 kHz.

3. Description of work methodology, materials and experiments

The experiments of longitudinal turning were conducted in order to investigate tool wear and its influence on tool vibrations. Sensors placement on tool shank, and workpiece are shown in Fig. 2. Experimental machining was performed on a CNC lathe, "POTISJE Ada", type PH 45. Cutting conditions: cutting speed v_{c1} = 200 m·min^{-1}, v_{c2} = 250 m·min^{-1}, feed f_1 = 0.3 mm, f_2 = 0.25 mm and cutting depth a_p = 1.5 mm. The cutting force were measured using a Kistler 3-axis tool force piezoelectric dynamometer 9257A and a Kistler CA 5001 charge amplifier. The force signals were recorded with a 12-bit PC-based data acquisition system. A sampling rate of 10 kHz was used. Accelerometer Kistler 8002 was fixed on to the tool holder, and used to measure acceleration of vibrations. This signal was sampled at 625 kHz, using A/D converter NI 625 USB, National Instruments. Work material was 42CrMo4, 45HRC hardness, with guaranteed mechanical and chemical properties given in Table 1. Diameter of working material 100 mm and length 500 mm. Dimension of tool shank PTGNL were use during experiment 20x20 mm. Coated tool insert tip P15, TNMG 110408 PGP-415 was mounted in a tool holder.

Vibration alternation is measured using the accelerometer set up at the lateral tool side and oriented towards the longitudinal workpiece axis. During the experiment, vibration accelerations were measured at each cutting pass, for the duration of 1s. Macro geometry, Morphology and microstructure of chip segments gathered during each machining operation were examined on an electronic microscope (SEM).

Table1 Chemical composition of work material

Tablica 1. Kemijski sastav materijala izratka

C%	Si%	Mn%	S%	P%	Cr%	Mo%	Ni%	Cu%	V%
0,4	0,43	0,6	0,3	0,35	0,8	0,15	0,3	0,2	-

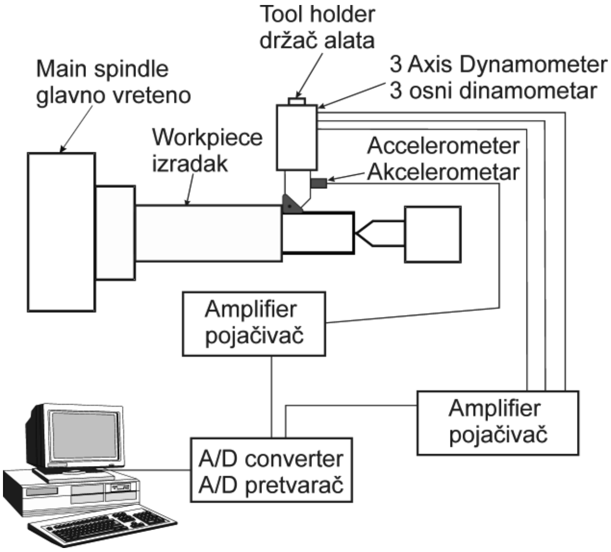

Figure 2. Experimental setup

Slika 2. Ispitni sustav

4. Analysis of chip formation frequency

Most researches in material processing are directed towards the chip formation mechanism and tool wear characterization. Significant for the research in the tool wear effects and chip formation morphology are also cutting conditions. It has been observed that the alteration in the tool wear degree and cutting conditions alters the shape of the occurring chip segments [12]. Tool wear, cutting process parameters and their influence on the chip appearance and shape have been monitored in the experimental research. The shape of the chip has been measured by a microscope depending on the tool wear degree, in diverse cutting conditions (cutting speed, feed and cutting depth). During the processing, the vibrations of the tool holder have also been measured, while the segmentation frequency has been calculated on the basis of the measured parameters for the chip cross section in an SEM.

Figure 3 presents the SEM picture of a collected chip. Chip morphology is characterized by its dimensional values in terms of: saw-tooth height p_{sb}, height of the chip part h'_{ch}, chip height of continuous portion (h'), shear band spacing (d_c), half shear band width (δ_{sb}), angle in the direction of the initial crack (Φ_{seg}).

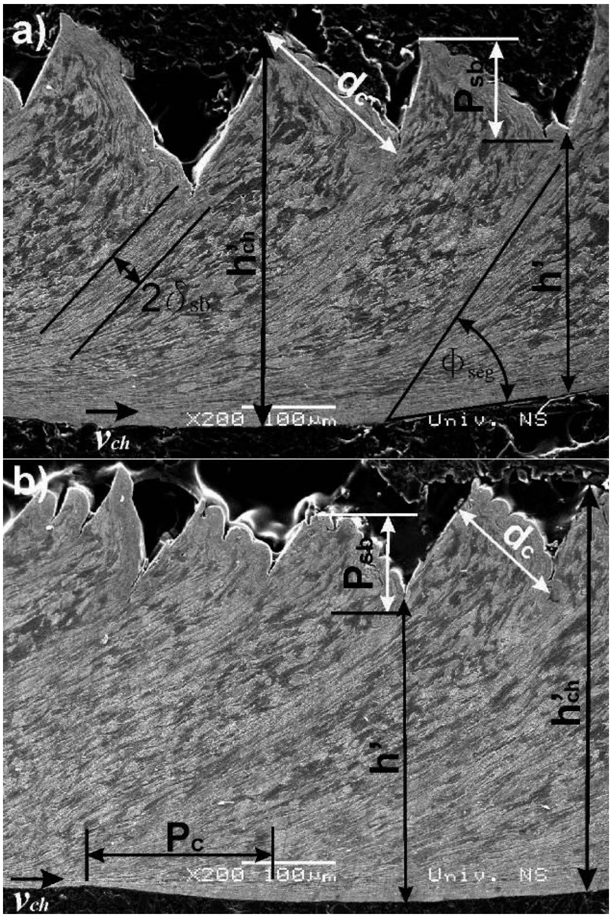

Figure 3. Characteristic dimensions of chip cross section geometry for calculation segmentation frequency, a) v_c=250 m·min^{-1}, f=0.25 mm, a_p=1.5 mm; b) v_c=200 m·min^{-1}, f=0.3 mm, a_p=1.5 mm

Slika 3. Karakteristična geometrija poprečnog presjeka odvojenih čestica za izračunavanje frekvencije segmentacije, a) v_c=250 m·min^{-1}, f=0.25 mm, a_p=1.5 mm; b) v_c=200 m·min^{-1}, f=0.3 mm, a_p=1.5 mm

Based on the processed results of the experimental research, the following conclusions can be drawn as a result of monitoring the chip morphology and tool wear condition:

- The medium value of the segmentation of the free chip part (lamella formation step) (p_c) and the saw-tooth height (p_{sb}) are increased with the increase of tool wear.
- Segmentation step, distance between lamellas (p_c), increases with the cutting speed.
- Height of continuous portion (h') is greater with a new tool.
- Segmentation frequency increases with higher cutting speeds.

Chip formation significantly influences the level of vibrations regardless of chip form and type. Generation of chip segments during cutting process can be considered as the process of excitation of machining system by a series of energy impulses. The frequency of those impulses can be determined with an acceptable error, by analyzing the cross section of generated chip.

It was established in this experiment that output vibration signal of the machining system features local changes at particular frequences which can be attributed to the change of form and frequency of chip segment generation. Cutting process and chip forming are also destabilized by the very primary shear zone, which changes in its upper zone, resulting in release of energy and elastic stresses. The results of the change in lamellae generation frequency can be observed in Fig. 4. The frequencies of lamellae generation obtained by expressions (3) and (4) are above 10 kHz, which is above the standard range of accelerometers.

Figure 4 presents the dependency between chip segmentation and tool wear level. The aforementioned chip dimensional information for each design was measured and averaged, and only the mean values are presented here. It can be observed that the increase in tool wear decreases the segmentation frequency for constant cutting conditions.

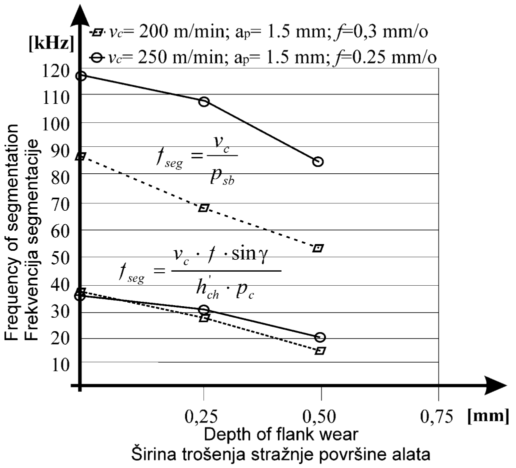

Figure 4. Dependency between chip formation frequency and tool wear level

Slika 4. Ovisnost frekvencije formiranja odvojenih čestica o stupnju istrošenosti alata

5. Modeling the dynamic tool behaviour

Within the research, the dynamic behavior of a turning cutting tool has been analyzed by applying the FEM (finite element method).

5.1. Modal analysis

3D-FEM model of cutting tool had 31450 nodes and 27950 elements. The numbers of degree of freedom are 86350. 3D model is built by use of ten-node tetrahedral finite element (Fig 5).

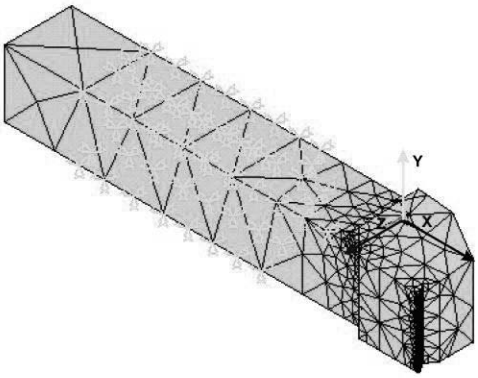

Figure 5. FEM model of the cutting tool

Slika 5. MKE model reznog alata

The first step of dynamic analysis is the modal analysis. The structure of cutting tool defined in this work is assumed to have linear behaviour. Modal analysis used to determine the mode shapes and the natural frequencies of the cutting tool structure that are important for dynamic analysis. The assumptions made for the modal analysis are as follows:

- The model has stable hardness and rigid-body motions.
- Damping is valid only for the damped mode extraction method and is ignored for the others.
- Forces are not time varying.

Displacements, pressures and temperatures are not taken into consideration. First 50 mode shapes are determined and natural frequencies (with the values in the range of 5 kHz–100 kHz) are calculated. Natural frequencies and the mode shapes are shown in Fig. 6.

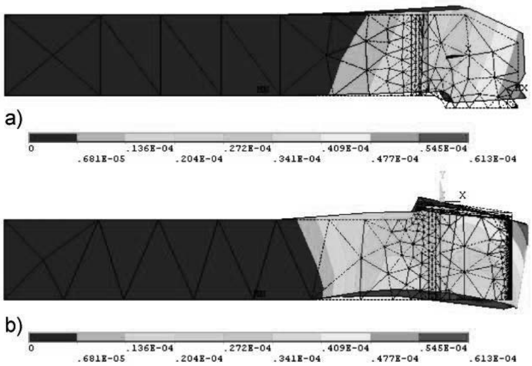

Figure 6. Natural frequencies and mode shapes of the cutting tool model, (a) 1. Mode f_1= 22927 Hz; (b) 2. Mode f_2=46632 Hz

Slika 6. Vlastite frekvencije i vibracijski oblici modela reznog alata, a) 1. Mode f_1= 22927 Hz; (b) 2. Mode f_2=46632 Hz

The presence of the tool’s natural frequencies in the upper part of the spectrum, in the actual example over 5 kHz, presents a problem in monitoring the tool wear condition, since this is the part of the spectrum where the frequencies occurring in the process of the chip segmentation formation are also situated [14]. In such a "deformed figure", the monitoring of the chip formation process by analyzing the adjoining frequency content will be significantly harder, if not even disabled. Presumptive information on the dynamic behavior of the tool can be used for separating the spectrum part that is not contaminated and whose monitoring can, with high precision, establish an unambiguous correlation between tool condition and tool vibration signal measured by an adequate sensor.

It is important to note that, due to the features of the tool carrier and other elements of the workpiece system linked to the mass, their influence on the dynamic behavior of the workpiece system measured on the tool shank is not critical. The frequencies of these elements are situated in the lower spectrum part which is significantly distant from the spectrum part where the frequencies generating the chip formation process are situated. Hence, the dynamic behavior analysis of the mechanical structure of the workpiece system is limited only to the tool behavior analysis ([15], [16], [17] and [18]).

Vibration signals originating from the cutting process are difficult to be measure by direct methods, and they are technically and practically rather inaccessible for measuring in order to define the real influence. In the practical sense, what can be measured are the reactions of the overall system "tool-workpiece-machine" on the tool. In measuring, certain limitations occur in identifying and separating the induction mechanisms and transferring vibrations from other machine elements. It practically means that for certain processing operations only the phenomenological explanation is possible. Determining the precise content of the measured vibrations from the cutting process in the output sensor signal presents a very important task. Dominant influences of natural frequencies of the tool in the signal spectrum can be relatively precisely calculated by applying certain calculation methods.

The analysis of the dynamic behavior of the turning cutting tool shank, using FEM, has an objective to determine natural frequencies and vibration amplitudes of the cutting tool shank in the machining process. Furthermore, the FEM analysis enables the establishment of connections between experimental research and certain models in the machining process linked to tool wear and cutting geometry alteration [19], [20] and [21].

5.2. The harmonic response analysis of a cutting tool

The analysis of measured vibration signals tends to identify the difference between natural and self-induced tool vibrations during the cutting operation and the entire system vibrations. FEM analysis of free non-damped vibrations is performed. The calculated natural frequencies of the cutting tool are presented by broken lines and compare with the Power Specter Density - (PSD) of the measured vibrations signal, show on Figure 7. Within the experimental research, apart from the turning cutting tool shank acceleration, the simultaneous measuring of the cutting forces has also been performed, and hence the turning cutting tool has been fixed to a dynamometer whose stiffness is lower than the tool carrier rigidity. Vibration alternation is measured using the accelerometer set up at the lateral tool side and oriented towards the longitudinal workpiece axis.

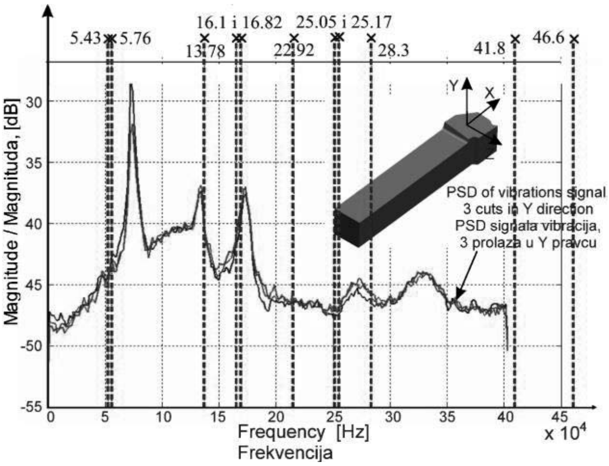

Figure 7. Characteristic frequency spectra of the cutting tool obtained by experimental testing and numerical (FEM) calculations

Slika 7. Karakteristični frekvencijski spektri reznog alata dobiveni eksperimentalnim mjerenjima i numeričkim (MKE) proračunom

Based on the presented results, one can observe that almost all natural frequencies of the tool are situated in the upper domain of the frequency spectrum. This confirms the feasibility of the adopted approach in modeling and analyzing the dynamic tool behavior. In this case, significant approximations in setting the model have not reduced the dominant vibration effects in the machining process.

The aim of harmonic response analysis of a cutting tool is to force the structure from certain points at a certain frequency and to determine the reaction of these points to the force applied. As the result of harmonic response analysis it is clarified that the maximum displacement of the cutting edge is happen to be in y axis. Peak harmonic response occurs at forcing frequencies that match the natural frequencies of tool structure. Before obtaining the harmonic solution, the natural frequencies of cutting tool were calculated by obtaining a modal solution. Harmonic analysis comprises the frequency range from 5 to 50 kHz. Figure 8a) presents the amplitude frequency cutting tool characteristics in the direction of the axes X, Y and Z. The analysis of the obtained results can argue that the oscillation amplitudes in the directions of the axes Y and Z are of the same size order in the larger number of natural frequencies, while they are significantly smaller in the direction of X axis, even at the frequency 46.5 kHz which presents the largest frequency in the direction of this axis. Figure 8b) shows PSD diagram of characteristic vibrations of tool shank generated by FEM analysis. The FEM analysis and experimental results in Fig. 7 reveal conformance between numerical and experimental results.

The analysis of the experimental results and the results obtained by FEM can be used to associate the vibration modes on calculated and measured frequencies with the conditions of their occurrence:

1. At 14 kHz there is cutting tool vibration in the directions of Y and Z axes where the largest amplitudes occur on the cutting tool top and they are around 30 to 35 [μm];
2. At 22.95 kHz the maximal displacement amplitudes in the direction of the stated axes are around 10-20 [μm] and occur on the cutting tool shank;
3. At other frequencies 23 and 46.5 kHz the maximal displacement amplitudes also appear on the turning cutting tool neck.

The mentioned natural frequencies entirely cover the part of the frequency range in which there are dominant components of induction generated by discontinuities during the chip segmentation formation.

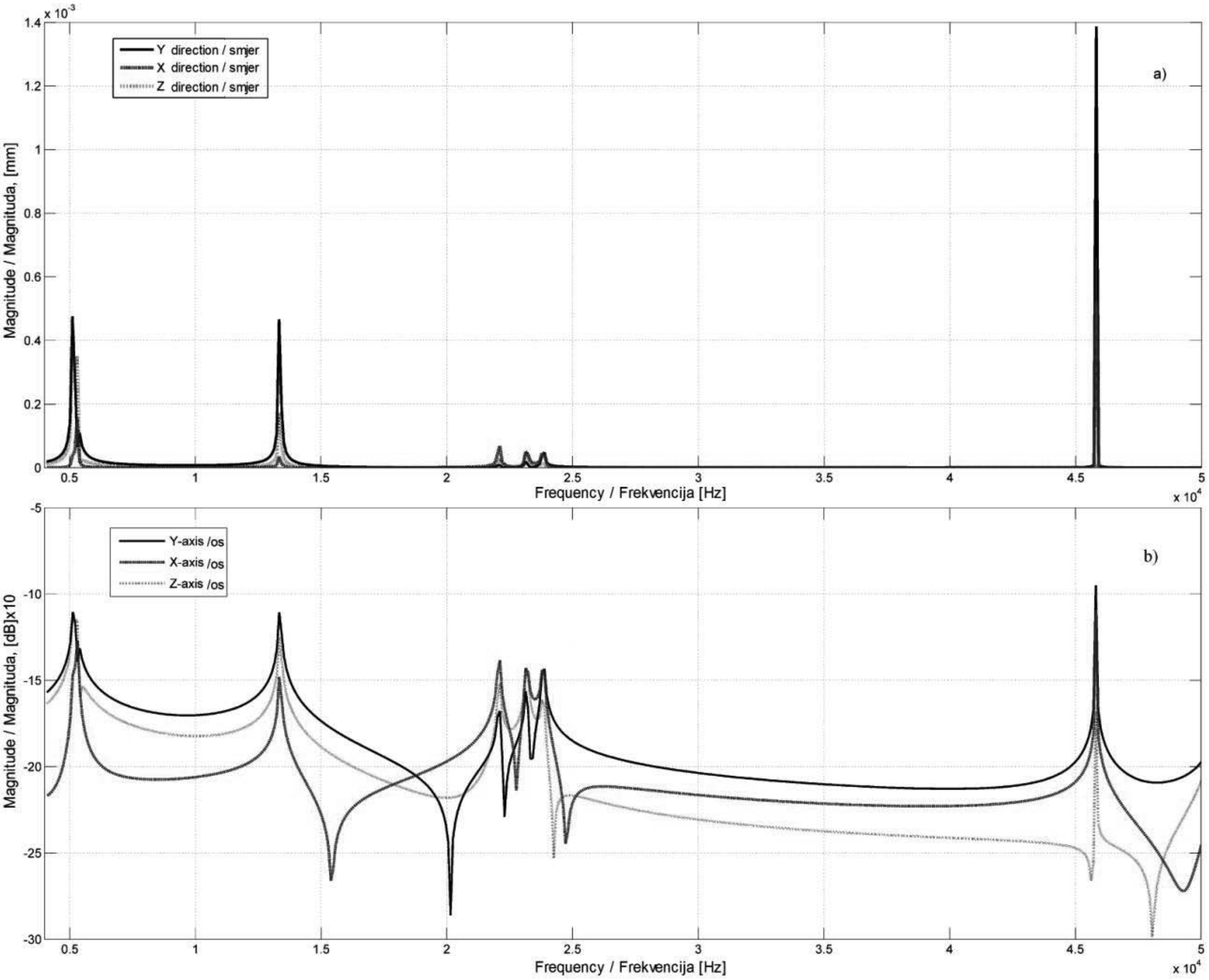

Figure 8. a) Amplitude frequency characteristic of the cutting tool in the directions of X, Y and Z axes, and b) PSD Characteristic frequency of vibration from FEM model

Slike 8. a) Amplitudno frekventna karakteristika reznog alata u X, Y i Z osi, i b) PSD dijagram karakterističnih frekvencija primjenom MKE

6. Conclusion

The results of experimental investigation confirm the initial hypothesis that the high-frequency spectral range - which is the result of varying frequency of lamellae generation - contains some useful information which can be of interest to tool wear monitoring process. The results of SEM analysis of chip cross section and the calculated lamellae generation frequencies, shown in Fig. 3 and 4, indicate that chip lamellae generation causes frequency changes in output signal at frequencies above 10 kHz. In the range between 10 and 50 kHz there are a larger number of the tool's natural frequencies, creating a space for the appearance of the resonance under the action of induced force generated by chip segmentation formation. The increase in the oscillation intensity induced by the tool resonance on a larger number of frequencies has a greater intensity and deforms the signal content occurring in the process of chip segmentation formation. Vibration output is variable, with distinctive peaks in individual frequencies overlapping with the chip segmentation frequency. The alteration in chip type stipulates the appearance of new frequency components (harmonics) which are close to lamella formation frequency.

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