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# Analysis of Circular Saw Tooth Marks Profile on Material Machined Surface After Filtering with Fast Fourier Transform (FFT)

# Analiza profila kinematičkih tragova zubi lista kružne pile na obrađenoj površini materijala provedena filtriranjem na načelu brze Fourierove transformacije (FFT)

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**ABSTRACT** • *The article presents theoretical analysis of machined surface roughness after sawing on circular saw and implementation of fast Fourier transform (FFT) as a possible simple filtering method for filtering out just the saw blade and saw tooth influence on the surface roughness. Surface roughness profile is represented as a signal that can be obtained as a sum of complex periodic signals that represent theoretical profile of tooth marks and lateral movement of tooth due to saw lateral movement and signals that represent structural roughness of wood combined with machining roughness, represented as a Gaussian noise. The application of FFT based filtering on such a signal can be effectively used to extract the main frequency components due to tool influence on total surface signal and the time domain of filtered signals display can then be obtained by use of the inverse Fourier transform. In order to test the theoretical assumptions, the machining tests in sawing of solid oak wood (Quercus robur L.) and medium density fiberboard (MDF) was conducted. Machined surface roughness was measured and analyzed in accordance with theoretical assumptions. It was concluded that a combination of discrete Fourier transform of surface roughness profile and standard roughness parameters can give a more complete representation of machined surface roughness after sawing with circular saws and that filtering of surface roughness profile signal with FFT filter can be used as a simple and effective method in quantifying tool influence on machined surface roughness after sawing on circular saw in varying machining conditions and on different workpiece material.*

**KEYWORDS:** *machined surface roughness; circular saw; solid wood; signal analysis; FFT*

**SAŽETAK** • *U radu je prikazana teorijska analiza hrapavosti obrađene površine nakon piljenja kružnom pilom i primjena brze Fourierove transformacije (FFT) kao moguće metode filtriranja profila hrapavosti radi jednostavnog načina kvantificiranja utjecaja bočnog pomaka lista pile i zubi na ukupnu hrapavost obrađene površine.*

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*Profil hrapavosti površine opisan je kao signal koji se može dobiti kao zbroj složenih periodičnih signala koji daju teorijski profil kinematičkih tragova zubi i njihova bočnog pomaka zbog lateralnoga gibanja lista pile te signala koji predočuje strukturnu hrapavost drva i hrapavost zbog obrade, a opisan je kao Gaussov šum. Primjena filtra utemeljenoga na FFT-u na takvom signalu može se učinkovito iskoristiti za izdvajanje glavnih frekvencijskih komponenata signala vezanih za utjecaj alata na ukupnu hrapavost, a prikaz filtriranog signala može se pritom dobiti primjenom inverzne Fourierove transformacije. Kako bi se provjerile teorijske pretpostavke, provedena su ispitivanja pri piljenju masivnog drva hrastovine (Quercus robur L.) i ploče vlaknatice srednje gustoće (MDF). Izmjerena je i analizirana hrapavost obrađene površine u skladu s teorijskim pretpostavkama. Zaključeno je da kombinacija diskretne Fourierove transformacije profila hrapavosti površine i standardnih parametara hrapavosti može dati potpuniji prikaz hrapavosti obrađene površine nakon piljenja kružnim pilama te da se filtriranje signala profila hrapavosti površine uz pomoć FFT filtra može primjenjivati kao jednostavna i učinkovita metoda za kvantificiranje utjecaja alata na hrapavost obrađene površine nakon piljenja kružnom pilom u različitim uvjetima obrade i na različitom materijalu uzorka.*

**KLJUČNE RIJEČI:** *hrapavost obrađene površine; kružna pila; masivno drvo; analiza signala; FFT*

## 1 INTRODUCTION
## 1. UVOD

Theoretical profile of tooth marks on machined surfaces after sawing with circular saw can be determined from the analysis of an ideal interaction of tool and workpiece in the given machining conditions. Based on such analysis, the profile of kinematic traces of the tool tip on machined surface can be determined and the parameter that is usually derived as the representative parameter is the maximum height of those traces in given machining conditions (Zdenković, 1965; Šavar, 1990; Goglia, 1994; Gottlöber, 2014; Csanády, 2015). On the other hand, the parameters that are usually used in solid wood machining research as a representative parameters to quantify the surface roughness or waviness based on measurements are $R_a$ ($W_a$), $R_q$ ($W_q$) and $R_z$ ($W_z$), which according to ISO 4287: 1997 represent the arithmetic mean of the absolute ordinate values within the sampling length, the root mean square value of the ordinate values within the sampling length and the average of the sum of height of the largest profile peak height and the largest profile valley absolute depth within a sampling length, respectively. Those parameters are used to determine the surface roughness which is the sum of the:

- structural roughness due to anatomical characteristics of wood, which is not a function of machining process,
- machining roughness caused by machining that cannot be represented as some periodic signals and
- kinematic roughness due to teeth marks and lateral movement of the saw blade, which can be represented as complex periodic signals.

The effect of structural roughness in solid wood machining can have a big impact on the overall surface roughness, depending on the wood species, and it can be hard to distinguish between structural roughness and roughness due to machining (Gottlöber, 2014). The possibility of removing or quantifying the impact of structural roughness from measured surface profiles has been a topic of research projects (Csiha, 2000; Magoss and Sitkei, 2003; Fujiwara *et al*. 2003; Hendarto *et al.* 2006; Gurau, 2006; Magoss, 2008; Thoma, 2015), but at present there is no single solution to this problem.

According to Goli (2005), in order to better evaluate the surface quality, the primary profile ($P$), which is the sum of all the deviations of the measured profile from the nominal profile, should be analyzed and it is used in some cases (Sandak *et al.* 2020). Also, the other standard profile parameters, like Abbott curve, $R_{vk}$, $R_{pk}$, $R_k$, are proposed for the assessment of surface roughness (Magoss, 2008; Gottlöber, 2014). Surface roughness is a key element in characterisation of surface quality and relation to human perception of that quality and some technological properties of those surfaces (Sinn *et al*., 2009). There are a lot of parameters introduced in order to quantify the relationship between measurable quantities associated with roughness and the end goal of such analysis (Sandak and Negri, 2005).

As can be seen from this short overview, the machined surface quality of solid wood is still hard to exactly define and connect to theoretical surface roughness, which can be calculated from the tool-workpiece interaction relations and there is no single best way to do it. On the other hand there is interest, even in circular sawing of solid wood, in using measurable roughness parameters to quantify the influence of different process parameters on machined surface quality (Budakçi *et al*., 2011; Kminiak and Gaff, 2015; Kminiak *et al*., 2015, Lee *et al*., 2017) or to optimize the sawing process based on measurable surface roughness or waviness parameters (among other influential quantities) (Nasir and Cool, 2019). According to authors' experience and based on the literature (Orlowski, 2010), common use of standard roughness parameters with standard filtering, which is usually used for analysis of machined surface roughness after sawing with circular saws, can give misleading results. According to Brock (1983), better results can be obtained by combining standard parameters with Fourier analysis of surface roughness signal, which can give a nearly complete description of surface roughness.

Combining the ideas of using Fourier transform for roughness analysis and signal filtering based on Fourier transform, a procedure for separating part of the signal that should describe kinematic roughness and the rest of the signal remaining after filtering that should mainly describe structural and machining roughness can be made. After that, individual signals can be described by standard roughness parameters and the influence of individual components on the overall roughness can be easily quantified. In the rest of the article, this procedure is presented from the theoretical and experimental point of view.

### 1.1 Theoretical analysis of machined surface roughness after sawing on circular saws

### 1.1. Teorijska analiza hrapavosti obrađene površine nakon piljenja kružnim pilama

The circular saw in conventional sawing, with parameters relevant for the calculation of the tooth marks theoretical height on a machined surface, can be represented by Figure 1.

In order to calculate the theoretical roughness height ($h_c$), we can use Eq. 1

$$h_c = \delta \cdot tan\varepsilon \quad (1)$$

Where $\delta$ is chip thickness and ε is saw tooth radial side clearance angle.

As can be seen, the theoretical roughness height changes during one tooth pass and the maximum value is given by

$$\begin{aligned} h_{c_{max}} &= \delta_{max} \cdot tan\varepsilon \\ h_{c_{max}} &\approx f_z \cdot cos\varphi_2 \cdot tan\varepsilon \\ h_{c_{max}} &\approx f_z \cdot cos\left[sin^{-1}\left(\frac{D/2-p}{D/2}\right)\right] \cdot tan\varepsilon \end{aligned} \quad (2)$$

Where $D$ is circular saw blade diameter, $f_z$ is feed per tooth and $p$ is protrusion of the saw blade above worktable.

From the theoretical roughness profile after sawing with circular saw (Figure 1), it can be seen that, if the actual roughness profile was dominated by kinematic traces of saw teeth, the standard roughness parameter that would closely resemble the theoretical roughness is $R_t$, which represents the vertical height between the highest and lowest points of the profile within the evaluation length, and the distance between consecutive peaks ($f_z$) would be equal to the spacing distance $RS_m$.

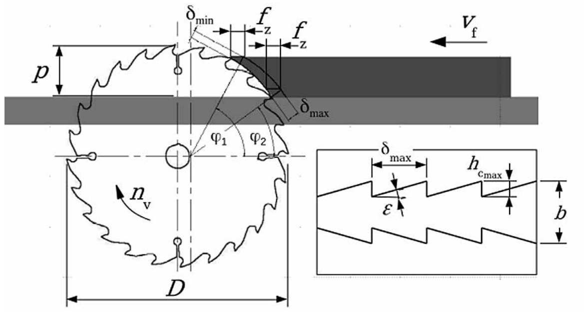



**Figure 1** Circular saw in conventional sawing and theoretical profile of tooth marks on machined surface after sawing
**Slika 1.** Kružna pila u protusmjernom rezu i teoretski profil neravnina na obrađenoj površini nakon piljenja

In such an ideal case, and according to recommended feed per tooth ranges (Leitz Lexicon, 2020), the maximum theoretical roughness height would be (if we take that $\delta_{max}$ is roughly equal to $f_z$ and side (radial) clearance angle for tungsten carbide (HW) tipped saw blade ε = 1°) in the range from 2 μm to 16 μm.

The real roughness profile is much more complicated and that is why all the different parameters, mostly $R_a$, $R_q$ and $R_z$, are used. One of the reasons for this can be attributed to the difference between the actual and ideal tooth shape, which can be due to different reasons (lack of tooth symmetry, deviation from the center line, wrong cutting angles) and results in a flutter or washboarding (Orłowski and Wasielewski, 2006). On the other hand, circular saw blade lateral vibration due to cutting-induced vibration is identified as a main cause for washboarding. All of this lateral vibration is superimposed on the ideal tooth path in the workpiece. What is common to all these influences on lateral movement is that they can all be represented as complex periodic functions (Tian and Hutton, 2001). Structural roughness of wood also plays an important role in roughness profile.

### 1.2 Signal analysis of machined surface roughness profile

### 1.2. Analiza signala profila hrapavosti obrađene površine

Surface roughness profile can be thought of as a signal. Signals are usually modeled mathematically in order to make them unambiguous, precise and manipulable (Lee and Varaiya, 2002). Theoretical profile of tooth marks on machined surface after sawing with a circular saw can be represented as a saw-tooth signal (Figure 1) and Eq. 3 used to describe it (Weisstein, 2020) can be derived as follows:

$$h_i(x) = h_c \cdot \left( \frac{1}{2} - \frac{tan^{-1}\left(cot\left(\frac{x \cdot \pi}{f_z}\right)\right)}{\pi} \right) \quad (3)$$

Where $h_i$ is instantaneous profile height as a function of position.

From a signal analysis perspective, it is more convenient to deal with functions of time, rather than position. Surface roughness profiles are mostly obtained by means of stylus, which traverses surface with speed ($v_s$) according to ISO 3274, and as a result of measurement, we get a finite set of points, which represent discrete signals that are separated by some constant distance ($\Delta x$). So, if the time difference is introduced between two samples ($\Delta t_s$)

$$\Delta t_s = \frac{\Delta x}{v_s} \tag{4}$$

then the time difference between two consecutive peaks of saw-tooth profile ($\Delta t_z$) is

$$\Delta t_z = \frac{f_z}{v_s} \tag{5}$$

Then the instantaneous profile height can be written as a function of time

$$h_i(t) = h_c \cdot \left( \frac{1}{2} - \frac{tan^{-1}\left( cot\left( \frac{t \cdot \pi}{\Delta t_z} \right) \right)}{\pi} \right) \tag{6}$$

According to Tian and Hutton (2001) the lateral movement of saw blade ($y_i$), if we assume that only one mode of vibration is excited, can be written as simple periodic function of time

$$y_i(t) = A_0 \cdot cos(2 \cdot \pi \cdot f_n \cdot t) \tag{7}$$

Where $f_n$ is the resonant frequency of the saw blade and $A_0$ is the amplitude of sawtooth tip lateral movement.

If there are $n$ teeth passing through the same horizontal line in the time period $\Delta t$, then the lateral displacement in the space domain - $y_z(x)$ is

$$y_z(x) = A_0 \cdot cos\left( 2 \cdot \pi \cdot \left[ \frac{f_t - f_n}{v_f} \right] \cdot x \right) \tag{8}$$

Where $f_t$ is the tooth passing frequency and it can be expressed as

$$f_t = n_v \cdot z \tag{9}$$

Where $z$ is the number of circular saw teeth and $n_v$ is rotational frequency of the saw.

As can be seen from (8), the wavelength of the washboarding pattern ($\lambda_x$) can be expressed as

$$\lambda_x = \frac{v_f}{f_t - f_n} \tag{10}$$

This wavelength could represent a problem for roughness analysis with standard cut-off filters and evaluation lengths. In some cases this wavelength can be in the range close to 30 mm (Tian and Hutton, 2001) and because of its large values it could be filtered out as a form signal or inadequate length of signal could be sampled for reliable determination of washboarding pattern frequency and its influence on machined surface roughness.

If $y_z(x)$ signal is to be represented as a function of time, than $\lambda_x$ can be converted to frequency ($f_{fx}$)

$$f_{fx} = \frac{v_s}{\lambda_x} \tag{11}$$

If we assume that structural roughness of wood can be represented as a Gaussian noise (Lemaster and Taylor, 1999) and machining roughness can also be represented as a Gaussian noise and combined in one non-deterministic signal - $p(x)$, then the signal that represents all of these influences on resultant profile would be a sum of these signals $y_r(x) = h_i(x) + y_z(x) + p(x)$. It is assumed that form errors are filtered out and do not influence the final roughness profile (this assumption holds if standard roughness or waviness profiles, obtained with adequate cut-off filters in line with ISO 4288, are analyzed). From this resultant signal ($y_r$), standard roughness parameters can be calculated. If such a profile was measured with digital surface roughness meter, it would be represented by discrete signal and $R_a$ parameter can be calculated as

$$R_a = \frac{1}{N} \cdot \sum_{i=1}^{N} |y_{ri}| \tag{12}$$

and $R_q$ parameter can be calculated as

$$R_q = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} y_{ri}^2}, \tag{13}$$

Where $N$ is the number of samples in measurement.

So, if one knew or measured all of the relevant parameters to quantify the $h_i(x)$ and $y_z(x)$, the calculation of tool influence on resulting surface roughness would be straightforward, but in practice that can be hard to accomplish and because much of the signal could be dominated by structural roughness, it can even lead to wrong conclusions (Brock, 1983).

According to Lemaster and Taylor (1999), low-pass filtering of roughness profile with different cut-off frequencies could be used for fuzziness or tear-out detection.

A combination of these methods can be used as a basis for filtering out most of the signal that represents the tool influence in measured surface roughness signal.

Any periodic signal can be represented by Fourier series (Kreyszig, 2011)

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left( a_n \cdot cos(n \cdot x) + b_n \cdot sin(n \cdot x) \right) \tag{14}$$

Where $a_0$, $a_n$ and $b_n$ are known as Fourier coefficients and can be calculated as

$$a_0 = \frac{1}{2 \cdot \pi} \int_{-\pi}^{\pi} f(x)\,dx$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cdot \cos(n \cdot x)\,dx \qquad n = 1, 2, \ldots, \quad (15)$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cdot \sin(n \cdot x)\,dx \qquad n = 1, 2, \ldots,$$

showing that any periodic signal can be represented as a sum of sines and cosines of different amplitudes and frequencies. As in practice there are finite discrete signals that represent function $f(x)$, the discrete Fourier transform (DFT) is used, but the meaning of analysis is the same (Randall, 1987; Lee and Varaiya, 2002).

So, if all of the signals in the measured roughness profile that represent the tool and machine influence can be represented as a complex periodic and structural and machining roughness as noise, then if a DFT is made of that signal, the amplitude of the periodic part of the signal should stand out above the noise floor. Fourier series of a sawtooth signal that represents the theoretical profile of tooth marks - $h_i(x)$ is composed of many cosine terms with falling amplitudes (Kreyszig, 2011), so it is certain that components whose amplitudes are in line with noise floor cannot be distinguished. If there are no frequency components that stand out above the noise floor in the DFT of surface roughness signal, then the direct influence of tool and machine on surface roughness cannot be quantified by this method.

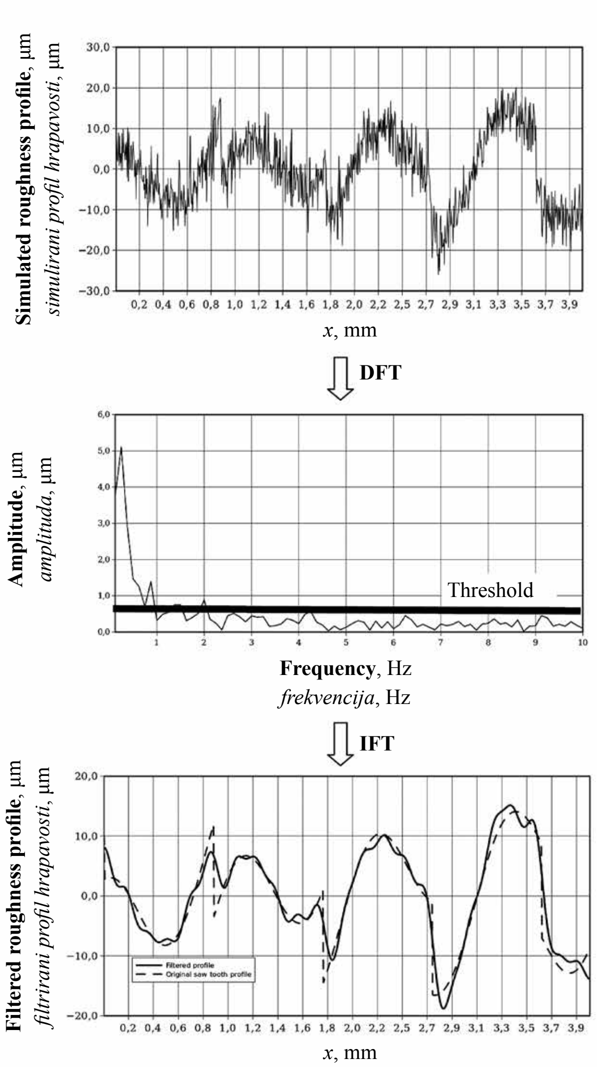



**Figure 2** Block diagram representing the procedure of filtering a simulated roughness signal after sawing with circular saw with FFT based filter
**Slika 2.** Blok-dijagram postupka filtriranja simuliranog signala hrapavosti nakon piljenja kružnom pilom uz primjenu FFT filtra

In order to try to extract just the periodic signals associated with tool influence on the resultant profile, we can use the DFT data. From the plot of the DFT data, a threshold can be defined and it can be used to remove all of the data below that threshold value. After extraction, the amplitudes and frequencies are left and they should represent the periodic components of the signal. As the DFT is a computationally intensive task, fast Fourier transformation (FFT) algorithms are usually used.

Inverse Fourier transform (IFT) is performed on this extracted signal in order to get the estimated profile of tooth marks as a function of time or position (Figure 2). From this signal, $R_a$ and $R_q$ values, that should now mostly represent the influence of tooth marks on overall surface roughness, can be calculated.

This method should allow a simple and effective way for quantification of tool influence on machined surface roughness after sawing with circular saw.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

In order to test the proposed method for the roughness signal analysis after machining with circular saw, the experimental part of the research was conducted in the Laboratory for Mechanical Wood Processing, which is part of the Faculty of Forestry and Wood Technology in Zagreb. Medium density fiberboard (MDF) and solid oak wood (*Quercus robur* L.) were chosen as test materials. MDF was chosen because of its more uniform cross section so it could be used as a reference material to test the proposed signal analysis procedure, and oak wood because it is a ring porous type of wood and large pores tend to be problematic in surface roughness assessment. The moisture content of test specimens was 9 %. The average density of MDF boards was 685 kg/m$^3$ and of solid oak 695 kg/m$^3$. The average cutting height (material thickness) for MDF samples was $h$ = 18 mm and for oak boards $h$ = 24 mm.

For the sawing, cabinet table saw Bratstvo SC-10 was used and the sawing setup was as in Figure 1. The circular saw blade used for the experiment was a new standard saw blade for cutting solid wood along the grain, with tungsten carbide (HW) teeth. The saw diameter was $D$ = 300 mm with 24 teeth with straight tooth shape (FZ type), saw thickness $a$ = 2.2 mm, cutting width $b$ = 3.2 mm and radial side clearance angle ε was not equal on both sides of the saw teeth due to sharpening inaccuracies, so on one side it averaged 0.7° and on the other side 1.1°. Limit rotational frequency for the saw blade is 6500 min$^{-1}$. The saw blade was fastened to the main shaft by a flange with a diameter of $d_f$ = 72 mm, so the clamping ratio was $d_f/D$ = 72/300 = 0.24. Saw blade stiffness was measured by applying lateral force at tooth tip by means of weighing scale, and lateral displacement was measured with a dial indicator. The average calculated initial saw blade stiffness measured at tooth tip was $k_t$ = 42 N/mm.

In order to be able to estimate if certain frequency components that were obtained from measured surface roughness are really due to lateral tooth movement and not some other factor, the circular saw vibration response to impact stimulus and frequency analysis of sound during idling and cutting was measured. The average electrical power required during sawing was also measured.

Before sawing, the resonant frequencies of the clamped saw blade were measured. The saw blade was lightly struck with a light hammer (impulse stimulus) and the response was measured with National Instruments NI USB-9162 with NI 9233 Signal IEPE Conditioning module and BSWA measurement microphone MPA 215 (Ser. No. 450051), which was positioned 1 meter from the saw blade. The whole measurement chain was calibrated before the measurement with Bruel & Kjaer pistonphone, Type 4230 (Ser. No. 656775). The sampling frequency was 50 kS/s. From the ten measurements of response signal, the average frequency response was measured and the dominant resonant frequencies were at 1.6 kHz and 3.6 kHz.

Rotational frequency of the saw blade was constant during measurements. During idling, it was measured with a laser tachometer and it was 3838 min$^{-1}$. The tooth passing frequency was $f_t$ = 1535 s$^{-1}$ and it was below the measured dominant resonant frequency of the clamped saw blade natural frequency. According to Tian and Hutton (2001), the largest unstable region of where washboarding can occur is associated with the case where the $f_t$ is somewhat greater than the natural frequency of the saw. There was no evidence of self-excited vibrations during idling of the saw. During idling of the saw, the main frequency components measured were at 63 Hz, 100 Hz, 391 Hz and 1536 Hz. These frequency components can be attributed to rotational frequency of the saw, rotational frequency of the main electromotor and tooth passing frequency. During cutting, there was no noticeable change and the dominant frequency component was due to tooth passing frequency, which changed a little bit during cutting due to the change in the rotational speed of the saw blade because of the higher load on the main electromotor.

During the cutting experiment, the variables were workpiece material and feed speed. Feed movement was obtained by power feed system with rubber rollers attached to the table saw and due to limitations of test setup the feed speeds chosen for the experiment were $v_f$ = (2, 4, 6.5 and 13) m/min. Corresponding feed per tooth was $f_z$ = (0.02, 0.04, 0.07 and 0.14) mm and feed per one revolution of the saw blade $f_o$ = (0.52, 1.04, 1.69 and 3.39) mm. These values are much lower than the values recommended for sawing solid wood along the grain, but this was not considered to be a problem for the purpose of the experiment. During cutting, the electrical power required for sawing was measured with Fluke Power Quality Analyzer 435-II (Ser. No. 462 13 102), which was connected to the main electromotor by standard three-phase delta connection for loads with no neutral wire.

After sawing, the machined surface roughness of MDF and solid oak test specimens was measured with surface roughness tester Mitutoyo SurfTest SJ-500 (Ser. No. B0007 1808), with an amplitude measurement range of 2 mm. The measurements were done in accordance with ISO 1997 and $R$ profile was measured. The stylus tip radius was 10 μm and, in accordance with the recommendations of ISO 3274: 1996, the $\lambda_s$ profile filter cutt-off was 25 μm and $\lambda_c$ profile filter cutoff was 8 mm. Gaussian filter was used, but it must be kept in mind that this type of filter can introduce artifacts, such as very high peaks, when filtering the roughness profile. Evaluation length was 40 mm. Stylus traversing speed was set to $v_s$ = 0.1 mm/s, which than corresponded to spatial resolution of 5 μm between two measurement points, which in the end was equal to sampling frequency of $f_s$ = 20 Hz, so the maximum analyzed frequency component of the surface roughness signal was 10 Hz. Before the measurements, the roughness tester was calibrated with a working gauge that provides reference roughness profile with $R_a$ = 2.97 μm (Mitutoyo, Ser. No. 393041807).

According to equation (5), the expected dominant frequency components due to feed per tooth or feed per one revolution were calculated as reciprocal values of $\Delta t_z$ and $\Delta t_o$ (time difference between two consecutive peaks due to saw tooth lateral movement for one revolution of the saw blade) and the values were $f_{fz}$ = (4.6, 2.3, 1.4 and 0.7) Hz and $f_{fo}$ = (0.19, 0.10, 0.06 and 0.03) Hz, respectively.

By visual examination of machined surfaces, it was determined that there were no repeating patterns with longer wavelengths that would be cut off by filtering, and that evaluation length was sufficient to sample a few cycles of the repeating pattern even in the worst case.

According to recommendations (Dagnall, 1998), in order to accurately determine the influence of the saw teeth on the surface roughness, the measurement stylus tip traversed the machined surface during measurement in the direction that corresponded to the direction of the feed movement vector and the position of subsequent measurements were chosen to provide the representative traces for later evaluation.

On every sawn surface of MDF and solid oak specimens machined with different feed speeds, five measurements of *R* profile data were obtained and exported to text (comma separated value) file. For the analysis of roughness profile signal data, a small script was written in Scilab (https://www.scilab.org). With this script, the original roughness profile signal was represented as a function of time and as such the discrete Fourier transform of that signal was obtained. The $R_a$ and $R_q$ values were calculated according to the equations (12) and (13). From the obtained spectrum plot of roughness signal, the threshold value was chosen by trial and error, because we were not able to determine some objective criterion for optimal determination of its value. The same value of threshold was used for all analyzed roughness signals, because in that case there was no need to change filter parameters due to changing machining conditions and the assumption that it can be used in this way was tested. In the next step, all values in the time domain signal that were below threshold were set to zero and that signal represented a filtered signal. The $R_a$ and $R_q$ values of the filtered signal were calculated, and the spectrum plot was also plotted for further analysis. For further analysis, only $R_a$ value was used because it is more often used as a parameter, but $R_q$ value shows the same trend.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

The results of the obtained $R_a$ values before and after filtering with FFT filter are presented in Figure 3.

Theoretical surface roughness $h_{cmax}$ for the given sawing conditions is in the range from 0.3 µm to 1.7 µm and the corresponding value of $R_a$ parameter, due to the fact that for saw-tooth waveform it can be easily calculated as $h_{cmax}/2$, is in the range from 0.15 µm to 0.85 µm. The measured values are much higher, even for the filtered signal.

As can be seen from the presented graphs, the roughness quantified by $R_a$ parameter, as expected, shows a linear relationship with feed per tooth and is

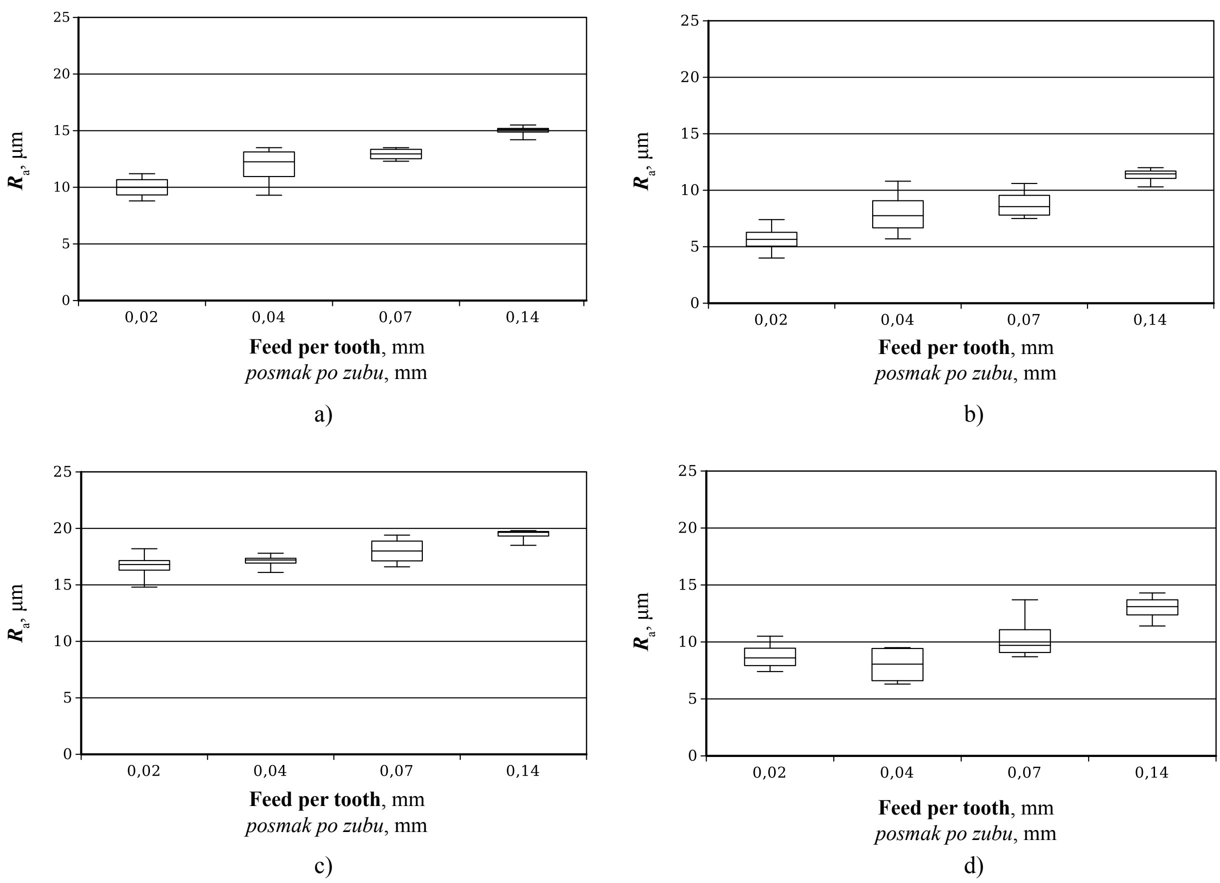
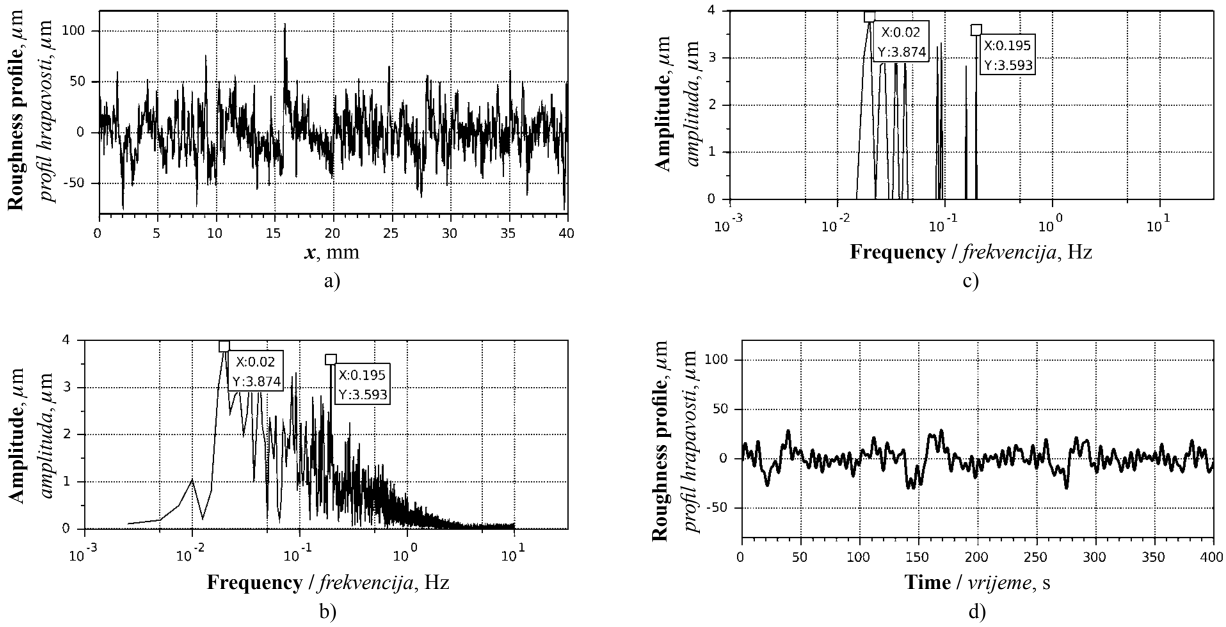


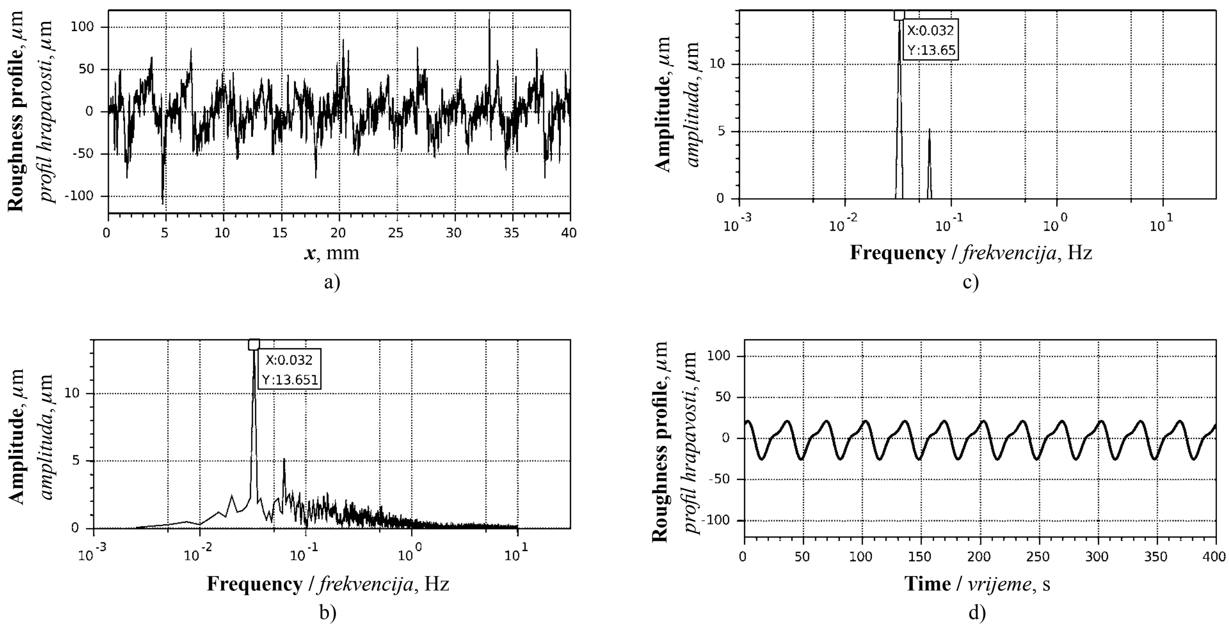

**Figure 3** Machined surface roughness expressed through parameter $R_a$: a) after sawing solid oak, b) after sawing solid oak and filtering the roughness signal, c) after sawing MDF and d) after sawing MDF and filtering the roughness signal
**Slika 3.** Hrapavost obrađene površine izražena putem parametra $R_a$: a) nakon piljenja hrastovine, b) nakon piljenja hrastovine i filtriranja signala hrapavosti, c) nakon piljenja MDF-a, d) nakon piljenja MDF-a i filtriranja signala hrapavosti

consistent for unfiltered and filtered profiles (only the first sample in machining MDF at $f_z$ = 0,02 mm does not fit into this trend and it was excluded from straight line fitting). The average difference between mean values of unfiltered and filtered $R_a$ values on machined surface of solid oak wood was (4.0 ± 0.3) μm and on MDF it was (7.7 ± 1,1) μm. This difference should represent the average value of surface roughness components due to structural roughness of wood, chipped, raised grain, etc. and it was on average higher on machined surface of MDF, which was verified by tactile testing and was mainly attributed to raised fibers.

The average slope of fitted trend line for $R_a$ values of filtered and unfiltered signals as a function of $f_z$ was approximately 44 μm/mm, the only big difference




* analysis of machined surface roughness signals after sawing MDF with $v_f$ = 2 m/min



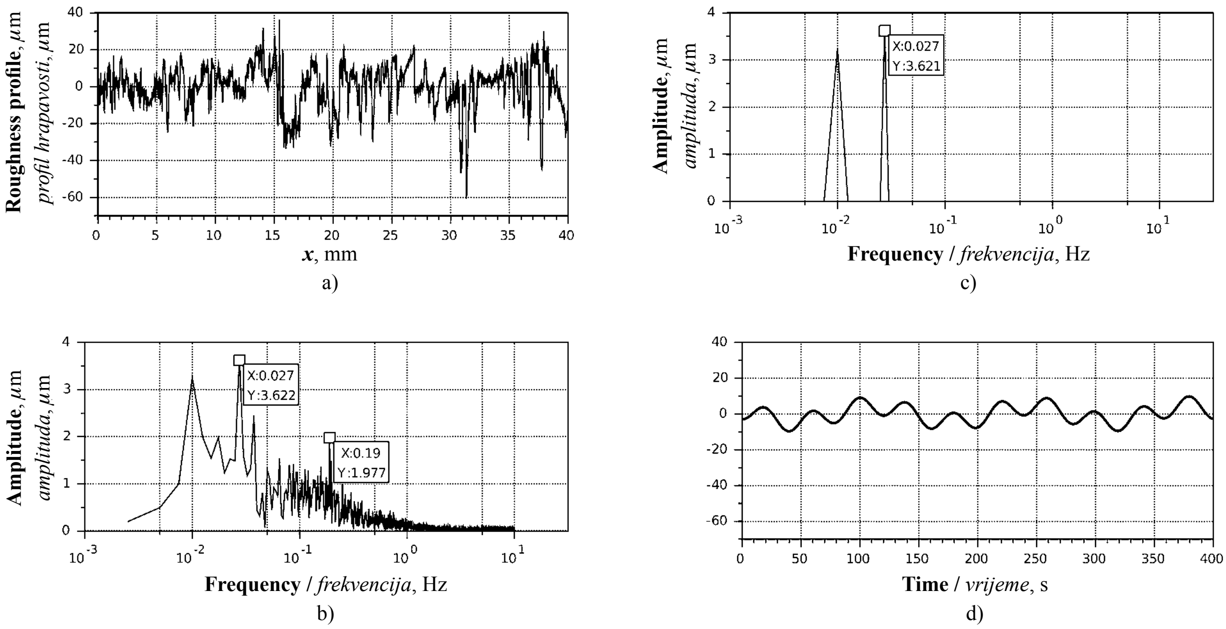

* analysis of machined surface roughness signals after sawing MDF with $v_f$ = 13 m/min

**Figure 4** Results of analysis of machined surface roughness signals: a) original surface roughness profile, b) frequency spectrum of the original roughness signal, c) frequency spectrum of the filtered roughness signal and d) surface roughness profile after filtering with FFT filter
**Slika 4.** Rezultati analize obrađenih signala hrapavosti površine: a) izvorni profil hrapavosti površine, b) frekvencijski spektar izvornog signala hrapavosti, c) frekvencijski spektar filtriranog signala hrapavosti, d) profil hrapavosti površine nakon filtriranja FFT filtrom

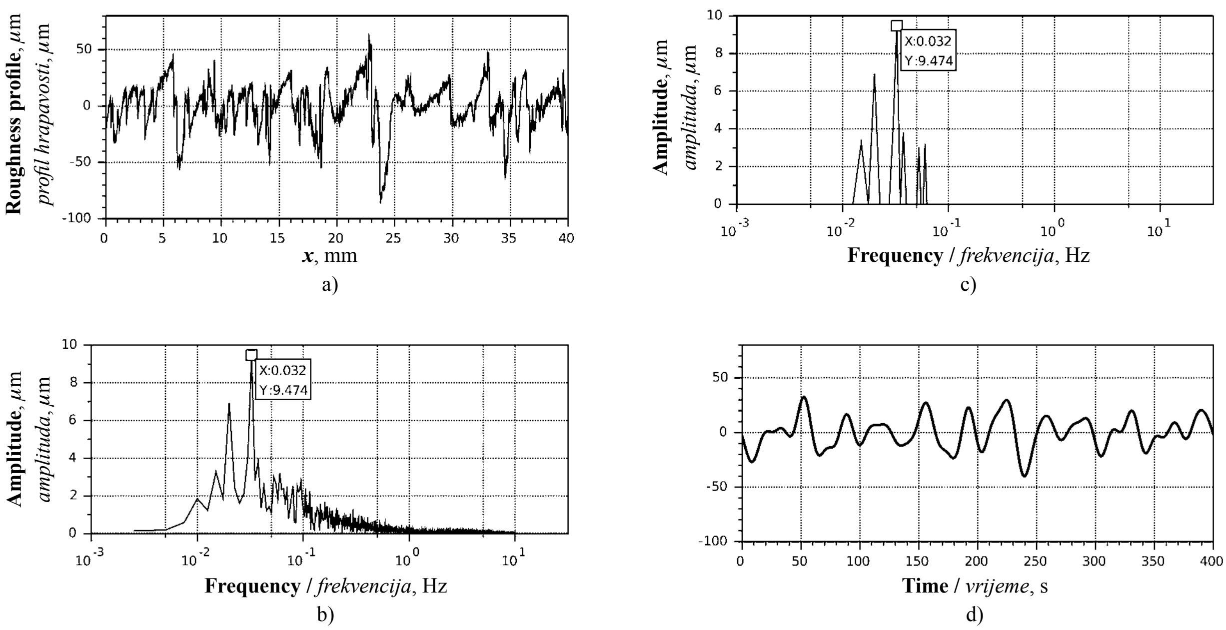
in the trend being in unfiltered signal of MDF machined surface where it was 23 µm/mm.

If the values of fitted straight line slopes obtained from the measured data is compared to the value of straight line slope from the calculated theoretical height of tooth marks as a function of $f_z$ in given sawing conditions obtained with Eq. (2), which is approximately 12 µm/mm, it can easily be seen that not only the values of theoretical surface roughness in relation to the value of surface roughness parameters, but also the sensitivity of those parameters to change in $f_z$ is quite different from the theoretically obtained values.

From the presented graphs and data, limited conclusions can be drawn. There is no clear indication if $R_a$ values of filtered roughness signal are caused by tool




* analysis of machined surface roughness signals after sawing solid oak wood with $v_f$ = 2 m/min




* analysis of machined surface roughness signals after sawing solid oak wood with $v_f$ = 13 m/min

**Figure 5** Results of analysis of machined surface roughness signals: a) original surface roughness profile, b) frequency spectrum of the original roughness signal, c) frequency spectrum of the filtered roughness signal and d) surface roughness profile after filtering with FFT filter

**Slika 5.** Rezultati analize obrađenih signala hrapavosti površine: a) izvorni profil hrapavosti površine, b) frekvencijski spektar izvornog signala hrapavosti, c) frekvencijski spektar filtriranog signala hrapavosti, d) profil hrapavosti površine nakon filtriranja FFT filtrom influence or something else, and which component is the main contributor to the final estimated roughness.

In order to see how filtering of the original surface roughness signal by FFT filtering affects the signal and to better understand the main factors that contribute to calculated values of $R_a$, for every measurement the set of four graphs was produced.

As stated above, the frequency components expected due to feed per tooth and feed per revolution were calculated as $f_{fz}$ = (4.6, 2.3, 1.4 and 0.7) Hz and $f_{fo}$ = (0.19, 0.10, 0.06 and 0.03) Hz and, as can be seen from Figure 4, the surface roughness profile after machining MDF is dominated by lower-frequency components. The frequency component that would be expected due to feed per tooth component of the signal could not be distinguished. From the lower values of the feed speed range up to the higher values, it was evident that the frequency component of the roughness signal that could be associated with the values of feed per one revolution of the saw was becoming dominant and for the $v_f$ = 13 m/min, it is evident from the frequency analysis of the filtered roughness signal that it is the main component that contributes to the overall roughness estimation of the filtered signal.

This component is also present for $v_f$ = 2 m/min, but it is not dominant; the lower frequency components are more dominant and probably some structural or machining roughness components made their way through the filtering procedure. As cyclical components were more pronounced, FFT filtering with constant threshold value did a better job in extracting tool impact on the overall surface roughness. The same trend is evident in the analyzed data of roughness signal from sawing solid oak wood (Figure 5).

As can be seen from the presented figures, filtering the original signal with FFT filter made filtering out the surface roughness components due to tool influence straightforward, even with no change in any parameter of the filter for changing machining conditions and for different materials. The selected threshold value may not be optimal for all of the cases and there still remains the problem of optimal and automatic setting of that value, but the general concept looks promising as a simple and effective way for filtering out the tool impact on the overall surface roughness.

The results of frequency analysis clearly show that, in this case, the main driver of surface roughness is saw blade lateral deflection due to lateral forces on saw teeth, probably caused by uneven lateral bite of saw teeth. As the lateral force on the saw teeth could not be measured, it could only be approximated from the cutting force. The average cutting force ($F_c$) during sawing was calculated by dividing the average cutting power during sawing ($P_c$) with cutting speed $v_c$ = 60 m/s. Cutting power was calculated as a difference between measured average electrical power during sawing ($P_{tot}$) and average electrical power during idling ($P_0$). The results are presented in Table 1.

**Table 1** Calculated average cutting forces ($F_c$)
**Tablica 1.** Izračunane vrijednosti prosječne sile rezanja ($Fc$)

| $f_z$, mm | $F_c$, N | |
|---|---|---|
| | Solid oak wood *masivno drvo hrasta* | MDF |
| 0.02 | 12 | 3 |
| 0.04 | 19 | 5 |
| 0.07 | 22 | 6 |
| 0.14 | 34 | 10 |

If the calculated values of average cutting forces are compared with measured saw blade stiffness at tooth tip ($k_t$ = 42 N/mm), it can be seen that lateral forces, even being a small percentage of the main cutting force, could cause measurable effect on the roughness of the machined surface. Combining this data and $R_a$ values (Figure 3), it can be concluded that the lateral forces for the smallest feed speeds in sawing MDF were not strong enough to show significant difference in $R_a$ values, but as soon as the lateral forces were strong enough, $R_a$ values started to rise in line with values obtained on solid oak wood, where from the smallest values of feed speed the lateral forces were strong enough to show the change in $R_a$ values with every change in feed speed.

There are still doubts about the values of measured $R_a$ parameters after sawing solid oak wood and MDF, because if the main contribution to $R_a$ values due to tool influence on the surface roughness is explained by lateral forces, the obtained values would be expected to be higher in value on machined surface of solid oak then on MDF. In our analysis, the result was the opposite. One possible explanation could be that, during sawing, the machined surface is produced by minor cutting edges with cutting angle of 90° and due to the fact that oak wood is harder than MDF for similar values of density, the oak wood has the necessary counterforce with less deformation compared to MDF, which in the end results in lower signal values due to structural and machining roughness (in this case it is mostly dominated by machining roughness and heavy deformation of material surface by saw teeth, as vessels characteristic of oak wood surface cannot be seen clearly from the measured signal).

As the main goal of this research was to implement FFT filter and to evaluate its usefulness in extraction of surface roughness components due to tooth marks and lateral movement of the saw, further analysis was not conducted, because the data analysis conducted so far has shown that the proposed method can be easy to implement and effective in quantifying the surface roughness components due to saw teeth marks and lateral movement of the saw blade.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

From the obtained research results, it can be concluded that the surface roughness profile of machined surface after sawing with circular saw can be adequately represented, for practical purposes, as a signal obtained as a sum of signals that represent theoretical profile of tooth marks, lateral movement of tooth due to saw vibration and structural roughness of wood, represented as a Gaussian noise. The combination of discrete Fourier transform of surface roughness profile and standard roughness parameters can give a more complete representation of machined surface roughness after sawing with circular saws. Filtering of surface roughness profile signal with FFT filter, even without changing the filter threshold value, can be a simple and effective method in quantifying the tool influence on machined surface roughness after sawing on circular saw in varying machining conditions and on different workpiece material. Appropriate choice of threshold value for FFT filtering is the main factor for adequate extraction of surface roughness component due to tool influence and it would be beneficial to have a method of automatic and objective determination of its level in given machining conditions, in order to eliminate the subjective trial and error method.

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