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THE COMPARATIVE ANALYSIS OF TWO METHODS FOR THE POWER CONSUMPTION MEASUREMENT IN CIRCULAR SAW CUTTING OF LAMINATED PARTICLE BOARD

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ABSTRACT

More advanced approach in the wood machining requires constant monitoring of the cutting process in real time. Such techniques can be provided by measuring different process outputs. The amount of heat generated during cutting, cutting forces, power consumed are common examples of cutting process output. The specific construction and the shape characteristics of the circular saw indicate possible relationship between the power consumption, acoustic emission and the cutting process progress. The results obtained in this paper for the power consumption and the acoustic emission spectrum analysis strongly suggest dependence of the former to the tool override.

The intention of this paper is to compare the results obtained from already existing, but slightly altered, technique of the power measurement and one still developing, the sound analysis. The actual environmental conditions performed in the research, incorporating auxiliary systems, such as exhauster installation, had to bring the results of the conducted research to the point of practical implementation. The utilization of the acoustic emission analysis as an instrument for fast determination of the consumed power during circular saw cutting of the laminated particle board might become powerful indicator of the state of materials involved in the cutting process, both the tool and the wood based board. The results presented would clearly indicate the possibility of such implementation of the frequency and spectrum sound analysis.

KEYWORDS: Cutting power consumption, laminated particle board, circular saw, tool override, acoustic emission, level of acoustic pressure.

INTRODUCTION

The cutting process monitoring is essential for numerous technological reasons such as: the surface quality, state of the cutting tool, energy consumed, wear and tear of the machine and optimum time usage in respect to cutting regimes. For example, sharpening schedule is predetermined routine based upon long time empirical observations. Introducing permanent monitoring of the certain cutting process output, it would become possible to make optimum decision whether to grind the tool or not, concerning surface quality, amount of consumed energy and exploitation life of the tool.

The circular saw blade is unique among the wood cutting tools for its motion instability caused by the dimensional proportion (Tian and Hutton 2001). The measurable output of the self generated (Orlowski et al. 2007) and induced vibrations (Stakhiev 2003; Tian and Hutton 2001; Ukvalbergiene and Vobolis 2007) of the rotating circular saw is the warping of the saw, the cutting width, the cutting power and force as well as the specific acoustic emission (AE).

The cutting force and respectively the cutting power are widely researched property of wood and wood based products. Some methods were developed for the purpose of the proper measurement, all of them indirect, relaying on one component of the cutting force measurement by the piezo-electric electric dynamometer (McKenzie et al. 2001), AC voltage measurement on the machine electromotor (Barcík et al. 2008) or upon the direct measurement by digital three-phase watt-meter (Morita et al. 1998).

There are very few researches related to the cutting power consumption of the particle boards and the other wood based composites (Svrzic 2004). The objective of this paper is to give some new possibilities of measurement methods for power consumption in circular saw cutting of laminated particleboard. The most reliable method for latter is measuring AC voltage drop on the drive electromotor measured with three-phase watt-meter.

The acoustic emission analysis, so far, are based upon determination of natural frequencies of the cutting tools (predominantly circular saw blades), critical rotation speeds introducing resonance (Orlowsky et al. 2007), stability, lateral stiffness, leveling and tensioning (Stakhiev 2003). Examinations were also directed towards the lowering idle noise of circular saw blades (Kopecký and Rousek 2012; Beljo-Lučić and Goglia 2001; Hattori and Lida 1999). Finally, the most important areas of implementation of the sound frequency analysis, from the perspective of this paper, is as an indirect indicator of the tool wear (Suetsugi et al. 2005, Wilkowski and Górski 2010), wood surface roughness, wood fiber direction, feed rate and the cutting width during routing (Iskra and Tanaka 2006).

Theory

The drive electromotor provides energy for movements of the moving parts of the machining system and for overcoming all frictions that occur between machine moving parts (Fig. 2).

$$P = P_u + P_0 \qquad \text{(W)} \tag{1}$$

where: P_u - useful power engaged for movement realization,
P_0 - friction overcoming power.

For the rotating tools such as circular saw blade, the useful power can be calculated as:

$$P_u = M \cdot \omega = F_r \cdot r \cdot \omega \quad \text{(W)} \tag{2}$$

where: F_r - circumferential edge force (cutting force) (N) ,
r - radius of the tool (m),
ω - angular speed of the tool (s^{-1}).

The cutting force could be calculated as:

$$F_c = K_{(n)} \cdot b \cdot h_s^n \quad \text{(N)} \tag{3}$$

where: K_n - specific cutting resistance
b and h_s - chip width and thickness respectively.

Usually F_c is unequal to F_r since the number of incidence teeth is unequal to one. Where K and n are constants determined from empirical test data. This expression has good validity for small chip thicknesses. (Grönlund 2004). From eq. 3 it becomes clear that the cutting force per tooth and due to it the cutting power depends on the cutting regimes reflected in average chip thickness. As already said the value of total force or circumferential edge force also depends on the average number of incidence teeth (Svrzic 2004; Kovač and Mikleš 2007). Consequently total cutting force depends both upon chip thickness and incidence angle (Fig. 1).

It is important to emphasize that the generated sound in the conducted experiment originates from different sources. For example: Exhauster installation, drive motors, rotating circular saw blade, tool to workpiece interaction as well as surrounding noise. The sound generated by rotating saw blade itself and tool to material interaction is in the focus of the conducted research and it originates from the tool vibrations.

The idling noise is produced from different sources: Air vortexes behind a tooth and natural frequency of the saw blade causing lateral moving of the tool (Hattori and Lida 1999). The idling noise does not completely disappear during cutting process, although the vortexes are much smaller due to the chips and the lateral moving is lesser as a result of saw fixation inside the material.

Major results for the cutting circular saw blade vibrations were obtained by Stakhiev (1997, 1998, 1999, 2000, 2001, 2003) and Tian and Hutton (2001). Stakhiev measured values of destructive rotation speed of the saws while cutting. The important conclusions of his work were that the fixity of the teeth increases natural static frequencies of the saw and brings new modes of vibrations.

Tian and Hutton (2001) did research on predicting vibrations when interacting with wood and on stability characteristics of the saw disc while subjected to cutting force. According to them one of the dominant influences upon cutting induced vibrations of the circular saw is "lateral force", or multiple moving regenerative cutting force, that produces extra flank cutting area.

MATERIAL AND METHODS

Material

The material involved in this investigation was the commercially available laminated particle board. The board was produced from the blend of the coniferous wood (fir, spruce and pine) and the lesser percentage of hardwood species, predominantly the beach. The adhesive used for the production of the board was urea-formaldehyde (UF) resin. The laminates used for overlaying the particleboard were consisted of the decorative paper impregnated with melamine-formaldehyde (MF) resin. The moisture content (MC) of the tested laminated particle during the cutting of the board was 5.3 %, whilst its density (ρ) was 0.649 g.cm^{-3}. The density of the board in absolute dry state (ρ_0) was 0.626 g.cm^{-3}.

Specimens were taken from the selected board for the purpose of the mechanical properties and the cutting power consumption determination. Dimensions of the samples were 16×20×700 mm.

The laminated board samples were subjected to the bending strength, tensile strength normal to board surface and the bending modulus of elasticity examinations. Investigations were conducted according to the European standards (EN 319 (1993) and EN 310 (1993)). The results presented were obtained from 30 samples for each for the bending strength in both perpendicular directions (directions 1. and 2.) of the board plane and 40 samples for the tensile strength (layering). Measurements of the mechanical properties were performed on Wood Tested WT4 machine in Wood Properties Laboratory at Faculty of Forestry in Belgrade, Serbia. The results obtained from the examination of the mechanical properties are given in Tab. 1.

Tab. 1: Values of some mechanical properties of the examined laminated particleboard.

Mechanical property	**Bending Strength (N.mm^{-2}) Direction 1.**	**Bending Strength (N.mm^{-2}) Direction2.**	**Modulus of elasticity (N.mm^{-2}) Direction 1.**	**Modulus of elasticity (N.mm^{-2}) Direction 2.**	**Tensile Strength (N.mm^{-2})**
Value	14.92	13.33	3003	2637	0.302

Cutting power consumption

Test cutting of the laminated particle board with circular saw took place at the Minimax CU410K machine in Laboratory for Machines and Apparatus at Faculty of Forestry, Belgrade University. The experiment was carried out on in the air and the atmospheric pressure. The feed rate was realized by Maggi Engineering Vario feed device, with available feed rates from 3-24 m.min^{-1}. The experiment variable was the incidence angle φ. Fig. 1 expressed by means of position of circular saw blade center *a*.

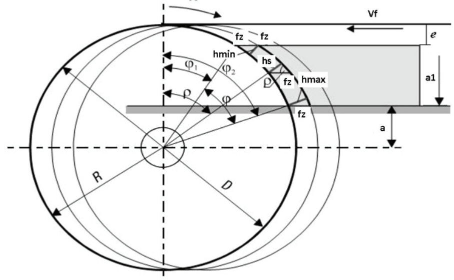

Fig. 1: Cutting process geometry: e – tool override, a_1 – cutting depth, a – distance of the tool center from the upper working table surface, φ – incidence angle, h_{min} – minimal chip thickness, h_{max} – maximal chip thickness, φ_1 – input angle of the tooth, φ_2 – output angle, D – tool diameter, R – tool radius, v_c – cutting speed, v_f – feed rate, f_z – feed rate per tooth .

In order to vary the value of incidence angle the position of circular saw blade, override of the tool, compared to upper working piece surface, was altered from 5 to maximum 30 mm. For each position of the tool fifteen cuts were performed.

The tool used during the experiment was circular saw blade AKE Cutting & Beetter saw wit following characteristics: Diameter 250 mm, inner diameter 30, width 2.2, cutting width 3.2 mm, number of saw teeth 78, tooth shape SK, rake angle 12° and clearance angle 15°. The blades are made of the hard metal, the body is of constructive steel and the tool has slots on the body for reducing the noise and vibrations. The primary application of this saw is for particleboard and plywood formatting. The speed of rotation and feed rate were constant throughout the experiment and they were set at n = 3750 min^{-1} and v_f = 20 m.min^{-1} respectively.

Cutting powers were determined indirectly by measuring engaged power of drive electromotor using the measurement-acquisition device SRD1 manufactured by UNO-NS, Belgrade, Serbia. The device was developed and applied in the Laboratory for Machines and Apparatus in order to measure, to monitor, to process and analyze the power consumption in the cutting with different types of the tools utilized. The device has Circutor CW-TAN active power transducer for the unbalanced three-phase systems with these characteristics: Altering current 5 A, altering voltage 230 V, frequency 50 Hz, accuracy 0.5 % and analog voltage output 0-10 V (Mandić et al. 2011). The possible measuring ranges are 5, 10, 15 kW. The operator is choosing expected range for better resolution of the results. The whole system is based upon Power Expert software platform. The device is also suitable for portable usage.

Some features of the cutting process important for further considerations have to be defined as well. Already mentioned incidence angle φ and arcs l (that corresponds to the active cutting path of each tooth) can be expressed, according to Fig. 1, as:

$$\varphi = \varphi_2 - \varphi_1 = \arccos\frac{a_1}{R} - \arccos\frac{a + a_1}{R} \tag{4}$$

$$l = \frac{\pi \cdot D \cdot \varphi}{360} \tag{5}$$

If Eqs. 4 and 5 are applied for different positions of circular saw blade center a, height in further text, corresponding incidence angles and arcs can be calculated as shown in Tab. 2.

Tab. 2: Geometric parameters influencing the power consumption.

Override *e* (mm)	5	10	15	20	30
Incidence angle *φ* (°)	17.43	14.56	12.87	11.74	10.26
Arc *l* (mm)	38.01	31.74	28.06	25.59	22.37

Acoustic emission analysis

The acoustic emission analysis was performed along with the cutting power consumption measurement. The experimental layout consisted of the receiver (SHURE Beta 181 microphone) and the PC with installed OscilloMeter commercially available software for the sound examination. In respect to previous researches (Iskra and Tanaka 2006 and Tanaka et al. 1988) the position of microphone was set at 1200 mm from the tool in horizontal direction normal from the center of the saw blade and 950 mm form the ground (Fig. 2). In order to accomplish the anechoic chamber effect the walls of the room were covered with heavy curtains. This way the deflection of sound waves was reduced as much as possible, especially from the wall behind the microphone. The latter was important for the fact that microphone was set to work cardioid capsule arrangement that is favorable to front direction of the sound source. The sound registered to microphone was undamped by any kind of filter since the whistling noise produced during idling, supposedly, should decrease while cutting (Cheng et al. 1997).

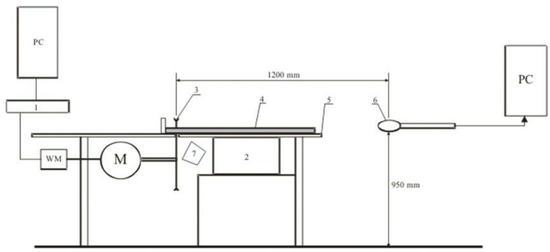

Fig. 2: Experimental setup: 1 – cutting power measuring-acquisition device; 2 – feeding device; 3 – circular saw blade; 4 – workpiece; 5 – feeding carriage; 6 – microphone; 7 – exhauster receiver; M – drive motor; WM – wattmeter.

Acoustic emission spectrum analyzer, incorporated in the software, works on algorithm of Fast Fourier transform (FFT). The size of each block a FFT is up to 2^24 samples of input signal. The following parameters of input signal could be calculated: peak frequency with inaccuracy of 5·10^-8 to 5·10^-7, peak amplitude with inaccuracy of 0.01 dB, peak phase and frequency ratio.

RESULTS AND DISCUSSION

The measurements of the cutting power were conducted as mentioned in section Material and Methods for different tool override values. Consequently separate groups of the results were acquired and processed. The corresponding analysis and table presentations are given below.

The mean values of cutting power and other cutting parameters for different overrides are presented in Tabs. 3 and 4.

Tab. 3: Statistical parameters of obtained cutting power results.

	Cutting power (W)				
	5 mm	10 mm	15 mm	20 mm	30 mm
Mean	736.8356	670.2463	633.5981	642.2700	553.2556
Minimum	728.3900	654.4100	615.3400	618.4900	531.9000
Maximum	738.7800	686.1300	653.5600	659.1200	577.4800
Std.Dev.	3.44304	8.55067	10.14816	13.21861	12.43949

Tab. 4: Values of the calculated cutting process parameters for different values of tool override.

Tool override (mm)	Incidence angle (°) - calculated	Cutting arc length (mm) - calculated	Average chip thickness (µm) - calculated
5	17.43	38.01	28.8
10	14.56	31.74	34.5
15	12.87	28.06	38.9
20	11.74	25.59	43
30	10.26	22.37	48.8

From the Tab. 4 it becomes quite obvious that the cutting arc length decreases as well as the incidence angle with increasing tool override. It is also evident that the mean values of cutting power descend with rising values of the middle chip thickness (Fig. 3).

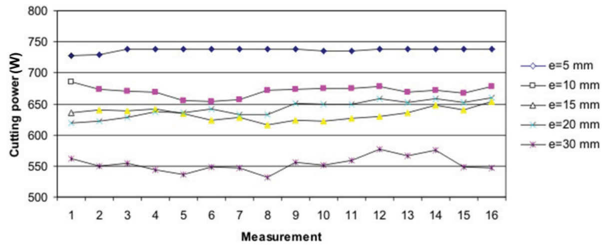

Fig. 3: Measured cutting powers at different values of the tool override e.

In order to prove statistically significant dependence of acquired results for the cutting power from tool override factor, univariate variance analysis ANOVA was applied. The obtained value of F statistics from Tab. 5 indicates statistically significant difference, so it could be considered that measured results belong to different series. For the purpose of statistic analysis software STATISTICA 7 was used.

Tab. 5: ANOVA test of significance results.

Effect	**Univariate tests of significance for cutting power (W) Sigma-restricted parameterization Effective hypothesis decomposition**				
	SS	**Degr. of Freedom**	**MS**	**F**	**p**
Intercept	33513686	1	33513686	323849.9	0.00
Tool override (mm)	281608	4	70402	680.3	0.00
Error	7761	75	103		

According to the Bonferroni Post Hoc test of multiple comparison at the level of significance α=0.05 it was shown that major difference of measured cutting powers is missing only for the samples processed with tool overrides of 15 and 20 mm (Tab. 6).

Tab. 6: Bonferroni test probabilities results at level of significance α = 0.05.

Cell No.	**Bonferroni test; variable Cutting power (W) Probabilities for Post Hoc Test Error: between MS = 103.49, df = 75.000**					
	Tool override	**{1} 736.84**	**{2} 670.25**	**{3} 633.60**	**{4} 642.27**	**{5} 553.26**
1	5		0.00	0.00	0.00	0.00
2	10	0.00		0.00	0.00	0.00
3	15	0.00	0.00		0.1835	0.00
4	20	0.00	0.00	0.1835		0.00
5	30	0.00	0.00	0.00	0.00	

In Tab. 6 the values of inverse hypothesis probabilities are presented. Each probability lesser then the set level of significance proves that the groups of measurements are significantly different and thus proves the hypothesis of the cutting power to tool override relation.

Simultaneously with cutting power data acquisition, sound recordings were performed. The background noise and self exited (idling) noise results as well as represents of groups of ten measurements per override are presented below (Figs. 4 and 5).

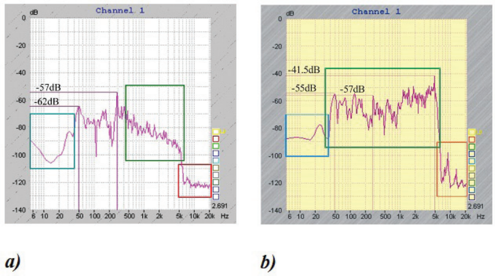

Fig. 4: a) Exhauster installation noise, b) Idling circular saw noise spectrum-

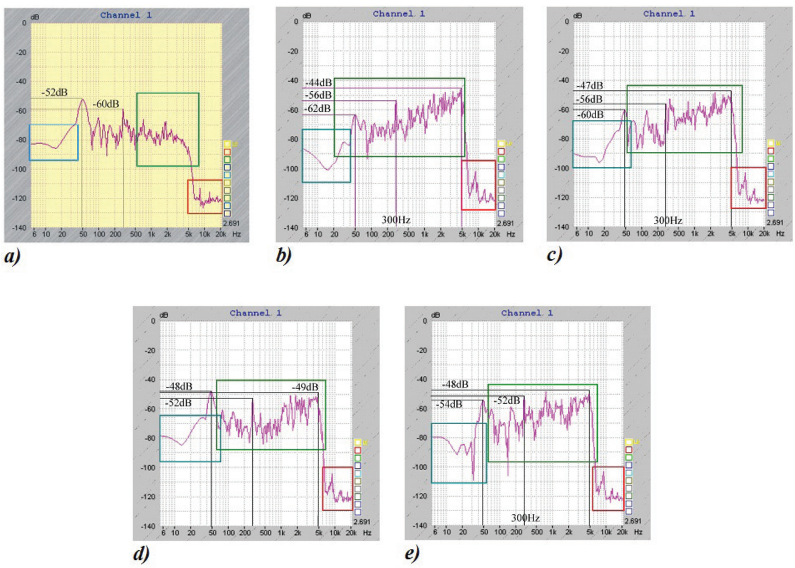

Fig. 5: AE spectrum for a) e=5 mm; b) e=10 mm; c) e=15 mm; d) e=20 mm; e) e=30 mm.

As expected, sounds of the pneumatic exhauster installation and the idling noise of saw have relatively low levels of intensity compared to the cutting sound spectrums, especially in spectrum scope between 500 and 5000 Hz. According to the cutting regimes and number of the tool teeth it is assumed that there would be "fingerprint of the tool" starting from 6 kHz frequency, and marked with red rectangle. Obviously there is a spectrum scope beyond 5 kHz that exist only for operating tool. The same pattern appears for all spectrums shown in Fig. 5 a) through e). The pattern above 5 kHz shown in Fig. 4b is the fingerprint for natural frequency of the circular saw at predetermined speed, and those at the Figs. 5 a) to e) are altered due to the tool and material interaction (Orlowski at al 2007; Hattori and Lida 1999; Tian and Hutton 2001).

Another interesting spectrum domain is from slightly above the hear threshold to about 5.5 kHz, marked with green rectangle. Peaks at 5 kHz behave in an interesting way, slightly decreasing the magnitude with increasing tool override and lessening cutting power. The absence of this peak for idling saw noise and exhauster spectrums indicates that it originates from tool to board interaction (Stakhiev 2003). This trend goes along with Stakhiev's results of saw frequencies for teeth fixity in wood. The amplitude for 5 mm tool override have the highest value since the average number of affected teeth is then at maximum. Moreover, there is a very obvious difference between the amplitudes of the 5 kHz peak for the tool overrides at 15 and 20 mm, making this type of analysis very accurate for the fast practical use. These results go along with the results obtained by the wattmeter, suggesting the same behavior for the cutting force for ascending values of the override. The total percent of the cutting power drop according the wattmeter measurements is approximately 25 and according to AE analysis about 18 %. Surprisingly, although the structure of the particle board is highly inhomogeneous, the result stayed in very close margins for both applied method.

There is also another acoustic pressure peak at the frequency of 300 Hz appearing at all presented graphs. It is reasonable to assume that the background noise form incorporated exhauster installation motor is responsible for the latter. This is very important from the practical point of view, allowing focusing on the emission that is vital only for circular saw blade AE.

Acoustic pressure peak at frequency of 50 Hz is drawing attention too. Its presence is noticeable in all AE spectrums presented. According to the available literature and the analysis of spectrums there was no explanation for its existence. However, the amplitude of it increases when circular saw is idling, varying slightly for different values of the tool override. Further researches should give an answer on the nature of this AE range.

CONCLUSIONS

According to result both for consumed power and for AE spectrums of acoustic pressure it is possible to conclude:

- Results for laminated board are provided using the same cutting power measurement equipment as for the massive wood;
- Result obtained for the cutting power consumption shows the trend of rising values for upward values of incidence angle and descending values average chip thickness. This can be explained by the stronger influence of average teeth involved then the influence of chip thickness;
- Statistical analysis of the mean values of the cutting power shows strong value dissimilarities for the different values of tool override (except for the e=15 and e=20 mm);
- The experimental setup for the AE analysis provided satisfactory results for comparison with those gained with wattmeter;
- The increase of the radial force increases the vibrations of rotating disc (circular saw); the same effect have been detected by comparing the results for the consumed power and spectrums of AE, in other words with more teeth fixed (average) in material and thus for the upper value of the total cutting force the peaks of AE spectrum were higher;
- In the spectrum are beyond 5.5 kHz changes in terms of acoustic pressure peaks growth suggesting that fixity of tooth alters the natural frequencies of circular saw ;

- The peak at 5 kHz appears only in AE spectrums when tool interacted with workpiece indicating the “true sound of cutting” dependant of the total cutting force or/and cutting power;
- Using this method can be seen as a new approach for determining the effects of blunting tools on energy consumption;
- Since the heterogeneity of particleboard structure the results obtained could be considered as highly non dissipative, presenting the adequate start point for further researches.

Previous conclusions lead to clear possibility of AE spectrum analysis utilization as a powerful tool in cutting process monitoring. All changes in sound response or outputs from cutting with the circular saw could be recognized and consequently reacted in manner of assuring the undisturbed process flow. However, there is still lot of room for further researches in the terms of varying other cutting process and tools parameters (feed rate, angular speed of the saw, types of saw etc.), making this research preliminary step towards integrated study of the sound implemented control device.

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