On Acoustic Emission Analysis in Circular Saw Cutting Beech Wood with Respect to Power Consumption and Surface Roughness

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A sound or a noise that accompanies wood machining processes is introduced by the tool rotation itself, by the friction of moving machine parts, or by wood-tool interaction. The sounds generated during machining with a circular saw could be analysed in order to monitor and possibly control the cutting process. Applying altered cutting parameters while cutting beech wood (*Fagus sylvatica* L.), which is the most common wood species in the Republic of Serbia, caused acoustic emissions that could be analysed throughout corresponding spectra. As shown in previous studies, altering the cutting parameters, *e.g.*, the feed speed and tool override, resulted in variations in power consumption, surface roughness, and acoustic emission (or acoustic pressure). The aim of this paper was to provide a possible correlation between the applied cutting parameters and the acoustic emission spectra with respect to consumed power and the state of the machined surface. Along with acoustic emissions, the power consumption and surface roughness data were also acquired in order to make a possible relationship. By associating the idle circular saw acoustic spectra with background noise and comparing them with those obtained during machining, it was possible to indicate spectrum areas of particular interest for further analysis.

Keywords: Acoustic emission; Acoustic pressure; Wood machining; Cutting power; Surface roughness Circular saw; Spectrum analysis

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INTRODUCTION

Different methods for monitoring wood machining processes are used for the purpose of obtaining proper work piece quality. A work piece should have the specified dimensions and desired surface characteristics. Along with the aforementioned results, the energy consumption, operational time, and machining system gearing state are observed as influential factors for desired machining process performance. The power consumption expressed by cutting power, along with acoustic emission, could potentially provide satisfactory data for permanent process monitoring (Mandić *et al.* 2015; Porankiewicz *et al.* 2021).

The acoustic emissions present an inevitable wood machining output. This comes from the moving (predominately rotating) parts of a machining system, producing vibrations and oscillatory sounds, which could be associated with the working state of the machine. Furthermore, the tool rotation and its self-generated and induced vibrations produce acoustic emission correlated to the state of the tool and its interaction with the work piece, *i.e.*, wood or wood based, material. An idling noise is produced from different sources: the air vortexes behind a tooth and the natural frequency of the saw blade causing lateral moving of the tool (Hattori and Iida 1999; Nasir and Cool 2020). The idling noise does not completely disappear during the cutting process, although the vortexes are much smaller due to the chips. In addition, the lateral movement is less as a result of saw fixation inside the material.

An adaptive control system based upon acoustic emissions in terms of surface roughness by adjusting the feed rate was proposed by Deja and Licow (2020) and monitoring sawing processes *via* means of acoustic emission was proposed by Nasir *et al.* (2019). Sound techniques were also proposed for cutting conditions (Nagatomi *et el.* 1993) and tool weariness monitoring (Banshoya *et al.* 1994).

Contact vibration measurement sensors, *e.g.*, accelerometers, are difficult to apply because they need to be placed as close as possible to the tool support (Delio *et al.* 1992). Contactless indirect vibration measurements providing acoustic emission spectra could be provided using a microphone as a sensor. The primary problem when using microphone is the inevitable mixing of sounds originating from the background, the machining system itself, or other sources. This was the primary reason for the purpose of this study; first, the idling acoustic spectra were recorded, and then these were compared with the acoustic spectra when the tool was interacting with the wood material.

Acoustic emission analysis, or acoustic pressure (AP), are currently based upon the determination of the natural frequencies of the cutting tools (predominantly circular saw blades), the critical rotation speeds introducing resonance (Orlowski *et al.* 2007), and the stability, lateral stiffness, levelling, and tensioning (Stakhiev 2003). Examinations were also directed towards the lowering idle noise of circular saw blades (Hattori and Lida 1999; Beljo-Lučić and Goglia 2001; Kopecky and Rousek 2012). Finally, the most important areas of implementation of the sound frequency analysis, from the perspective of this paper, were used as an indirect indicator of the tool wear (Suetsugu *et al.* 2005; Wilkowski and Górski 2011), wood surface roughness, wood fiber direction, feed rate, and the cutting width during routing (Iskra and Tanaka 2005, 2006; Durcan and Burdurlu 2018).

Parallel to recording the AP spectra, the power consumption was also measured. The power consumption measuring method was the AC voltage drop on the drive electromotor measured with a three-phase watt-meter.

Since the feed rate has a large impact upon the cutting power and the tool override influence on the circular saw lateral movement, it was reasonably to expect them to have mutual effects on the acoustic emission recordings obtained during the tool-wood interaction.

The hypothesis of this study was that different values of the feed rate and the tool override would elevate the AP at the certain frequencies of the acoustic emission spectra in a predictable manner, and that output can provide new possibilities for monitoring the cutting process in the terms of the power consumption and the surface quality for the circular saw cutting of beech wood.

EXPERIMENTAL

In this study, beech (*Fagus sylvatica* L.) wood, as a widely spread tree species in the Republic of Serbia, was chosen for the material for this experiment. The average moisture of the beech planks was 9.04%, with a density of approximately 0.680 g/cm^3. The dimensions of the planks were 1000 mm × 150 mm × 30 mm. The specimens were later cut along the grain. The samples had been conditioned before testing in the laboratory environment conditions: relative humidity of 45 ± 5% and room temperature of 20 ± 3°C.

The research presented in this paper was conducted at the Laboratory for Machines and Apparatus at the Faculty of Forestry, University of Belgrade (Beograd, Serbia). The machining system used for cutting the wood samples was a Minimax CU 410K combined machine (SCM, Rimini, Italy) equipped with a 3 kW three-phase asynchronous electrical motor. The exhausting system was involved throughout the entire experiment. The feed rate measurement took place before each series of samples *via* a Maggi Engineering Vario feed device (Maggi Technology, Certado, Italy), equipped with a 0.45 kW three-phase asynchronous electrical motor with an available measuring range of feed rates from 3 m/min to 24 m/min, which covers most common feed rates in practice. The tool overrides were set by means of a machine corresponding mechanical system deploying spindle and gears.

The tool used in this research was a circular saw blade CMT ORANGE TOOLS multi-rip with rakers (Pesaro, Italy) with the following characteristics: a diameter (D) of 300 mm, an inner diameter (d) of 70 mm, a width of 2.2 mm, a cutting width (W) of 3.2 mm, the number of saw teeth (z) equalling 24, an ATB tooth shape, a hook angle (α) of 18°, and a grind angle (β) of 10°. The blades were made of a hard metal cemented carbide (HV10), the body was made from constructive steel, and the tool had slots on the body to reducing noise and vibrations. The primary purpose of this saw is for rip cuts, where the rakers prevent wood contact with the steel plate and is applicable for wet and dry softwood and hardwood.

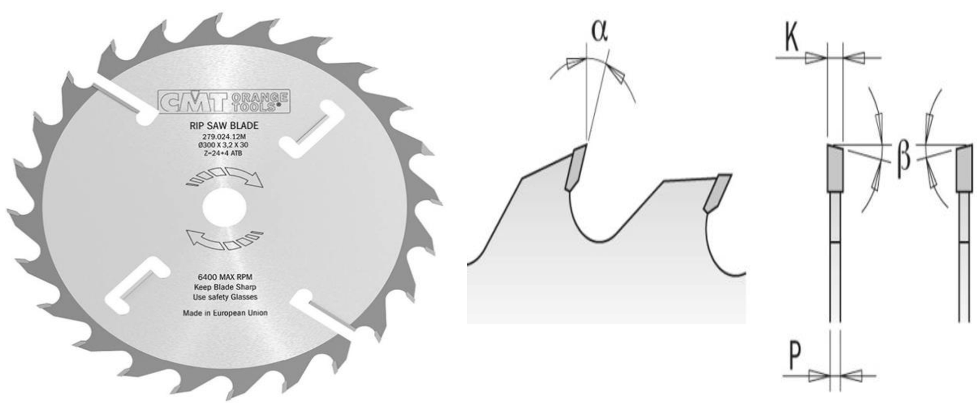

Fig. 1. Working tool CMT Orange tools

The override values, as the distance from the top point of the tool and the upper surface of the working piece, were measured as 10 mm, 20 mm, and 30 mm, which influenced the incidence angle (φ). Testing was performed with a constant number of rotations per minute (RPM) of the working spindle (3750 RPM, *i.e.*, at a constant cutting speed (v_C) of 58.875 m/s), whilst the values of the feed rate were 8 and 12 m/min, as suggested by other authors (Souza *et al*. 2011; Nasir and Cool 2019).

The method for determining the cutting power was based on the indirect measurement of the engaged power of the drive electromotor *via* means of a measurement-acquisition portable device (SRD1, Unolux, Belgrade, Serbia) with a sampling frequency of 1 kHz, which was used for data measurement, acquisition, analysis, and processing. The primary purposes of the SRD1 were the measuring, monitoring, processing, and analysing of the data correlated to the power consumption during different types of wood machining. The scale range of the measuring equipment could be set to 5, 10, and 15 kW, according to expected values of engaged power in order to achieve better resolution of the obtained results. The whole system was based upon Power Expert 2.0 software platform (Mandić *et al*. 2015).

The measurement of the surface roughness was performed with a stylus contact tester (TimeSurf TR200, Beijing TIME High Technology Ltd., Beijing, China) in accordance with ISO standard 4287 (1997). The measured roughness parameter was the R_a, which is the arithmetic average value of the filtered roughness profile determined from deviations about the centre line within the evaluation length. During data acquisition, the reference length was set at 2.5 mm (in accordance with the recommendation of ISO standard 4288 (1996)), whilst the diameter of the diamond stylus tip was 2 μm, and the stylus was pressed on the surface with a force of 4 mN. The measurements were made perpendicular to the direction of the wood grain.

The acoustic emission data were sampled using OscilloMeter 7.31 software with a recording frequency range between 0 and 20 kHz. It was possible to obtain both 2D and 3D time dependant spectra, which were analysed latter. The experimental setup used in this research was the same as in a previous paper (Mandić *et al*. 2015).

The distance from the saw blade to the microphone was 1200 mm away from the operating tool in the horizontal direction and 950 mm in the vertical direction from the ground, aligned with the machine work surface (Tanaka 1988; Iskra and Tanaka 2006). The sound produced was undamped, as suggested by Cheng *et al.* (1998). The microphone was a SHURE Beta 18 (Niles, IL). In order to simplify the presented results, the different cutting regimes will be denoted as follows: the feed rate (V_{F1}) is 8 m/min and V_{F2} is 12 m/min; the tool override (h_1) is 10 mm, h_2 is 20 mm, and h_3 is 30 mm. The number of cuts for each plank and each cutting regime was 5 (6 groups of specimens with 5 repeats). The number of replicates for every step of the experiment (as shown in Fig.2) was 20, except in the case of *Ra* where it was 40.

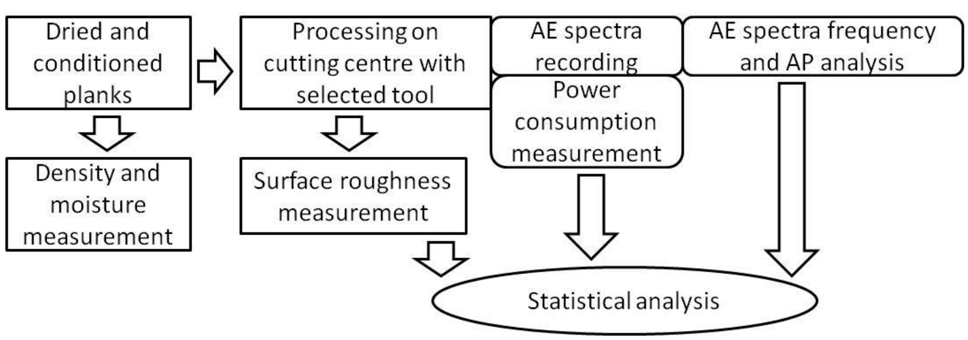

Fig. 2. Schematic illustration of experimental steps

RESULTS AND DISCUSSION

Simultaneously with recording the acoustic emissions, the data for the cutting power (*P*) were recorded. The results for the obtained average power consumption values are presented in Table 1.

Table 1. Average Values of Power Consumption for Different Cutting Regimes

No.	V_F (m/min)	*h* (mm)	*P* (W)	No.	V_F (m/min)	*h* (mm)	*P* (W)
1.	8	10	740.15	16.	12	10	1033.88
2.	8	10	727.24	17.	12	10	1042.03
3.	8	10	707.43	18.	12	10	1003.18
4.	8	10	686.19	19.	12	10	984.72
5.	8	10	678.5	20.	12	10	945.1
6.	8	20	747.28	21.	12	20	928.28
7.	8	20	748.72	22.	12	20	900.63
8.	8	20	782.59	23.	12	20	888.16
9.	8	20	734.84	24.	12	20	986.1
10.	8	20	749.45	25.	12	20	984.37
11.	8	30	787.97	26.	12	30	1012.18
12.	8	30	834.15	27.	12	30	972.32
13.	8	30	824.59	28.	12	30	927.35
14.	8	30	782.65	29.	12	30	914.65
15.	8	30	750.11	30.	12	30	963.63

Analysis of the obtained data, *i.e.*, the power consumption during circular saw cutting of beech wood, is presented below. A univariate variance analysis ANOVA was applied for testing the significant dependence of the cutting regimes on power consumption.

Table 2. Univariate Significance Test for *P* with Respects to the V_F and *h*

	SS	Degrees of Freedom	MS	F	p
Intercept	22133750	1	22133750	18177.17	0.000000
V_F (m/min)	342341	1	342341	281.14	0.000000
h (mm)	5347	2	2673	2.20	0.133162
V_F **h*	24789	2	12395	10.18	0.000629
Error	29224	24	1218	-	-
* Significant results are highlighted in red					

With a probability threshold of 95%, it is possible to say that the feed rate significantly influenced the level of power consumption in a positive manner. At the same time, the override was not enough to influence the measured power consumption (Table 2). However, the mutual impact of the feed rate and override was shown to have a significant effect upon the power consumption (a *p*-value of 0.000629 was less than 0.05).

According to the results presented in Table 2, the effect of the feed rate (set at a value of 12 m/min) on the power consumption was the highest when the tool override was 10 mm, which was a possible influence of the average number of incidence teeth (Kovač and Mikleš 2010; Kvietkovà *et al.* 2015).

Table 3. Tukey HSD Test Results

	V_F (m/min)	*h* (mm)	{1} 707.90	{2} 752.58	{3} 795.89	{4} 1001.8	{5} 937.51	{6} 958.03
1	8	10	-	0.358633	0.006479	0.000138	0.000138	0.000138
2	8	20	0.358633	-	0.391307	0.000138	0.000138	0.000138
3	8	30	0.006479	0.391307	-	0.000138	0.000149	0.000139
4	12	10	0.000138	0.000138	0.000138	-	0.073151	0.380590
5	12	20	0.000138	0.000138	0.000149	0.073151	-	0.934841
6	12	30	0.000138	0.000138	0.000139	0.380590	0.934841	-
* Significant results are highlighted in red								

As shown in Table 3, it became obvious that there was no significant influence of the feed rate (V_F of 8 m/min) for gradual changes in the *h*, from 10 mm to 20 mm, and from 20 mm to 30 mm. However, it was clear that considerable changes in power consumption could be expected when the *h* at 10 mm was increased to 30 mm. Altering the values of *h* had no significant importance when the value of V_F was set to 12 m/min (as shown in Fig. 3).

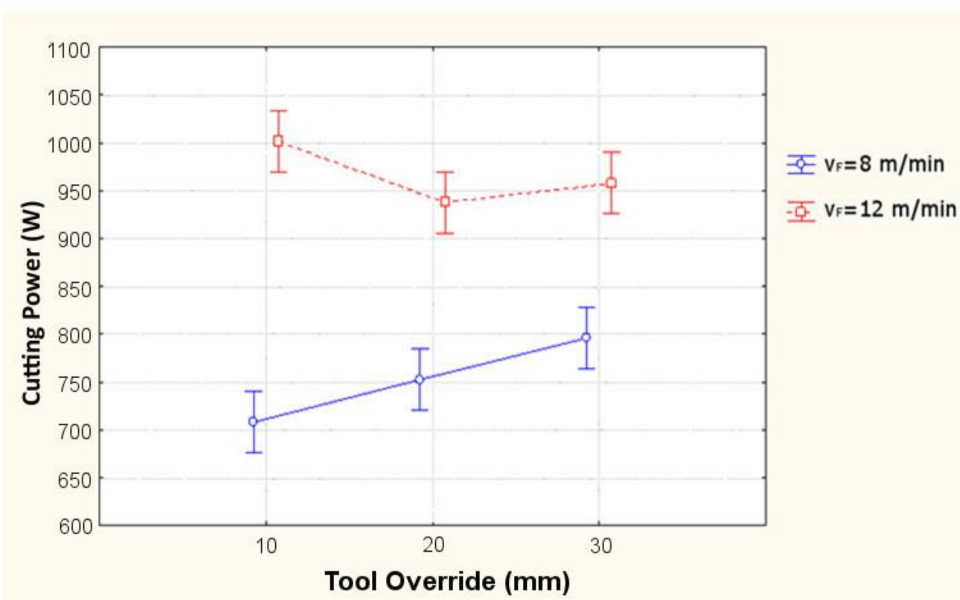

Fig. 3. Mutual impact of the feed rate and tool override on the power consumption

The results of the average values for the R_a of different cutting regimes are presented in Table 4.

Table 4. Average Values of the R_a for Different Cutting Regimes

No.	V_F (m/min)	*h* (mm)	R_a (µm)	No.	V_F (m/min)	*h* (mm)	R_a (µm)
1.	8	10	5.4279	16.	12	10	7.0825
2.	8	10	6.8762	17.	12	10	6.4053
3.	8	10	8.9955	18.	12	10	5.9295
4.	8	10	5.9027	19.	12	10	8.2352
5.	8	10	5.1291	20.	12	10	7.382
6.	8	20	5.8101	21.	12	20	8.3066
7.	8	20	6.2847	22.	12	20	7.7285
8.	8	20	7.3951	23.	12	20	5.777
9.	8	20	7.0389	24.	12	20	8.5468
10.	8	20	6.1895	25.	12	20	10.0569
11.	8	30	8.1567	26.	12	30	4.8967
12.	8	30	6.5133	27.	12	30	8.5618
13.	8	30	7.6998	28.	12	30	8.7259
14.	8	30	8.6662	29.	12	30	9.8191
15.	8	30	8.9519	30.	12	30	10.0601

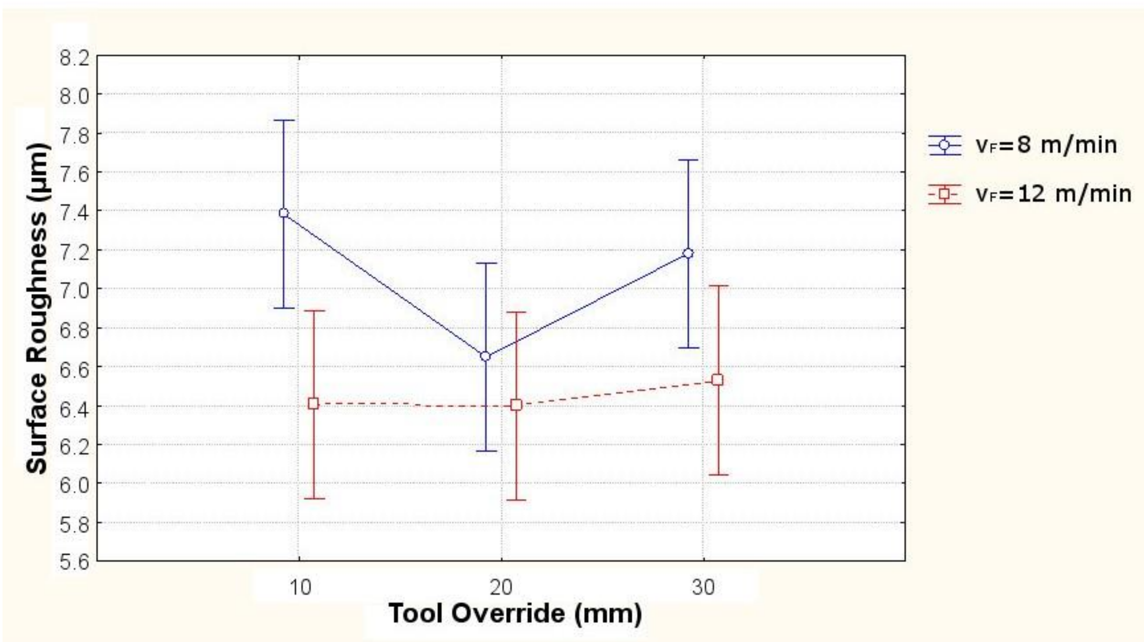

Fig. 4. Mutual impact of the feed rate and tool override on the R_a

At a significance threshold of 5% and a probability level of p = 0.95 it was found that the V_F had a significant influence upon the surface roughness, whilst there was no notable impact of the *h* values on the surface roughness (Table 5).

Table 5. Univariate Significance Test for the R_a with Respect to the V_F and h

	SS	Degrees of Freedom	MS	F	p
Intercept	13700.90	1	13700.90	4545.057	0.000000
V_F (m/min)	29.44	1	29.44	9.767	0.001955
h (mm)	8.22	2	4.11	1.364	0.257194
V_F *h	6.66	2	3.33	1.105	0.332664
Error	886.25	294	3.01	-	-

* Significant results are highlighted in red

It is also possible that the combined effect of the V_F and h did not cause a significant change in the R_a. As a matter of impact nature, it could be said that the increased V_F increased the R_a (Table 3).

Results obtained during the acoustic emission recordings are presented as 2D and 3D spectra. Examples of the investigated spectra are given in Figs. 5 and Fig. 6.

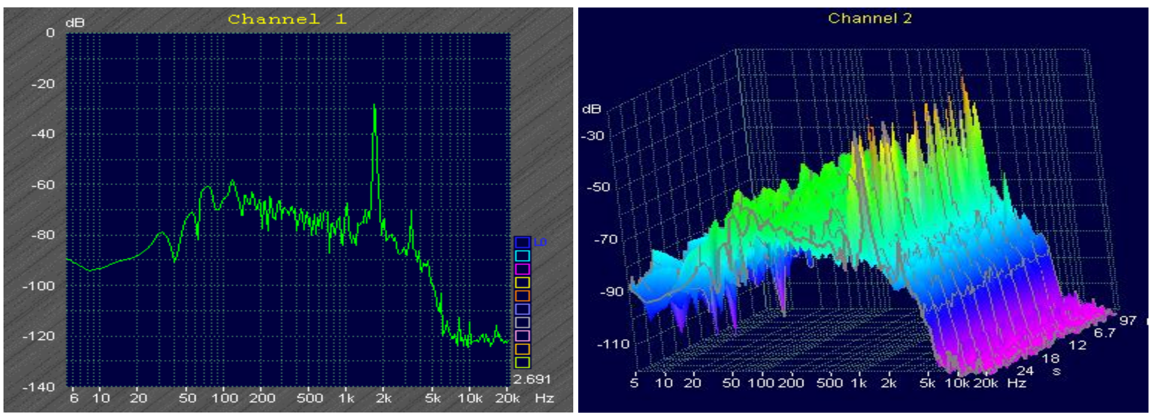

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Fig. 5. Acoustic pressure spectra for idling machine in: (a) 2D, frequency on the x-axis and AP on the y-axis; and (b) 3D, time axis added

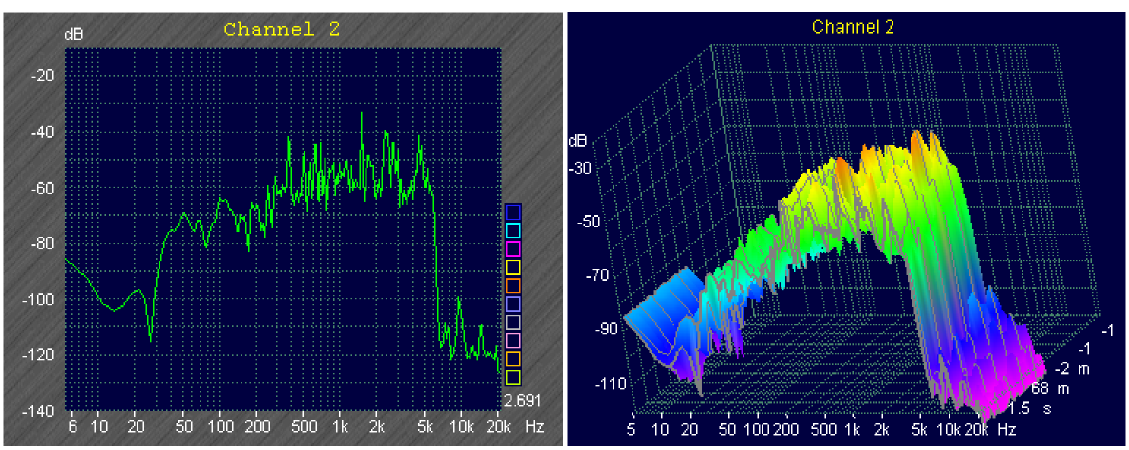

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Fig. 6. Acoustic pressure spectra for u2 and h1 in: (a) 2D, frequency on the x-axis and AP on the y-axis; and (b) 3D, time axis added

There was obvious difference between the AP spectra of the idling and operating machine. The solo AP peak at 1.8 kHz on the spectra of the idling machine did not appear on other records related to the operating machine. The entire spectral area of the operating machine spectra was elevated compared to the idling machine spectrum, with some constantly repeating peaks. The AP peaks of particular interest were at 1.6 kHz, 3 kHz, 9 kHz, and 15 kHz whilst investigating a frequency area ranging from 200 Hz to 1.5 kHz on the spectra of the operating machine. The results of the AP obtained from the selected frequency areas are presented in Table 6.

Table 6. Results of the Acoustic Pressure for Different Feed Rate and Tool Override Values at Characteristic Frequencies

Frequency		200 Hz to 1.5 kHz					1.6 kHz				
V_F (m/min)	*h* (mm)	AP (dB)					AP (dB)				
8	10	-70,5	-69,6	-66,2	-69,3	-68,9	-35	-36	-33	-38	-35
8	20	-65	-73	-64	-62	-65	-33	-41	-31	-35	-33
8	30	-63,5	-56	-55	-59	-58	-29	-31	-39	-33	-32
12	10	-61	-63	-65	-68	-67	-25	-31	-32	-33,3	-28
12	20	-58	-57	-59	-56	-61	-28	-28	-32	-25	-31
12	30	-55	-56	-53	-57	-55	-29	-31	-22	-27	-30
Frequency		3 kHz					4.5 kHz				
V_F (m/min)	*h* (mm)	AP (dB)					AP (dB)				
8	10	-35	-39	-35	-33	-36	-41	-42	-40	-39	-42
8	20	-35	-39	-33	-30	-32	-31	-30	-32	-36	-31
8	30	-33	-37	-36	-31	-33	-30	-29	-30	-31	-31
12	10	-32	-40	-50	-52	-37	-31	-38	-32	-40	-40
12	20	-25	-28	-32	-31	-31	-32	-33	-29	-28	-27
12	30	-30	-29	-21	-30	-31	-29	-28	-29	-29	-30
Frequency		9 kHz					15 kHz				
V_F (m/min)	*h* (mm)	AP (dB)					AP (dB)				
8	10	-100	-100	-100	-96	-100	-110	-110	-110	-108	-107
8	20	-88	-84	-91	-86	-85	-100	-96	-103	-97	-95
8	30	-88	-90	-89	-90	-92	-99	-100	-100	-100	-103
12	10	-89	-96	-90	-100	-110	-101	-108	-103	-110	-115
12	20	-94	-92	-98	-90	-100	-110	-120	-121	-123	-116
12	30	-94	-91	-86	-85	-87	-108	-105	-99	-98	-100

According to the presented results in Table 7, it is possible that both the feed rate and tool override had a significant influence on the AP values at frequency areas ranging from 200 to 1.5 kHz, with confidence of 95%. The statistical analysis of the mean values of the areas observed, demonstrated an increase in AP as both the V_F and *h* increased.

Table 7. Univariate Significance Test for the *AP* (dB) with Respects to the V_F and *h* at a Frequency Range of 200 Hz to 1.5 kHz

	SS	Degrees of Freedom	MS	F	p
Intercept	114824.5	1	114824.5	15183.41	0.000000
V_F (m/min)	182.5	1	182.5	24.14	0.000052
h (mm)	510.3	2	255.2	33.74	0.000000
V_F **h*	27.9	2	14	1.85	0.179632
Error	181.5	24	7.6	-	-
* Significant results are highlighted in red					

Results for the significance of the influence of the cutting parameters on the values of the AP peak at 1.6 kHz are presented in Table 8. According to the results, a significant influence was only found for the V_F. The significance was determined with a probability of 95%.

Table 8. Univariate Significance Test for the *AP* (dB) with Respects to the V_F and *h* at a Frequency of 1.6 kHz

	SS	Degrees of Freedom	MS	F	p
Intercept	29846.30	1	29846.30	2806.312	0.000000
V_F (m/min)	222.77	1	222.77	20.946	0.000122
h (mm)	27.40	2	13.70	1.288	0.294120
V_F **h*	0.84	2	0.42	0.039	0.961454
Error	255.25	24	10.64	-	-
* Significant results are highlighted in red					

The AP values obtained from the spectral peak at 3 kHz for different cutting regimes indicated that *h* alone had a significant influence, and the combination of *h* and V_F also had a significant influence, with probability of 95%. However, V_F alone had no significant influence on the AP. This statement is confirmed with the results shown in Table 9.

Table 9. Univariate Significance Test for the *AP* (dB) with Respects to the V_F and *h* at a Frequency of 3 kHz

	SS	Degrees of Freedom	MS	F	p
Intercept	34408.53	1	34408.53	1710.449	0.000000
V_F (m/min)	10.80	1	10.80	0.537	0.470830
h (mm)	381.27	2	190.63	9.476	0.000926
V_F **h*	230.60	2	115.30	5.732	0.009230
Error	482.80	24	20.12	-	-
* Significant results are highlighted in red					

Table 10. Tukey HSD Test Results for the Mutual Effect of V_F and *h* on the AP at 3 kHz

	V_F (m/min)	*h* (mm)	{1} -35.60	{2} -33.80	{3} -34.00	{4} -42.20	{5} -29.40	{6} -28.20
1	8	10	-	0.987208	0.992528	0.222509	0.280631	0.133757
2	8	20	0.987208	-	1.000000	0.066083	0.636459	0.385154
3	8	30	0.992528	1.000000	-	0.076485	0.593098	0.348122
4	12	10	0.222509	0.066083	0.076485	-	0.001878	0.000745
5	12	20	0.280631	0.636459	0.593098	0.001878	-	0.998103
6	12	30	0.133757	0.385154	0.348122	0.000745	0.998103	-
* Significant results are highlighted in red								

The nature of the influence of *h* on the AP at 3 kHz indicated an increase in AP as the *h* increased. This increase in the AP values was higher when the *h* shifted from 10 mm to 20 mm than when it shifted from 20 mm to 30 mm. The mutual effect of different cutting regimes is illustrated by the results of the Tukey test (as presented in Table 10). It can be said the same effect noticed for the influence of *h* on the AP at a frequency of 3 kHz was also found in the combined effect of V_F and *h*.

The Tukey test verified the previously stated effects and also indicated a greater growth in the AP at 3 kHz when the V_F was 12 m/min, which also meant that there was a significant mutual effect only when the *h* values were 20 mm and 30 mm.

Another point of interest on the operating machine spectra was at 4.5 kHz. The results of the significance test presented in Table 11 demonstrated the significant influence of both cutting parameters, but not their mutual impact, on the recorded values of the AP.

Table 11. Univariate Significance Test for the AP (dB) with Respects to the V_F and *h* at a Frequency of 4.5 kHz

	SS	Degrees of Freedom	MS	F	p
Intercept	32670.00	1	32670.00	5714.869	0.000000
V_F (m/min)	53.33	1	53.33	9.329	0.005451
h (mm)	462.20	2	231.10	40.426	0.000000
V_F *h	15.27	2	7.63	1.335	0.281936
Error	137.20	24	5.72	-	-
* Significant results are highlighted in red					

The effect of the V_F on the AP at a 4.5 kHz peak suggested the AP increased as the V_F increased. The effect of the *h* on the AP at a 4.5 kHz peak indicated that an increase in the AP resulted from an increase in the *h*, in the same manner as the effects at a 3 kHz peak.

The significance test of the AP at a 9 kHz peak demonstrated similar behaviour to the 3 kHz peak, which showed the significant influence of the *h* alone and the mutual effect of both cutting factors (Table 12).

Table 12. Univariate Significance Test for the AP (dB) with Respects to the V_F and *h* at a Frequency of 9 kHz

	SS	Degrees of Freedom	MS	F	p
Intercept	257798.7	1	257798.7	13152.99	0.000000
V_F (m/min)	17.6	1	17.6	0.90	0.352327
h (mm)	450.2	2	225.1	11.48	0.000317
V_F *h	158.1	2	79.0	4.03	0.030919
Error	470.4	24	19.6	-	-
* Significant results are highlighted in red					

The effect of the *h* values essentially yielded the same pattern as previously shown, which greatly influenced the AP values, when increase from 10 mm to 20 mm and slowly increasing the AP when further increased. Following the previous statement about the combined influence of the cutting regimes on the AP peak at 9 kHz, with respects to the data shown in Table 13 and Fig. 7, it is possible to say that the effect of the V_F was stronger when it was equal to 8 m/min.

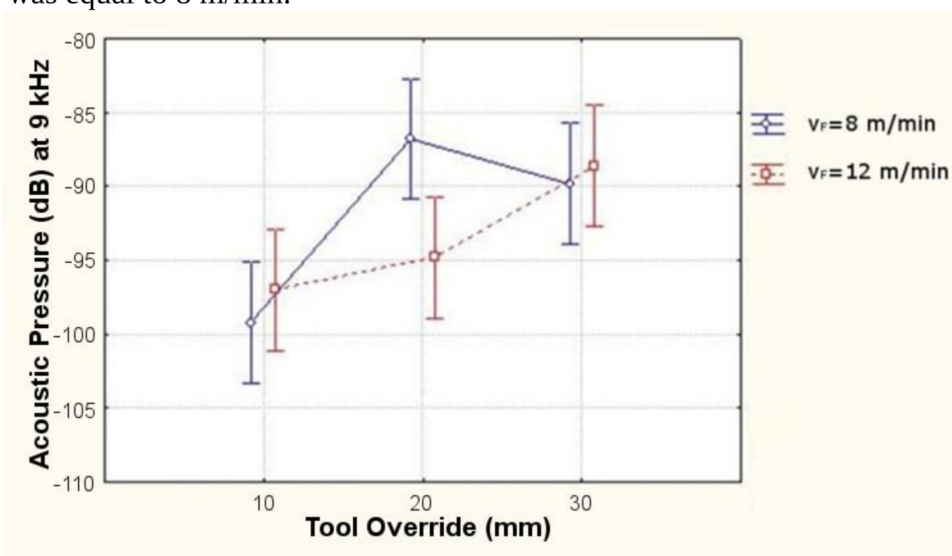

Fig. 7. Mutual impact of the feed rate and tool override on the *AP* at a frequency of 9 kHz

Table 13. Tukey HSD Test Results for the Mutual Effect of V_F and *h* on the AP at 9 kHz

	V_F (m/min)	*h* (mm)	{1} -99.20	{2} -86.80	{3} -89.80	{4} -97.00	{5} -94.80	{6} -88.60
1	8	10	-	0.002280	0.027958	0.967376	0.624006	0.010426
2	8	20	0.002280	-	0.887891	0.014557	0.081929	0.986440
3	8	30	0.027958	0.887891	-	0.143495	0.492929	0.997981
4	12	10	0.967376	0.014557	0.143495	-	0.967376	0.060915
5	12	20	0.624006	0.081929	0.492929	0.967376	-	0.268063
6	12	30	0.010426	0.986440	0.997981	0.060915	0.268063	-
* Significant results are highlighted in red								

According to the Tukey test (Table 13), the significant mutual effect of the cutting parameters was shown for altering values of *h* when the V_F equals 8 m/min, which agreed with previous statements.

The analysis of the AP at 15 kHz proved to be interesting, since a significant influence was recognized for the effects of the V_F, *h*, and mutual v_F*h on the AP value, with a probability of 95% (Table 14).

Table 14. Univariate Significance Test for the AP (dB) with Respects to the V_F and *h* at a Frequency of 15 kHz

	SS	Degrees of Freedom	MS	F	p
Intercept	336020.8	1	336020.8	22082.42	0.000000
v_F (m/min)	326.7	1	326.7	21.47	0.000105
h (mm)	322.1	2	161.0	10.58	0.000507
v_F *h	666.2	2	333.1	21.89	0.000004
Error	365.2	24	15.2	-	-
* Significant results are highlighted in red					

In the case of the V_F, it is interesting that the dependence of the AV was different from all other investigated peaks. As the V_F value increased, the value of the AV at a frequency of 15 kHz decreased. The separate effect of the *h* on the AP at a frequency of 15 kHz did not behave in the same manner as previous frequencies, slowly increasing the AP value from 10 to 20 mm and drastically increasing its value from 20 to 30 mm. The combined effect of the cutting regimes is shown in Fig. 8, which suggested that when the V_F was 8 m/min, the effect of the h yielded the higher AP values at 15 kHz, especially when the *h* was 20 mm and 30 mm.

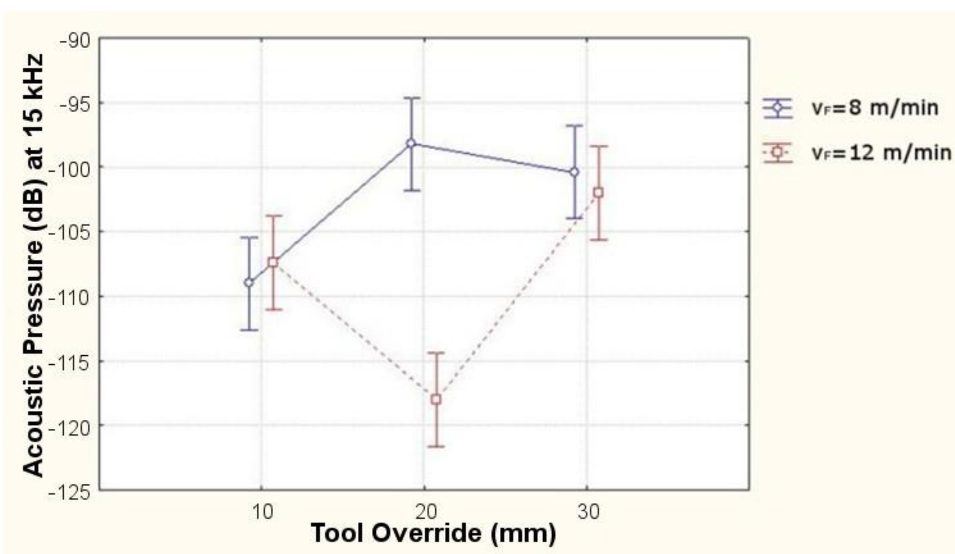

Fig. 8. Mutual impact of the feed rate and tool override on the *AP* at a frequency of 15 kHz

Table 15. Tukey HSD Test Results for the Mutual Effect of V_F and *h* on the AP at 15 kHz

	V_F (m/min)	*h* (mm)	{1} -109.0	{2} -98.20	{3} -100.4	{4} -107.4	{5} -118.0	{6} -102.0
1	8	10	-	0.002569	0.020897	0.985897	0.014385	0.085300
2	8	20	0.002569	-	0.944868	0.011915	0.000138	0.643098
3	8	30	0.020897	0.944868	-	0.085300	0.000139	0.985897
4	12	10	0.985897	0.011915	0.085300	-	0.003108	0.279241
5	12	20	0.014385	0.000138	0.000139	0.003108	-	0.000147
6	12	30	0.085300	0.643098	0.985897	0.279241	0.000147	-
* Significant results are highlighted in red								

According to the Tukey significance test of the mutual effects of the cutting regimes, when the V_F was 8 m/min, there was a significant influence on the AP at a 15 kHz peak, which agreed with previous statements. However, when the V_F was 12 m/min, the mutual effects were not significantly influential.

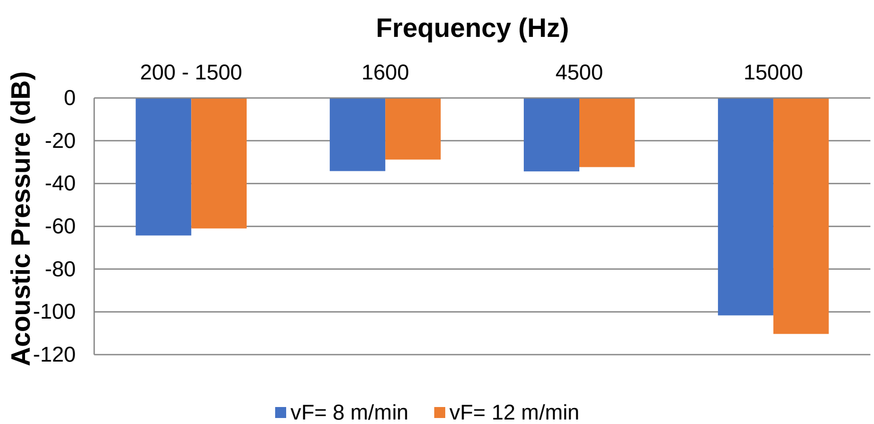

Fig. 9. The effect of the feed rate on the *AP* at observed frequency areas

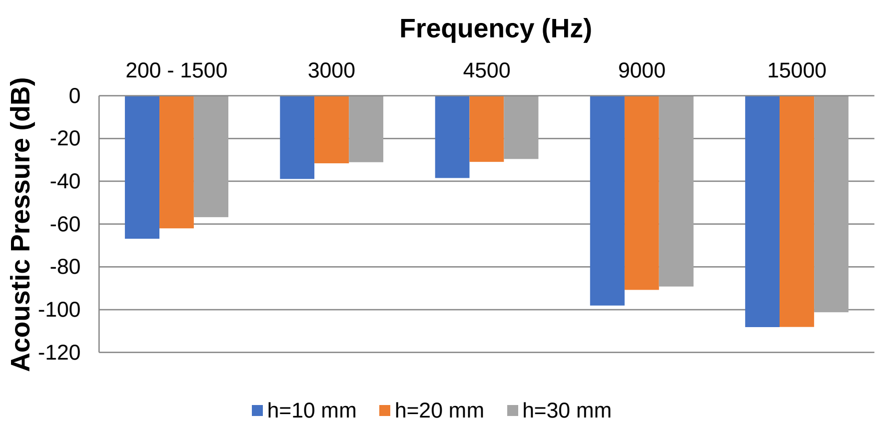

Fig. 10. The effect of the tool override on the *AP* at observed frequency areas

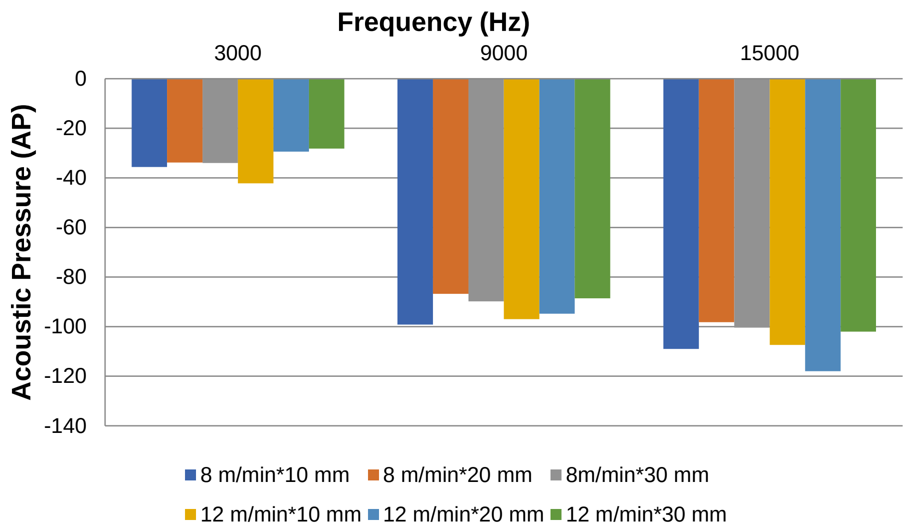

Fig. 11. The combined impact of the feed rate and tool override on the *AP* at observed frequency areas

The impact of the V_F alone was detected at a frequency peak of 1.6 kHz and incorporated with the *h* effect at frequencies of 200 to 1.5 kHz, 4.5 kHz, and 15 kHz. The mutual effect of both cutting parameters was found at 3 kHz, 9 kHz, and 15 kHz frequency peaks (as shown in Fig. 9 through Fig. 11).

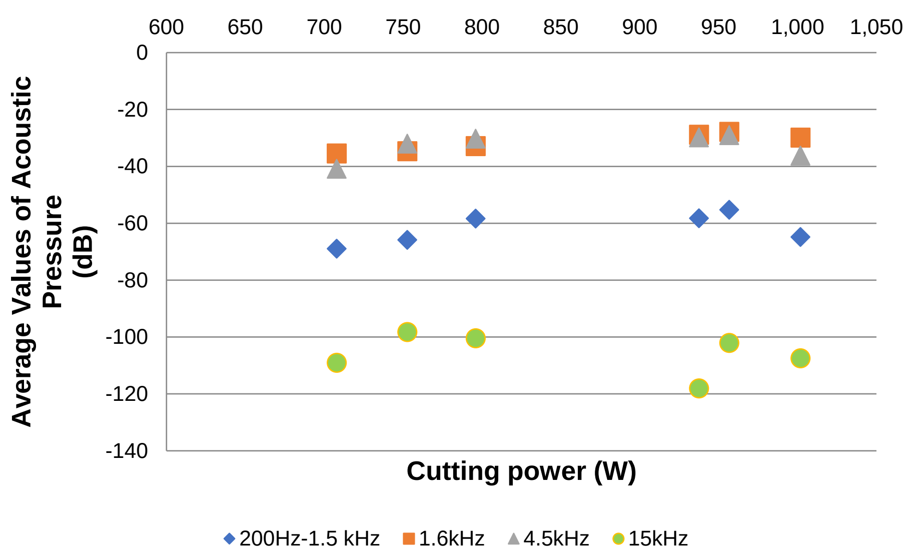

Fig. 12. The AP to the cutting power correlation for observed spectral areas

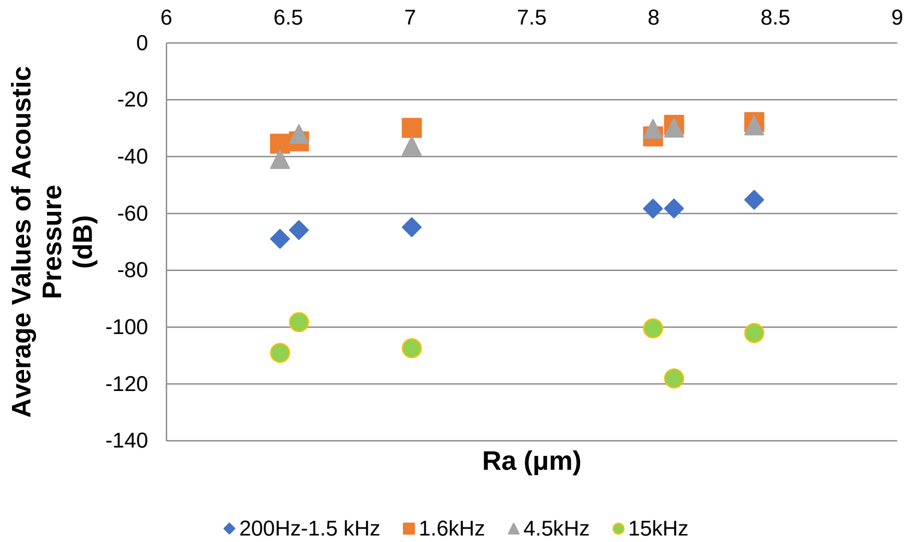

Fig. 13. The AP to the R_a correlation for observed spectral areas

According to the established significant relationships between the AP areas and the V_F and h and the impact of the cutting parameters on the P and R_a, it is possible to recognize a relationship between the AP areas and the P and R_a. Namely, by observing the behaviour of the AP was dependant on the cutting power and surface roughness, it was possible to determine four spectral areas of particular interest for cutting process monitoring. These areas were as follows: 200 to 1500 Hz, 1.6 kHz, 4.5 kHz, and 15 kHz. As shown in Fig. 12 and Fig. 13, it was found that in the case of spectral areas at 200 Hz to 1500 Hz, 1.6 kHz, and 4.5 kHz, the P and the R_a increased, as the recorded acoustic pressure increased. For spectral area 200 to 1500 Hz, a steady increase for both P and R_a was noted for elevated values of the AP, except for the P at the 1000 W point. The same behaviour of the P and the R_a can be observed for the AP peak at 1.6 kHz. For the 4.5 kHz frequency peaks almost the same performance occurred with the exception for 1000 W of the P and slightly slipping of the trend for R_a just above 6.5 µm. No clear correlation was observed for the AP peak at 15 kHz, since there was no obvious ascend or descend of the AP values with increased P and R_a values.

CONCLUSIONS

1. The power consumption analysis showed a strong relationship between the feed rate and the consumed power. In addition, a strong relationship between the power consumption and tool override was found, but only if the latter changed from 10 to 30 mm.
2. Surface roughness consideration indicated a significant influence of the feed rate on the increase in R_a, without the tool override impacting the surface quality.
3. The acoustic pressure spectra for an operating machine performed the same alterations for the chosen values of the cutting parameters. For the instances of the AP peaks at frequencies of 1.6 kHz, 4.5 kHz, and 9 kHz, as well as for the analyzed spectral area ranging from 200 Hz to 1.5 kHz, a strong influence of V_F was noticed. The latter, along

with the previous two statements, led to the conclusion that by recording the AP intensities at these frequencies, the cutting process can be monitored as a means to learn about experimental and production issues.

4. The effect of the *h* on the AP was noticed for all investigated spectral areas, except at the 1.6 kHz peak. However, the influence of the *h* alone on the *P* and R_a was not noticed. Considering the mutual influence of the *h* and V_F on the *P* in terms of acoustic emission, the machining system straining could be monitored for the *h* value increasing from 10 mm to 30 mm.
5. According to the effects of the cutting regime on the *P* and R_a, as well as on the AP throughout the spectra areas of interest: at frequencies of 200 to 1500 Hz, 1.6 kHz, 4.5 kHz, and 15 kHz. For the first three mentioned frequencies, there was an obvious relation between the increased AP and the cutting regime augmentation. However, it is not possible to make the same conclusion for the 15 kHz peak.
6. For a selected *h*, it is possible to track the changes in observed spectral areas in order to determine the machining system load, expressed as power consumption, for different wood materials in respect to altering the values of V_F.

ACKNOWLEDGMENTS

This research was realized as a part of the project “Agreement for Funding Scientific Research NIO in 2020” (Registration No. 451-02-68 / 2020/14/2000169) and financed by the Ministry of Education, Science, and Technological Development of the Republic of Serbia.

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Article submitted: June 3, 2021; Peer review completed: September 18, 2021; Revised version received and accepted: September 21, 2021; Published: October 25, 2021.
DOI: 10.15376/biores.16.4.8239-8257