COB-2023-0492
APPLICATION OF VIBRATION AND SOUND SIGNALS FOR EVALUATING MACHINING PARAMETERS RELATED TO THE MILLING PROCESS OF AISI D6 STEEL

Wallif Campos Alves de Souza
Emerson dos Reis
Instituto Federal de Educação, Ciência e Tecnologia de São Paulo (IFSP), Câmpus São João da Boa Vista.
wallif.a@aluno.ifsp.edu.br.
emersonr@ifsp.edu.br.

Roberto Giani Pattaro Junior
Serviço Nacional de Aprendizagem Industrial (SENAI), Escola e Faculdade de Tecnologia "Roberto Mange".
roberto.gjunior@sp.senai.br

Abstract. *Mechanical vibration signals are produced naturally in machining processes. They can be acquired and processed in order to obtain indicators of quality, efficiency or even failure in these processes. In short, such indicators allow to determine the most suitable configurations and machining parameters, avoiding damage, premature wear of the cutting tool or inadequate surface finish of the part. In this work, a single-axis accelerometer and a low-cost omnidirectional microphone were used to acquire mechanical vibration and sound intensity signals from the milling process of AISI D6 steel. Tests performed regarding three cut parameters, which were varied with values were above and below those recommended by the manufacturers, which were assumed as a reference. They were the cutting depth, the rotation of the spindle and the work penetration. Thus, the objective was to determine the effects of these parameters on the intensity of vibration and sound, and consequently, on the surface finish of milling, in which the average roughness of the surface was measured in each experiment. The acquired signals were analyzed in the time and frequency domains based on statistical parameters and by the fast Fourier transform (FFT). The results indicate that work penetration is the parameter that has the greatest impact on the analyzed machining process. When set to 90%, the amplitude of acceleration signals increases approximately 36%. On the other hand, work penetration at 30% caused these signals to increase by about 10%. The microphone used to acquire the sound signals proved to be ineffective due to the action of the automatic gain control, which distorts the amplitude of the captured signal components. On the average measured values of machined surface roughness, the quality on this point of view was almost the same. This indicates that none of the three machining parameters had important impact on the machined surface rough, which was above 1 µm.*

Keywords: *signals, vibrations, sound, milling.*

1. INTRODUCTION

Milling is one of the most used machining techniques. In general, milling involves performing simple face and contour operations, but it can also include more complex machining forms such as grooves, slots, helices, etc. All these operations can be carried out using a milling cutter, which can have different shapes and sizes depending on the type of machining and desired result (Stemmer, 1995). The advantage of milling lies in the variety of shapes and surfaces that can be produced, the quality of the machined surface finish, the large amount of chip removal per unit time, and the diversity of materials that can be processed (Machado et al., 2015). In milling processes, various phenomena occur, including noise, forces, mechanical vibration, and temperature rise, the intensity of which depends on the so-called cutting parameters: cutting speed (v_c), feed rate (v_f), axial depth of cut (a_p), radial depth of cut (a_e), and type and quality of the cutting tool (Bašovská and Peterka, 2014).

During milling, a certain amount of mechanical energy is dissipated through plastic deformation and friction between the tool and the workpiece, and a fraction of it is directly transferred to the system elements, thus generating mechanical vibrations (Stephenson and Agapiou, 1997). Therefore, material machining is inevitably accompanied by mechanical vibrations. These vibrations are related to the relative movements between the tool and the workpiece, which can cause premature wear or breakage of the equipment, tool breakage, and excessively high noise levels. Such occurrences can lead to deterioration in surface finish quality, negative impact on cutting force, and other factors that reduce productivity and increase costs (Choudhury et al., 1997).

Among the various types of vibrations present in milling processes, regenerative or self-excited vibrations stand out. These vibrations are not caused by external forces but by forces generated by the cutting process itself. They result from a self-excitation mechanism in the generation of chip thickness during the machining operations. A wavy surface resulting from the passage of an edge is removed by the subsequent one, which also leaves a wavy surface due to structural vibrations. Depending on the phase difference between two successive waves, vibrations can be attenuated or amplified. In the worst cases, the maximum chip thickness can grow exponentially, oscillating at a frequency close to the dominant structural mode of the system, thus causing instability in the milling process (Atabey et al., 2003). Regenerative vibrations can occur in various metal removal processes and have various negative impacts, such as low surface quality, unacceptable dimensional variation, excessive noise, disproportionate and accelerated tool wear, damage to the machine tool, reduced material removal rate, increased production time costs, etc. (Quintana and Ciurana, 2011).

The maximum tolerable level of vibrations, that is, the maximum amplitude of vibrations in a machining process, depends on its application. In roughing operations, where a significant amount of material is removed from the workpiece, the acceptable level of vibrations is primarily determined by their effect on tool life. In finishing operations, surface quality and dimensional precision are the parameters that determine the maximum level of vibrations (Bašovská and Peterka, 2014). The depth of cut has a direct influence on the occurrence of vibrations in the machining process, making it one of the most significant cutting parameters and decisive in the planning of a machining process. For small depths of cut, the cut is stable, i.e., free from vibrations. For higher depths, vibrations can directly lead to the breakage of the cutting tool. The depth of cut varies according to the characteristics of the machined material (Atabey et al., 2003).

In this context, the notion of stability is not employed in the sense of control techniques, but from a technological perspective, prioritizing the outcome of the work and vibration levels considering the acceptable quality of the piece. A stable process can be identified by the characteristics of the workpiece surface, which can be evaluated by the average surface roughness level measured with the aid of a profilometer. A stable process also exhibits a reduced rate of tool wear. An unstable process is associated with a deteriorated surface finish, which, in some cases, is visible even to the naked eye, as irregular milling leaves patterns and surface discrepancies easily visible to a trained professional. Another negative factor of irregular machining is pronounced tool wear. Another important factor to consider in machining processes is the material being machined. Each material has its own physical characteristics, such as hardness and wear resistance. For example, steels are more resistant to machining than aluminum, which directly influences the selection of controllable machining factors.

Therefore, considering the proven relationship between machining parameters, vibration, stability, and, consequently, the sound generated during the machining process, it becomes feasible to develop a real-time monitoring technique for milling processes and improve safety by means of analyzing which machining parameters have the best and worst impact on specific machining processes. According to Pattaro (2019), every workpiece, when milled, presents a direct indication of the quality and regularity of the milling process on its surface. This indication is called roughness and is expressed and measured in micrometers (µm). Surface roughness is composed of fine irregularities or micro-geometric errors resulting from the inherent action of the cutting process, such as feed marks, false cutting edges, tool wear etc. Roughness can be influenced by various factors, with vibration being the main and most aggravating factor present in the machining process.

The main parameters for measuring the surface roughness of a workpiece are the average roughness (R_a), which is the arithmetic mean of the absolute values of the ordinate deviations of the roughness profile from the mean line within the measurement length. The maximum roughness (R_{max}) represents the highest value among the partial roughness values observed within the measurement length. The arithmetic mean roughness (R_z) is the arithmetic mean of the five partial roughness values. A partial roughness refers to the sum of the absolute values of the ordinate deviations within the sampling length, known as the cut-off (Pattaro, 2019). Typical average roughness values for each machining process can be observed in Table 1.

Table 1. Valores típicos de rugosidade média (Ra) de acordo com o processo de fabricação.

Process	**Ra (µm)**
Planing, Profiling	1 - 25
Milling	1 - 6
Finishing, Extrusion	1 - 3
Turning, Drilling	0.4 - 6
Grinding	0.1 - 2
Honing	0.1 - 1
Polishing	0.1 – 0.4
Buffing	0.05 – 0.04

This study presents an analysis of the signals of sound and mechanical vibrations captured during the milling process of AISI D6 steel, with the aim of associating them with the impacts caused by variations in each machining parameter and their influence on the average surface roughness of the milled workpiece.

2. MATERIALS AND METHODS

2.1 Experimental Bench and Components

The specimen used in this study consists of a prismatic geometry made of D6 tool steel, with dimensions of 40 mm x 40 mm x 120 mm, and its properties and characteristics are listed in Table 2.

Table 2. Information and characteristics of AISI D6 tool steel

Chemical composition and characteristic AISI D6 steel						
Product designation	Type	C	Cr	V	W	Rockwell (HRC)
VS7	AISI D6	2.10%	11.50%	0.15%	0.70%	56 - 62

For the milling operation, a straight-end mill from Lamina Technologies with a diameter of 20 mm and a rake angle of 90° was selected. This mill can accommodate two cutting inserts. The cutting inserts used are made of carbide, with an APKT geometry, from the same brand, and have a corner radius of 0.4 mm. The surface roughness of the test specimens was measured in each experiment using a digital profilometer from MAHR, model M300C. This equipment has a profile resolution of 8 nm and utilizes the contact probing method as the measurement principle.

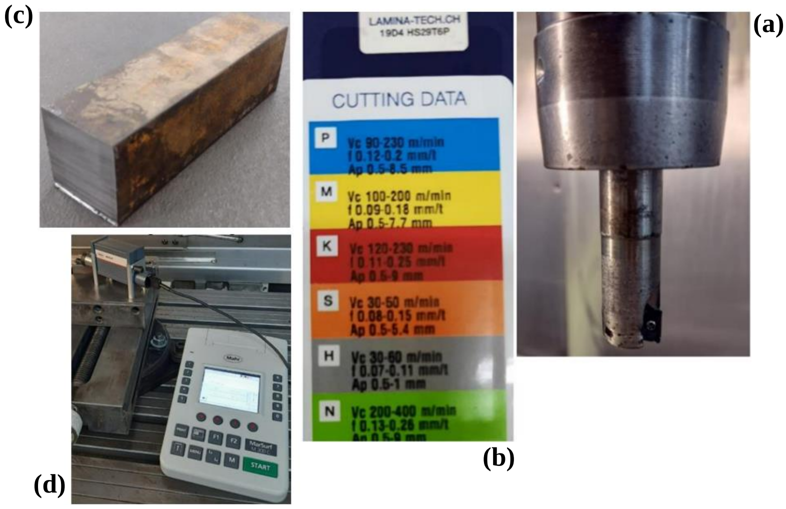

Figure 1. (a) Milling cutter, (b) cutting inserts, (c) D6 tool steel test specimen and (d) MAHR digital roughness meter.

Specific equipment was used for signal acquisition in this study. It included a single-axis accelerometer from SKF (model CMSS2200) with a sensitivity of 100 mV/g and a frequency range of 0.5 to 10 kHz. Sound signals during milling were captured using the MAX9814 sensor from Analog Devices, which featured automatic gain control (AGC) and covered a frequency range of 20 Hz to 20 kHz. The signal acquisition was performed using the NI USB-6212 data acquisition system from National Instruments, which provided analog and digital inputs, digital outputs, and integrated amplification.

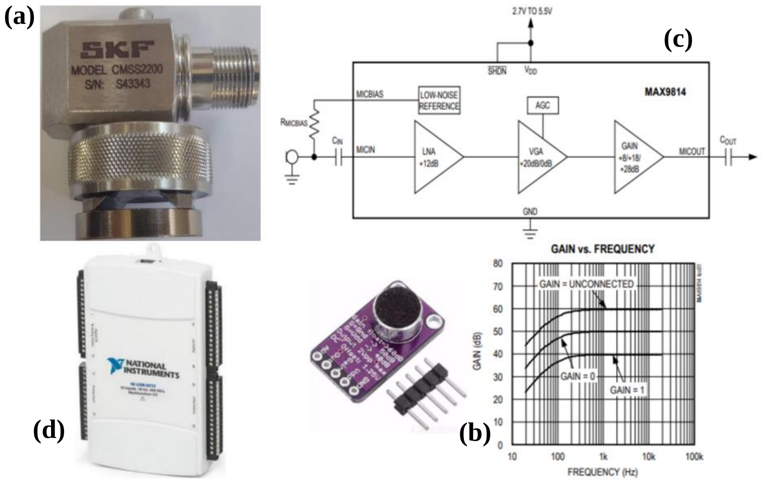

Figure 2. (a) Accelerometer, (b) sensor MAX9814, (c) Simplified Block Diagram and (d) DAQ NI USB-6212.

A MIKRON VCP 600 CNC machining center with a power range of 12 to 16 kW and a spindle rotation speed of 100 to 20,000 rpm was used. This equipment is available at the SENAI School and Technology College "Roberto Mange" in Campinas. Figure 1 represents a schematic drawing of the test setup and its main components, including the CNC spindle (also known as the spindle axis), the workpiece (AISI D6 tool steel) fixed to the CNC feed table using a hydraulic vise, the sensor and accelerometers to be used, and the cutting tool, a mill with two inserts. The X-axis represents the tool's movement towards the workpiece. It is important to note that, in a typical milling process, the tool remains stationary, and it is the feed table with the workpiece fixed on its surface that moves. The Y-axis represents the frontal control of the machining. In a milling process, for each rotation of the mill on the workpiece, there is an initial impact of the insert's (cutting tooth of the mill) surface on the side surface of the workpiece. This results in a varying force that creates vibration in the tool-workpiece system in the Y-axis direction, caused by the insert entering and immediately removing material directly from the workpiece. The same varying force occurs when the insert loses contact with the workpiece, but this vibration caused by the insert's exit will not be directly in the Y-axis direction. The vibrations caused by these phenomena have a significant impact on the entire milling process. However, in the Y-axis direction, which is the direction of insert entry, the generated impact is higher and more significant. Therefore, the accelerometer's axis was adjusted in this direction to directly capture these vibrations.

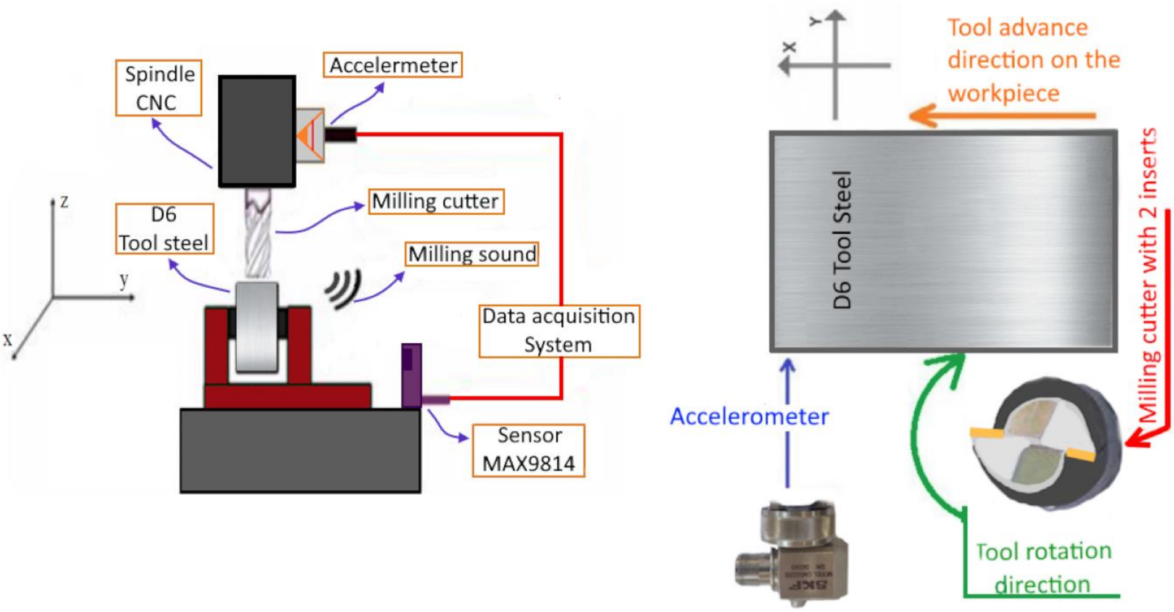

Figure 3. Experimental bench, main components and Accelerometer axis adjustment for capturing signals.

2.2 Methodology and Procedures

The signals obtained from the vibration and sound sensors were acquired in Single-ended channel mode, the only configuration available in the data acquisition system used. The signals were acquired and processed using scripts developed in MATLAB R2014b software. It is important to note that both the acceleration and sound signals were acquired in volts. However, while the conversion to acceleration is done using 1 g = 0.1 V, there is no information provided by the manufacturer regarding the relationship between the electrical voltage and the sound intensity at the microphone. Consequently, the signals from the microphone will be analyzed in volts (V).

Firstly, it was necessary to define the cutting parameters for the tests. Tabulated information for machining processes using carbide tooling for roughing operations on D6 tool steel was utilized. The values were calculated following the standard equations for cutting speed, table feed, and feed per tooth, to calculate the *rpm*. With a recommended cutting speed (v_c) of 100 m/min provided by the manufacturer and a milling cutter diameter of 20 mm, the calculated RPM was 1,591. For the table feed, a value of 382 mm/min was calculated based on the insert manufacturer's recommendations.

Furthermore, in milling, the geometric position of the tool relative to the workpiece is also an important cutting parameter, commonly known as the axial depth of cut (a_e). It represents the percentage of the milling cutter's diameter that has constant contact with the workpiece during milling. The larger the contact arc, the higher the temperature generated during the machining process. In milling processes, an ae value greater than 50% is recommended for good machining stability. For the tests, Experiment I was defined as the regular experiment according to the manufacturer's recommendations and the calculated values. The remaining experiments had values for feed, depth, or axial depth of cut that were lower or higher than the recommended values. This resulted in various combinations of "irregular" cutting parameters, which were tested in Experiments II to VII.

Table 3. Experimentos e condições de fresamento.

Experiment	Milling parameters		
	1	2	3
	n (*rpm*)	a_e (%)	a_p (mm)
I	1591	60	2
II	1591	60	1
III	1591	60	3
IV	1591	30	2
V	1591	90	2
VI	1291	60	2
VII	1891	60	2

To isolate the vibration signals for analysis, a "void" experiment, called Experiment 0 (zero), was conducted to capture the machine vibrations that are not part of the actual machining process. For this purpose, the CNC was configured with the same parameters as Experiment I, but without the workpiece in contact with the tool. This allowed for the analysis of the natural vibration of the system itself. After each experiment listed in Table 3, a digital profilometer will be used to measure the average surface roughness of each machined workpiece.

Considering the analysis by Olejárová et al. (2017), one of the frequencies of the system corresponds to the rotation speed of the machine spindle during the test conditions, which was 1591 *rpm* (rotations per minute) or 26.5 *rps* (rotations per second). Therefore, considering that the tool has 2 cutting inserts, the main frequency due to the acting forces during the process was calculated as follows:

$$ft = \frac{n\,NT}{60\ (s)} = \frac{1591\ (rpm)\ 2\ (1)}{60\ (s)} \cong 53\ Hz \tag{1}$$

where *ft* is the cutting frequency of the milling cutter, *n* is the spindle rotation speed, and *NT* is the number of inserts present in the milling cutter.

Considering the results of Olejárová et al. (2017), it is considered that the spectrum of acceleration signals in a milling process extends up to approximately 5.5 kHz. Assuming a linear time-invariant system (LTI), a minimum sampling frequency of 11,001 samples per second is required. However, considering that the tool rotation speed used by the author was 280 *rpm*, which is about 6 times lower than the speed used in this study, a sampling rate of 50,000 samples per second was adopted. This ensures a limit of approximately 25 kHz for the analyses, acquired over a 5-second interval. In other words, there were 250,000 samples from both sensors, allowing for a spectrum resolution of 0.0002 Hz (50/250,000). These samples were acquired simultaneously in each of the 7 experiments indicated in Table 3.

3 Results and Discussion

The MATLAB R2014b software was used for both signal acquisition and processing in the experiments from Table 3. The analyses were performed in both the time domain and the frequency domain, assuming a linear time-invariant system (LTI). Figures 4 and 5 show the amplitude versus time graphs containing samples of 0.5 seconds out of a total of 5 seconds for the accelerometer and microphone signals, from Experiment 0 to Experiment VII.

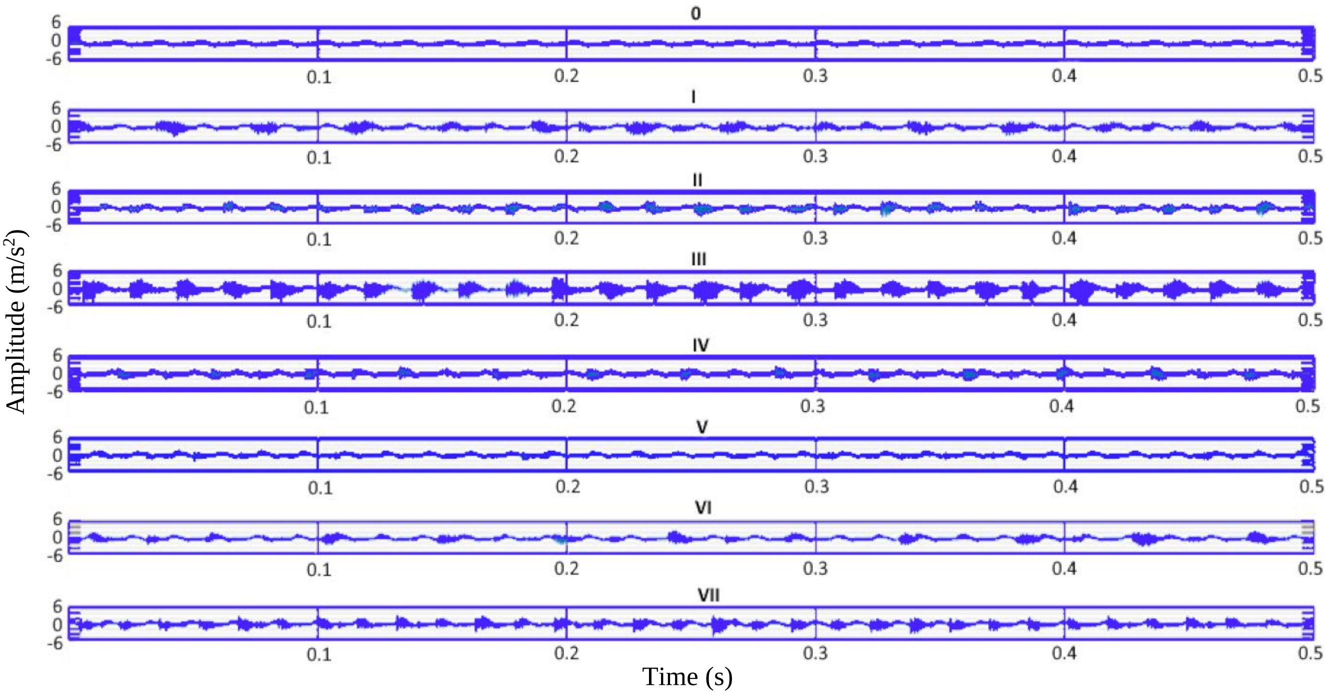

Figure 4. Signals samples of 0.5 s for experiments from 0 (at top) to VII (at bottom).

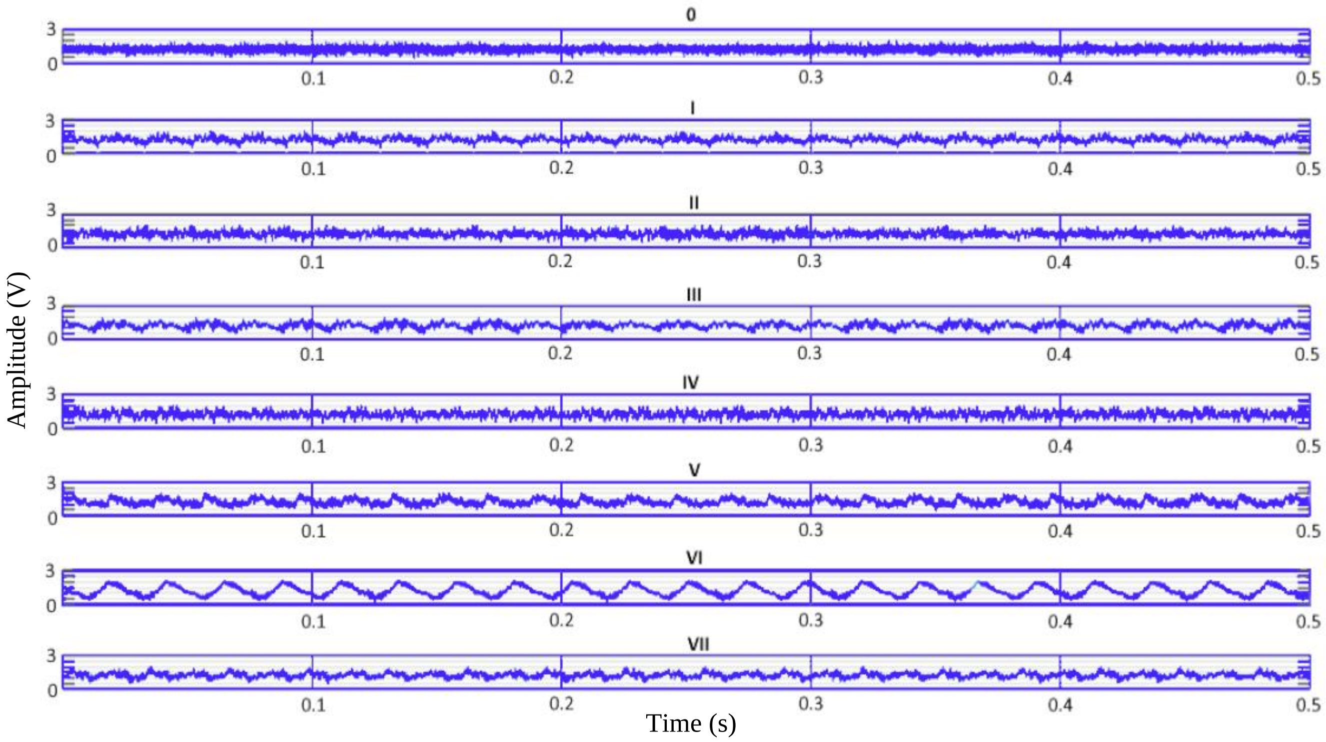

Figure 5. Signals samples of 0.5 s for experiments from 0 (at top) to VII (at bottom.

In a general overview, it can be observed that the amplitude of all acceleration signals is within the range of -6 m/s2 to 6 m/s2. It is noticeable that the amplitudes in the signals corresponding to Experiments 0 and V are lower than the others. In Experiment 0, this is due to the lack of cutting effort from the tool on the workpiece, as this signal results solely from the system-machine-tool components. In Experiment V, however, the lower intensity of the signal is due to a penetration of 90%. Additionally, it can be noted that the amplitude range in Experiment III is the largest of all, which is attributed to an increase in the depth of cut by 1 mm, resulting in a greater penetration of the tool inserts into the workpiece during cutting. In Figure 6, it can be observed that Experiment 0 had the highest noise level, while Experiment VI had the lowest. In this case, the presented signals are not a direct representation of the sound present in the milling process, but rather a characteristic of the MAX9814 microphone itself, which has Automatic Gain Control (AGC) that maximizes the output when there is no intense nearby sound source. As a result, the microphone captures environmental noise with maximum gain, leading to a noisy signal, as seen in Experiment 0A characteristic observed in the signals presented in Figures 4 and 5 is a certain periodicity, mostly formed by repeated signals of the same frequency and amplitude, reinforcing the assumed hypothesis of a linear and time-invariant system under the adopted test conditions.

During the signal analysis in the time domain, several statistical parameters were calculated: standard deviation, range, and kurtosis of each experiment's curve. Table 4 presents the values of all signals obtained from both the accelerometer and the microphone. By analyzing the results in this table and the graphs in Figures 4 and 5, several aspects can be inferred. Firstly, concerning the acceleration signals, the experiments marked in green generated lower accelerations and, consequently, lower mechanical vibrations, while those marked in red produced more intense mechanical vibrations. These aspects are related to the occurrence of a more stable or unstable milling process, as mechanical vibrations hinder machining. According to Polli (2005), stable processes are characterized by an acceptable average surface roughness and attenuated tool wear, while unstable processes are associated with rough surface finishes. The intensity of vibrations present in a machining process directly influences the stability of a system. Table 1 provides the acceptable average roughness values for considered stable machining processes.

Table 4. Parameters calculated in the time domain of each signal from experiment 0 to VII.

Indexes	**Acceleration (m/s^2)**	**Sound Int. (V)**	**Acceleration (m/s^2)**	**Sound Int. (V)**
	Experiment 0		**Experiment IV**	
Maximum	1.310	2.131	3.240	2.080
Minimum	-1.180	0.300	-4.751	0.421
Range	2.489	1.832	7.990	1.659
Average	-0.078	1.233	-0.164	1.233
Standard deviation	0.422	0.212	0.577	0.249
Kurtosis	2.308	3.038	4.437	2.846
	Experiment I		**Experiment V**	
Maximum	2.954	2.044	1.826	2.080
Minimum	-3.948	0.394	-2.561	0.397
Range	6.902	1.649	4.386	1.683
Average	-0.237	1.233	-0.123	1.233
Standard deviation	0.681	0.238	0.504	0.276
Kurtosis	4,056	3.184	2.782	2.426
	Experiment II		**Experiment VI**	
Maximum	3.095	2.065	3.536	2.178
Minimum	-3.606	0.403	-4.622	0.224
Range	6.701	1.662	8.158	1.955
Average	-0.233	1.233	-0.301	1.232
Standard deviation	0.546	0.249	0.787	0.443
Kurtosis	5.605	2.803	4.442	1.818
	Experiment III		**Experiment VII**	
Maximum	3.966	2.050	3.266	2.068
Minimum	-6.707	0.407	4.751	0.395
Range	10.674	1.643	8.017	1.673
Average	-0.585	1.233	-0.211	1.233
Standard deviation	1.139	0.261	0.636	0.246
Kurtosis	4.201	2.828	4.128	2.892

The analysis of Table 4 reveals important findings. Experiment V, with a 90% working penetration (a_e), demonstrates the lowest acceleration range, indicating a stable milling process (highlighted in green). In contrast, Experiment III, with a depth of cut (a_p) of 3 mm, exhibits the highest amplitude range and peak values among all experiments, indicating significant vibrations (highlighted in red). It can be concluded that a smaller depth of cut and a larger ae result in lower acceleration and improved stability in milling D6 tool steel. The influence of automatic gain control (AGC) on the sound intensity signals is evident, as indicated by nearly identical average values (highlighted in yellow) and peak values exceeding the sensor's limit of 2 V. The amplitude spectra of the acceleration and sound signals are depicted in Figures 6 and 7, respectively, with frequency on the X-axis and amplitude on the Y-axis.

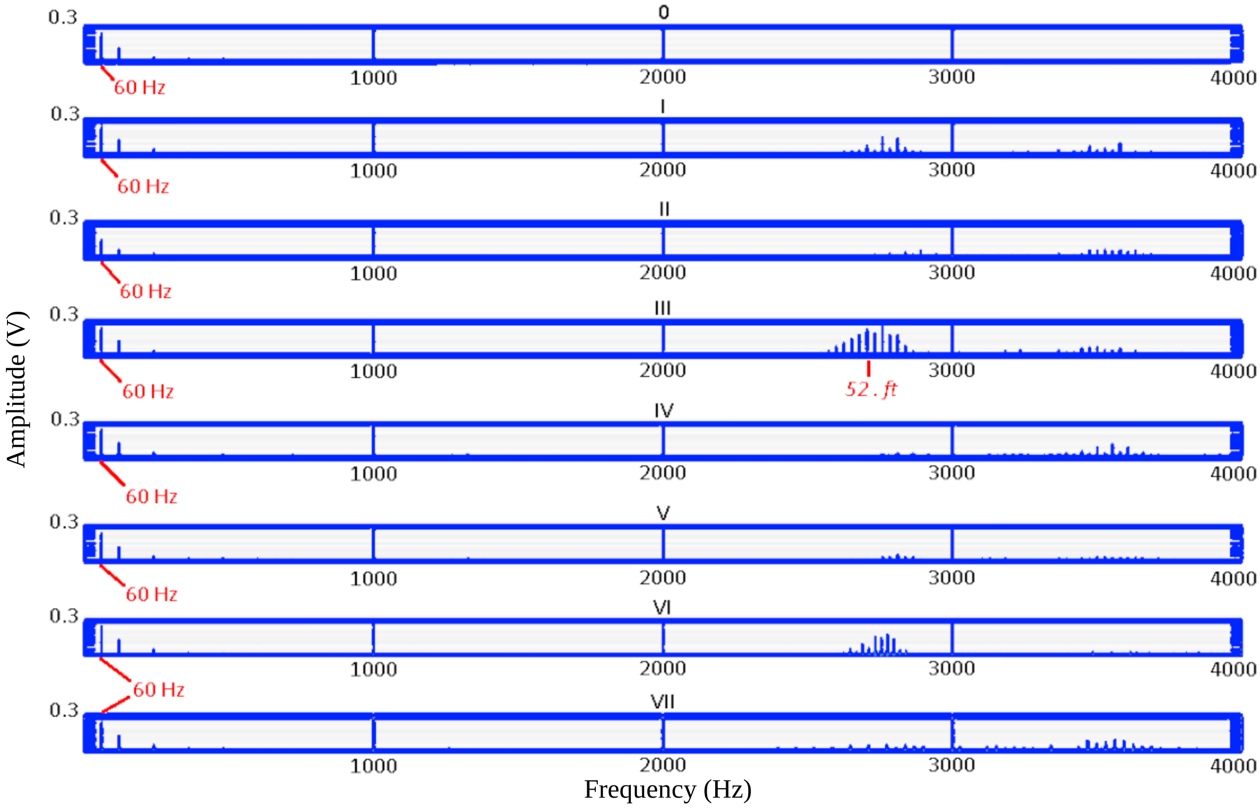

Figure 6. Amplitude spectrum of acceleration signals from 0 to 4 kHz.

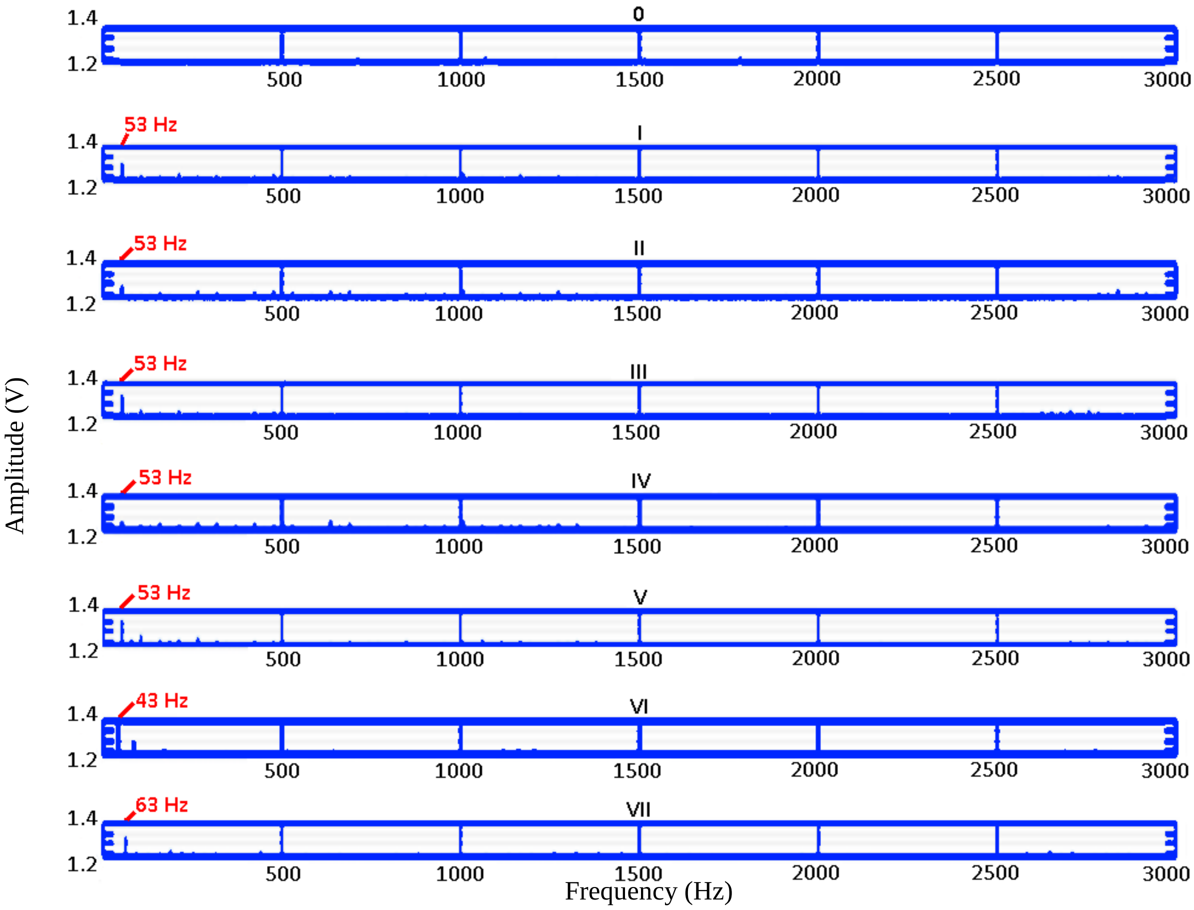

Figure 7. Amplitude spectrum of intensity signals from 0 to 4 kHz.

Vibrations occur when there is a variation in the forces present in the milling process. In the experiments, forces occurring in the y-axis direction were captured when the tool inserts enter the workpiece, removing material, and when the insert exits the workpiece, relieving cutting pressure. However, in this case, vibrations are not specifically in the y-axis direction. Considering these factors, it was expected to capture an acceleration only a few times higher than ft (cutting frequency). However, it is observed that this type of frequency, or the working frequency of the milling cutter (ft), was not present in any of the experiments, with the predominant acceleration frequencies being higher than 2 kHz. This is due to self-excited vibrations caused in the milling process, specifically regenerative vibrations. According to Maia (2009), this phenomenon occurs when a wavy surface encountered immediately after the tool insert pass is removed during the subsequent pass, causing detrimental variation in cutting force. Many of the vibrations that occur in machining operations are regenerative vibrations, and this phenomenon can be evidenced by the wavy appearance on the machined surface. This wavy aspect is observed on the machined surface of the AISI D6 tool steel workpiece, as shown in Figure 9.

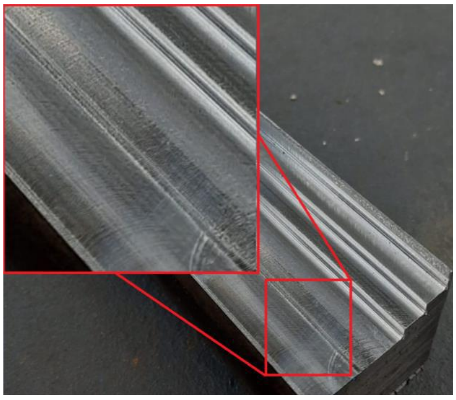

Figure 8. Surface of the machined test specimen.

Table 5. Roughness measured on the machined surface in each experiment.

Average roughness of milled surfaces (µm)	
Experiment I	0.631
Experiment II	0.557
Experiment III	0.602
Experiment IV	0.691
Experiment V	0.516
Experiment VI	0.644
Experiment VII	0.654

After each experiment, the average surface roughness of the milled surface was measured using a digital roughness meter. Table 5 presents the values of the average surface roughness after each experiment. Despite the presence of a wavy pattern caused by the milling cutter teeth in material removal on the milled surface in all experiments, the measured average surface roughness remained below 1 µm, indicating stable milling processes. This is compared to the standard average for a milling process, as shown in Table 1.

4 Conclusions and Remarks

Based on the conducted tests, it is evident that the machining parameter that had the most impact on the vibration amplitude in the milling process of D6 steel is a_e. There was a 36.54% attenuation of the acceleration in the machining process when comparing Experiment I to Experiment V. This indicates that machining parameters calculated using formulas and manufacturer recommendations should also consider the working penetration, as increasing the value of a_e to 90% resulted in vibration attenuation during milling.

Using the MAX9814 sound sensor, it was possible to clearly observe the working frequency of the milling cutter, *ft*, and its change in Experiments VI and VII due to alterations in the *rpm* value. However, it was noted that the sensor was not the best choice when comparing signal amplitudes across all experiments due to the presence of AGC, low sensitivity to higher-frequency noise, and other characteristics of the device itself.

Analyzing the measured roughness in each experiment, it can be concluded that, from the perspective of machined surface quality, considering average roughness as the primary quality and stability parameter in the milling process, all experiments exhibited stability. This indicates that the parameters were not significantly altered to produce a rough machined surface above 1 µm. Therefore, the study achieved its objective, indicating that each machining parameter, when altered, has a direct and proportional effect on the vibrations present in a milling process. However, within the scope of changes adopted in the tests, there was no visible impact on the average surface roughness of D6 tool steel.

5 REFERENCES

Atabey, F., Lazoglu, I., Altintas, Y. 2003. Mechanics of boring processes - Part I. *International Journal of Machine Tools and Manufacture*, 43(5), 463–476. https://doi.org/10.1016/S0890-6955(02)00276-6. Acessed 22 april 2023.

Bašovská, K., Peterka, J. 2014. Influence of tool balancing in high speed machining. ACTA Universitatis Cibiniensis, 65(1), 7–12. Technical Series, vol.65, no.1, pp.7-12

Choudhury, S. K., Goudimenko, N. N., Kudinov, V. 1997. A. *On-line control of machine tool vibration in turning. International Journal of Machine Tools and Manufacture*, New York, v. 37, n. 6, p. 801-811. http://dx.doi.org/10.1016/s0890-6955(96)00031-4. Acessed 22 apr. 2023.

Maia, L. H. A. *Influence of ABNT 4140 low alloy steel milling cutting conditions on vibrational and acoustic emission signals* Master's thesis, Graduate Program in Mechanical Engineering, Pontifical Catholic University of Minas Gerais, Belo Horizonte, Brasil.

Machado, Á. R., Coelho, R. T., Abrão, A. M., Silva, M. B. 2015. *Material Machining Theory*. (in Portuguese) Editora Blucher.

Olejárová, Š., Dobránsky, J., Svetlík, J., & Pituk, M. (2017). *Measurements and evaluation of measurements of vibrations in steel milling process*. Measurement, 106, 18–25. https://doi.org/10.1016/j.measurement.2017.04.023

Pattaro, R. G. J. 2019. *Study of energy consumption during machining a mold cavity with different strategies*. Master's thesis, Graduate Program in Mechanical Engineering, State University of Campinas, Campinas, Brasil. http://repositorio.unicamp.br/Acervo/Detalhe/1129072. Acessed 22 april 2023.

Polli, M. 2005. *Analysis of the dynamic stability of the milling process at high cutting speeds*. Ph.D. thesis, Graduate Program in Mechanical Engineering, Federal University of Santa Catarina, Florianópolis, Brasil.

Quintana, G., Ciurana, J. 2011. Chatter in machining processes: A review. *International Journal of Machine Tools and Manufacture*, 51(5), 363–376. https://doi.org/10.1016/j.ijmachtools.2011.01.001

Stemmer, C. E. *Cutting tools II*. 2 ed., Florianópolis, Federal University of São Carlos, Brasil, p. 141-216, 1995.

Stephenson, D. A., Agapiou, J. S. (2018). *Metal cutting theory and practice (3rd ed)*. CRC Press. v. 49.

6 RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.