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DEVELOPMENT OF VISCOELASTIC DYNAMIC NEUTRALIZER (VDN) TO MINIMIZE THE AMPLIFICATION OF REGENERATIVE VIBRATIONS IN SIMULTANEOUS TURNING

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Abstract: Regenerative vibrations have been a chronic problem studied due to the complexity of the factors that arise during machining. When it comes specifically to simultaneous external turning, there are few studies that address the incidence of regenerative vibrations in machines with this constructive characteristic. Machines with greater material removal capacity have been increasingly present in the metallurgical industries. Decreased productivity, reduced tool life and surface quality problems are common challenges in this type of machine in the dynamic instability stage, due to the low dynamic stiffness in situations such as machining long shafts. One of the objectives of this work is to understand the main factors associated with the dynamics of the simultaneous external turning process. This work aims to achieve two primary objectives: firstly, to comprehensively understand the principal factors linked to the dynamics of the simultaneous external turning process, and secondly, to diffuse neutralizers in industrial applications with high material removal rates. For this, the influence of the machine-support-tool set with the cutting parameters was analyzed in view of the dynamic stability of the process. The natural frequency of the tool and support was determined considering the inserts and supports of both turrets through impact tests with simultaneous measurement of the vibratory response. Subsequently, the turning of an electric motor shaft was carried out with the addition of passive damping through a dynamic neutralizer previously made to minimize the amplification of regenerative vibrations in the upper tower that was presenting dynamic instability. Subsequently, the turning of an electric motor shaft was carried out with the addition of passive damping through a dynamic neutralizer made of Dyal 601 and a rectangular key constructed to effectively operate at the natural frequency of 2080 Hz and 10 g 0-peak of the upper turret tool holder. The evaluation of the process stability was carried out by monitoring the vibration acceleration signals. As a result, it was possible to obtain a better understanding of the behavior of regenerative vibrations in simultaneous external turning, as well as verify the effectiveness of the neutralizer for minimizing the amplification of vibrations in machines with this dynamic characteristic through the use of viscoelastic dynamic neutralizer.

***Keywords**: Simultaneous turning, Viscoelastic Dynamic Neutralizer, Chatter.*

1. INTRODUCTION

Simultaneous turning, which involves the use of multiple tools, has gained increasing importance in the manufacturing industry due to its ability to produce components with a high material removal rate. However, the dynamic interaction between tools and vibrations from the machining process can directly affect the quality of the parts. Understanding and controlling these phenomena is a challenge for researchers, aiming to optimize the machining process and achieve greater efficiency (Grzesik, 2016). Compared to machines that work with a single tower, lathes performing simultaneous machining require greater control of cutting variables and tool characteristics (Hassan et al., 2021). In turning operations, it is essential to find a point that optimizes productivity and minimizes unwanted vibrations, since higher material removal rates increase tool wear, while lower material removal rates significantly influence the vibrations of the turning process (Peixoto, 2013). Regenerative vibrations, known as chatter, are a complex problem and can cause damage to the machine tool, reduced surface quality of the workpiece, excessive noise and other linked and historically known problems. The understanding and mitigation of these vibrations are important research areas in manufacturing (Quintana & Ciurana, 2011; Altintas, 2000; Polli, 2005).

Simultaneous turning with multiple tools has slightly less stability compared to conventional turning with a turret. To deal with the unwanted phenomenon of chatter, several regenerative vibration control techniques have been developed. However, most of these approaches are focused on conventional turning of a turret, where adjusting the rigidity of the cutting tools and the correct selection of machining parameters and the addition of damping through active and passive techniques can contribute to effectively suppress the regenerative vibrations. (Budak & Ozturk, 2011; Lee et al., 2001). In the case of simultaneous external turning, studies have been carried out to analyze the stability of the process and determine the most robust machining parameters, taking into account the mutual interaction of the tools during machining (Öztürk et al., 2016; Gouskov et al., 2018). The dynamic interaction between the tools can influence the stability limits, especially when the natural frequencies of the tools are close to each other (Budak & Ozturk, 2011). In systems with low dynamic stiffness, forced and regenerative vibrations are significant problems during the machining process, resulting in the deterioration of the surface quality of the parts and, consequently, an increase in the shape error (Altintas, 2000). In order to avoid regenerative vibrations, it is common to adopt conservative cutting parameters which reduces the material removal rate and consequently productivity. Yamato et al. (2021) developed a real-time simultaneous machining vibration suppression system using the Spindle Speed Variation (SSV) method, demonstrating its effectiveness in reducing vibration during machining. Meanwhile, Zheng et al. (2020) focused on the stability of the orthogonal turning-milling machining process, developing a Stability Lobes Diagram (SLD) with a tool for selecting process parameters, emphasizing the importance of preventing chatter during machining. Siemiatkowski and Deja (2021) addressed the optimization of simultaneous machining in multitasking machines, presenting an efficient algorithm for configuration and operation planning. They underscored the importance of multitasking machines in production optimization and the ongoing need for research in process planning automation.

Research in the field of vibration suppression in machining processes has focused mainly on active techniques, which, due to their high cost, are still feasible for large-scale industrial applications (Baz, 2019). However, there is a significant gap in the literature regarding the application of techniques for adding passive damping through dynamic viscoelastic neutralizers (VDN) since their cost is very low compared to vibration dissipation systems with active techniques for applications industrial applications, especially with regard to simultaneous external turning (Bavastri et al 2014). Thus, this article presents the development of a viscoelastic dynamic neutralizer for machining electric motor shafts on a double turret CNC lathe, in order to provide greater precision and stability in the scale roughing operation. In addition, this research contributes to the dissemination of viscoelastic dynamic neutralizers in industrial applications.

2. SIMULTANEOUS TURNING

According to Grzesik (2016), combined tools are applied with the aim of increasing productivity and economic gains in the manufacturing process, especially with regard to finishing the characteristics of a product. Simultaneous turning with two tools cutting at the same time can be seen in Figure 1. In this case, as an example, the external turning of an electric motor shaft is represented. Since they are cutting the same surface, the cutting speed should be the same for the two tools, however the depths of cut may be different.

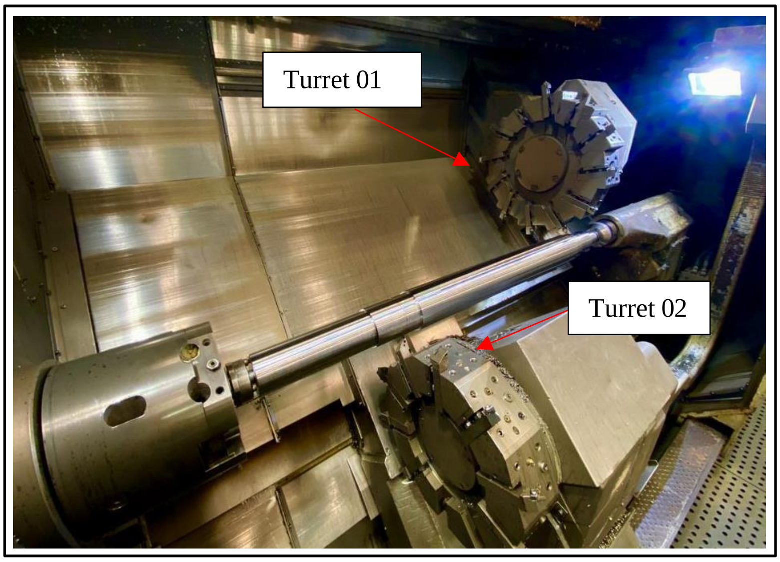

Figure 1. Electric motor shaft turning with two tools in different turrets.

Dynamic interactions between tools can work in favor of stability limits compared to operations with just a single tool, this effect is noticed when the natural frequencies of turning tools are close to each other (Budak & Ozturk, 2011). However, the dynamics of these machines is a crucial aspect that needs to be understood and controlled to guarantee machining quality.

2.1 Vibrations in simultaneous machining processes

Research on external turning is mainly focused on single-turret machining, but the dynamics of simultaneous turning are more complex, and further research is needed, especially regarding simultaneous external turning (Budak et al., 2014). There are two possibilities to carry out simultaneous turning, the first is by placing two tools in different turrets with an angle equal to or different from one hundred and eighty degrees between each other and always different from zero, as shown in the schematic demonstration in Figure 2, which will be addressed in this research. where each tool can be modeled as being attached to a rigid machine surface with springs k_1 and k_2 and shock absorbersc_1 and c_2 respectively, in addition, there are interactions between the plate k_s and c_s the tailstock k_p and c_p and the workpiece k_w and c_w the second possibility would be represented through the arrangement of tools arranged in the same tower and with an angle equal to zero between them. In both situations, the forward dynamic movement occurs simultaneously on the part (Öztürk et al., 2016). Due to these interactions the process is dynamically simultaneous, for example, the dynamic cutting forces in each tool influence the dynamic displacement of each other, vice versa.

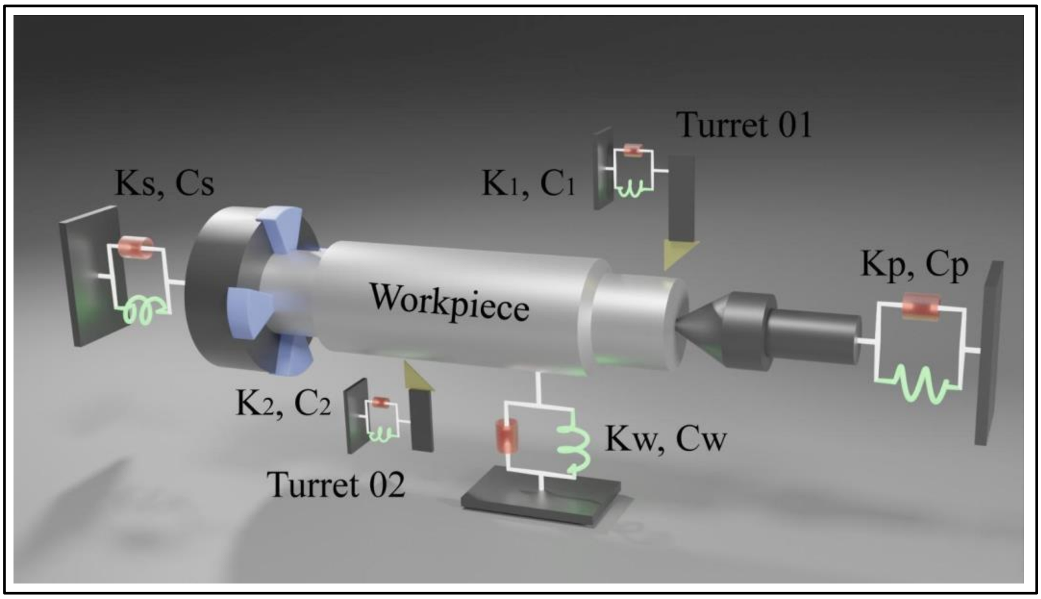

Figure 2 . Supports and tools mounted on different turrets cutting a shared outer surface.

When machining a flexible part using rigid tools, dynamic coupling between the inserts is caused by the part flexing in the radial direction. However, when machining a rigid part using flexible tools that are installed in a single turret, the dynamic coupling between the inserts occurs due to the flexibility of the turret/tool holder structure in the radial direction (Azvar, 2017).

3. VISCOELASTIC DYNAMIC NEUTRALIZERS

The use of viscoelastic materials in dynamic neutralizers or dynamic vibration absorbers in turning processes has been a investigated approach. These materials have viscoelastic properties, combining characteristics of elasticity and viscosity, which gives them the ability to dissipate vibratory energy (Bavastri et al 2014; Lee et al., 2001). Figure 3 shows a cutting tool with an additional degree of freedom due to a dynamic vibration damper, the equation of motion that governs the cutting tool with the dynamic vibration damper can be expressed as (1)

$$[M]\begin{bmatrix}\ddot{x}\\ \ddot{x}_a\end{bmatrix} + [C]\begin{bmatrix}\dot{x}\\ \dot{x}_a\end{bmatrix} + [K]\begin{bmatrix}x\\ x_a\end{bmatrix} = \begin{bmatrix}f_0 sin\omega t\\ 0\end{bmatrix} \quad (1)$$

Where [M], [C] e [K] are the system coefficient matrices that can be expressed as:

$$[M] = \begin{bmatrix} m & 0\\ 0 & m_a\end{bmatrix},\ [C] = \begin{bmatrix} c + c_a & -c_a\\ -c_a & c_a\end{bmatrix},\ [K] = \begin{bmatrix} k + k_a & -k_a\\ -k_a & k_a\end{bmatrix} \quad (2)$$

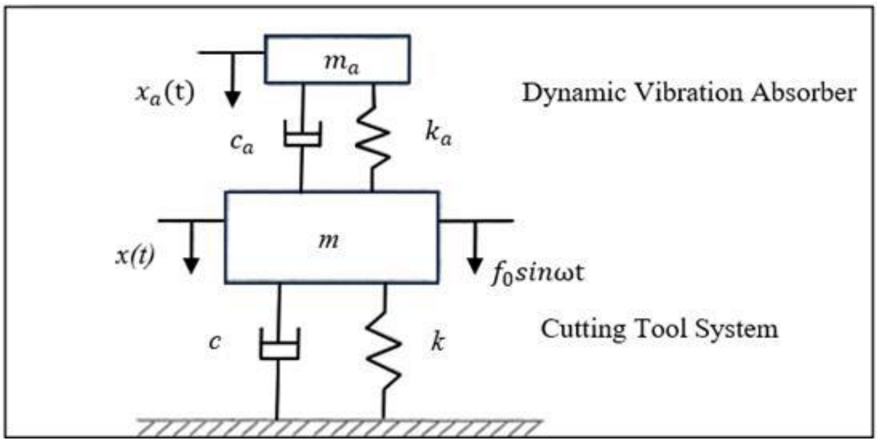

Figure 3. A VDN associated with a single degree of freedom cutting tool (Lee et al., 2001).

Where m, c e k are the mass, damping and spring parameters of the cutting tool and m_a, c_a, and k_a are the mass, damping and spring parameters of the VDN. The steady-state vibration of the cutting tool, represented by x, and the steady-state vibration of the VDN, representing for x_a, are described by the following equations:

$$x = X sin\omega t \quad (3)$$

$$x_a = X_a sin\omega t \quad (4)$$

Considering X as the magnitude of vibration in the steady state of the cutting tool and X_a as the magnitude of vibration in the steady state of the neutralizer. Substituting equations 3 and 4 into equation 1 allows for the calculation of the magnitude of vibration in the steady state of the cutting tool, denoted as X, as well as the magnitude of vibration in the steady state of the absorber, represented by X_a. Once the magnitude of vibration in the steady state of the cutting tool, X, is obtained, it is possible to calculate a dimensionless amplification ratio R, often used to describe the steady-state vibration response of the vibratory system (Lee et al., 2001; Gonçalves, 2012).

$$R = \frac{X}{f_0/k} \quad (5)$$

When attached to vibration-dissipating devices such as tool holders, viscoelastic materials have demonstrated good effectiveness in reducing unwanted vibrations during turning. This results in significant benefits, including improved machined surface quality, increased tool life, as well as the reduction of noise levels and oscillations in the machining system (Lee et al., 2001). Figure 4 shows the amplification ratio R of the cutting tool in relation to the vibration absorber as a function of the frequency ratio. ω/ω_n.

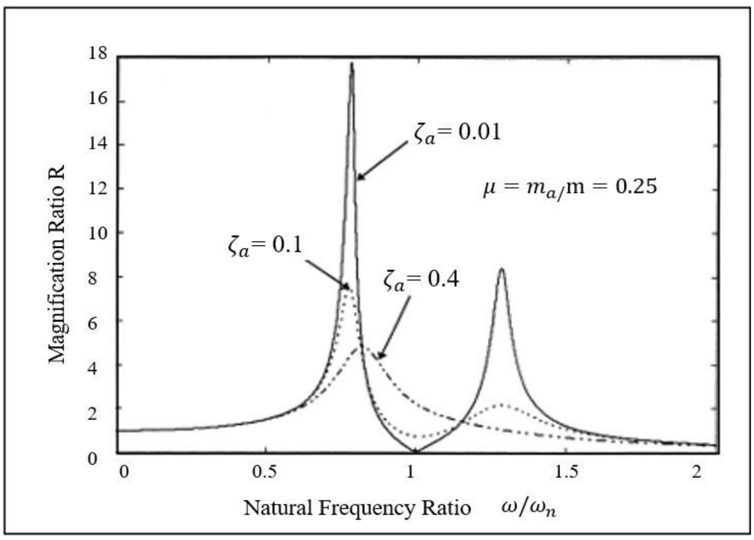

Figure 4. Amplification ratio relative to the frequency ratio with β = 1.0 (Lee et al., 2001).

4. METHODOLOGY

The experimental procedures carried out in turning were conducted at WEG Equipamentos Elétricos S.A. – Motors, in Jaraguá do Sul. The CNC lathe used for the study is the IMPACT LU-35 model with the OSP P200L control system from the Japanese manufacturer Okuma. The tool holder MTJNL 2525-M16 with the TNMG 160408 insert was used to perform the scale removal operation on a 127 mm diameter, 1050 mm long SAE 1045 steel bar. A cutting speed of 200 mm/min, a feed rate of 0.4 mm/revolution, and a cutting depth of 3.5 mm were used. The tailstock pressure was set at 3.4 MPa, and the chuck pressure at 3.0 MPa. To conduct the impact test to determine the natural frequencies of the tool holders and the workpiece, as well as to monitor vibration levels, accelerometers in the radial and axial directions were used, along with a measurement module and a signal acquisition and processing program described in Table 1.

Table 1. Instruments used to perform the impact test and vibration monitoring.

Function	Description
Excitement	Endevco 8208 Impact Hammer, 0.22 mV/N (1 piece) Shaker B&K 4808 B&K 2719 Power Amplifier
Answers	Accelerometer IMI 603C01, sensitivity 100 mV/g (6 pieces) Accelerometer PCB 354B14, sensitivity 5 mV/g (6 pieces)
Acquisition and processing of data	Notebook HP Probook 6460B Acquisition module: LMS SCS Scadas Mobile Type SCM01-8 channels Program: Test Lab 12A

For the manufacturing of the dynamic neutralizer, the viscoelastic material Dyal 601 was used, which in the study conducted by Bavastri et al. in 2014, demonstrated a higher effectiveness in suppressing regenerative vibrations in turning operations.

5. RESULTS AND DISCUSSION

First, an impact test was carried out to identify the natural frequencies of the raw shaft, Figure 5 represents this test later, the vibration levels were monitored through accelerometers fixed to the towers and the vibration signals were collected and analyzed through the acquisition module. Subsequently, it was observed that the level of vibrations measured during machining were close to the first natural frequency of the raw shaft. The vibration data collected in the on-site analysis showed a high level of vibration, in both towers, at a frequency of 2080 Hz with a magnitude of almost 2.8 g [rms] (Figure 6), the effect of the high level of vibration was noticeable due to the high characteristic noise when there is the chatter phenomenon.

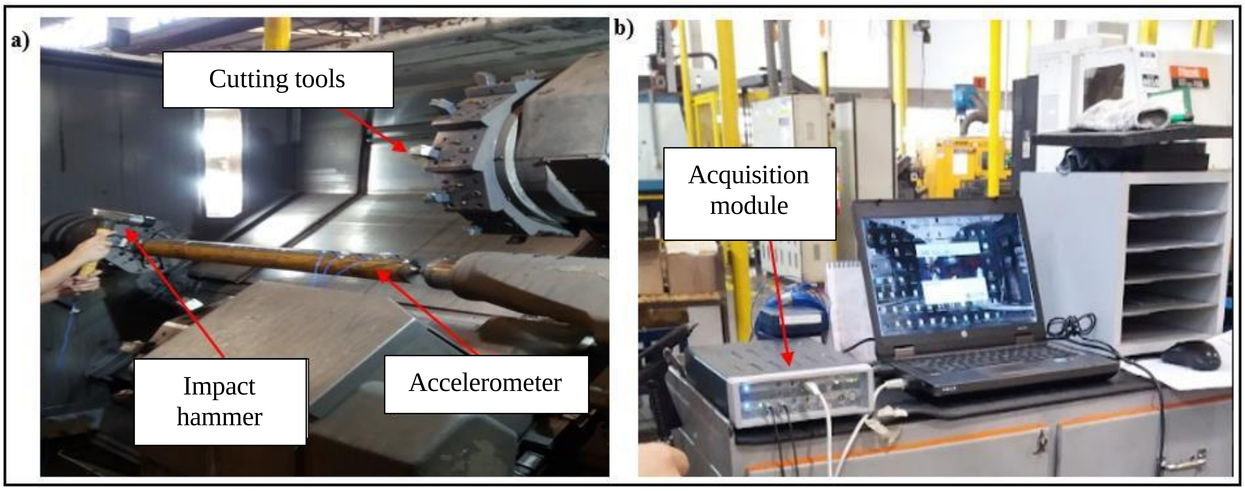

Figure 5 - a) Impact test on the raw shaft, b) vibration measurement during machining using the signal acquisition and processing module.

In figure 6 it is possible to observe the superimposed vibration signals, the scale roughing machining spectra are in red and the result of identifying the natural frequency in the cutting tool in black. It is noticeable that the two spectra are very close, leading to the condition of dynamic instability of the explicit system through chatter.

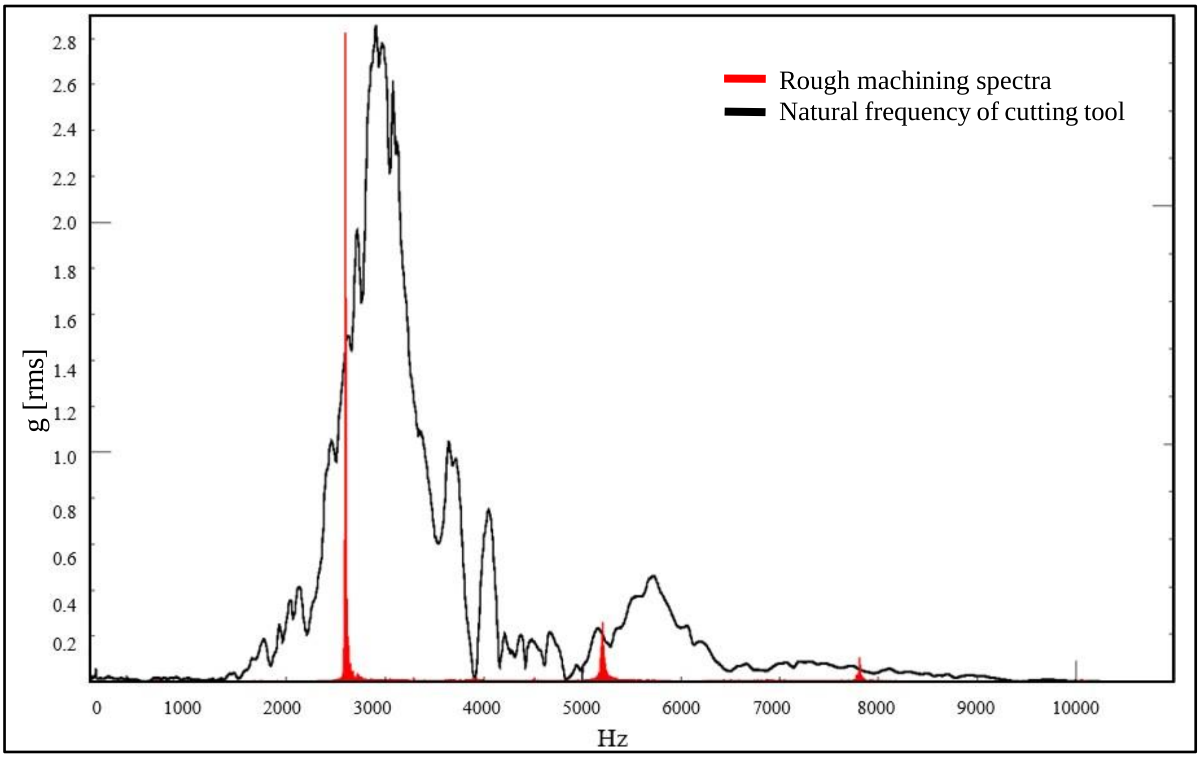

Figure 6. Overlapping spectra during machining with the natural frequencies of the part.

The waveform of this same signal indicated that the highest measured vibration level was 10 g 0-peak shown in figure 7. The instant in which this vibration spectrum was measured, the noise that the amplification of this vibration propagated was clear, a few moments later after collecting this spectrum, the tool broke, highlighting the importance of controlling the incidence and amplification of this phenomenon.

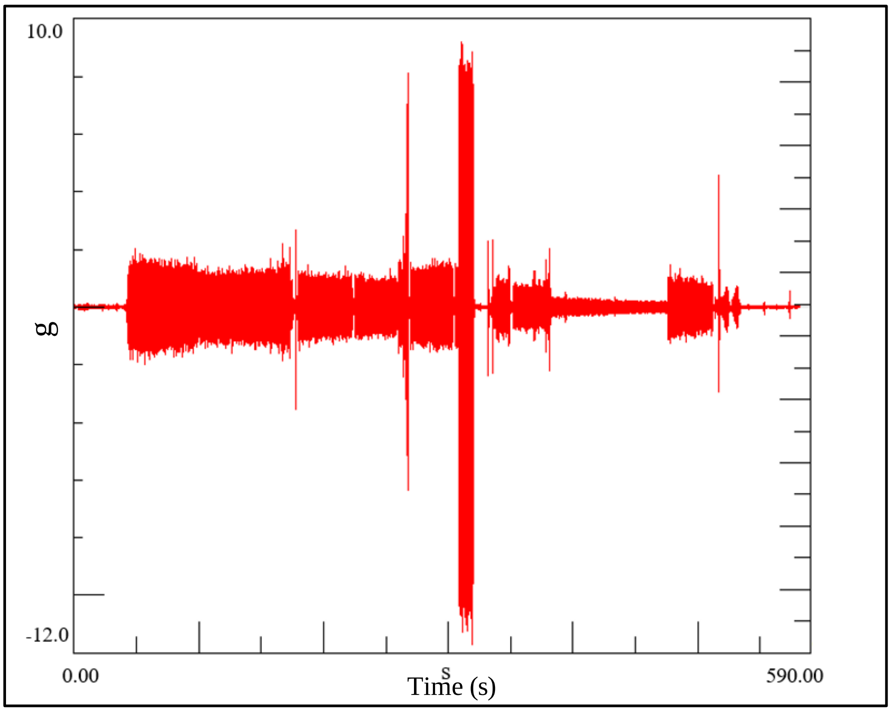

Figure 7. Vibration in the time waveform measured in the towers.

Other modes were identified at 138 Hz and 371 Hz but were not considered at this stage of the analysis because they did not manifest themselves during vibration measurements. As the system in question is a complex combination of the part to be machined, tool holder and machine, all composed of metallic alloys, it is expected that they present low levels of damping. In addition, excitation characteristics during machining that involve high levels of friction, result in a random frequency force over a wide range of frequencies. In this way, the natural frequencies of the tools, spindle or other machine components can be easily excited.

5.1 Neutralizer design and addition of passive damping

In order to achieve the optimal design of a neutralizer, it is necessary to initially identify the primary system. After carrying out the impact test to identify the first natural frequency of the tool and verifying that it is the main and only one to be excited during machining, the primary system was modeled as a 1 degree of freedom system and numerically adjusted from the Inertance Frequency Response Function of the neutralizer model, in this case the frequency of interest was the one identified in the experimental tests of 2080 Hz.

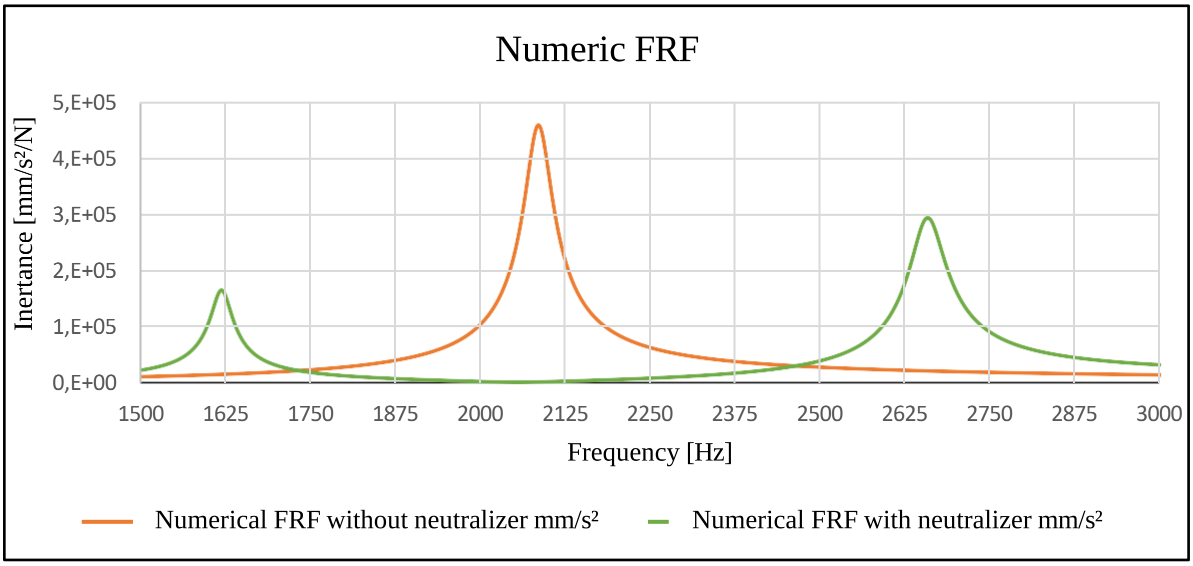

Figure 8: Magnitude of simulated cutting tool frequency response function with and without dynamic neutralizer.

Based on figure 4, which shows the FRF of the cutting tool with the vibration absorber as a function of the frequency ratio ω/ω_n, the parameters of the vibration system for the cutting tool are selected as mass m=100 grams, natural frequency of 2080.0 Hz and the mass ratio of the neutralizer to the mass of the cutting tool of $\mu = m_a/m = 0.25$. The damping used in this calculation is obtained from the characterization data of the Dyal 601 viscoelastic. Additionally, the neutralizer has its natural frequency equal to the natural frequency of the cutting tool, that is, $\beta = \omega_a/\omega_n = 1$, through the numerical FRF it is possible to observe that two new natural frequencies are generated and located to the right and to the left of the natural frequency of the cutting tool when the neutralizer is coupled to the cutting tool. Furthermore, the introduction of passive damping changes the amplitude of inertance of the cutting tool and neutralizer assembly. The magnitude of the amplifications located on the left and right sides of the natural frequency of the cutting tool is significantly minimized when the damping ratio ζ is increased.

Therefore, it is possible to reduce the amplitude of the inertance of the cutting tool assembly by adjusting the natural frequency of the dynamic neutralizer to be equal to or close to the natural frequency of the cutting tool, using a dynamic neutralizer with a higher damping rate.

5.2 Fixing the neutralizer and actuating the VDN

Based on the description given in the previous section, the neutralizer was built as shown in figure 8. It shows the prototype of the neutralizer fixed below the cutting tool support that performs the mill scale thinning operation. The viscoelastic material was glued into a rectangular key with dimensions of 45 mm x 10 mm x 10 mm. Through a signal generation and amplification system, a shaker was used to tune the natural frequency of interest (experimentally identified in the tool holder) with the dynamic neutralizer made.

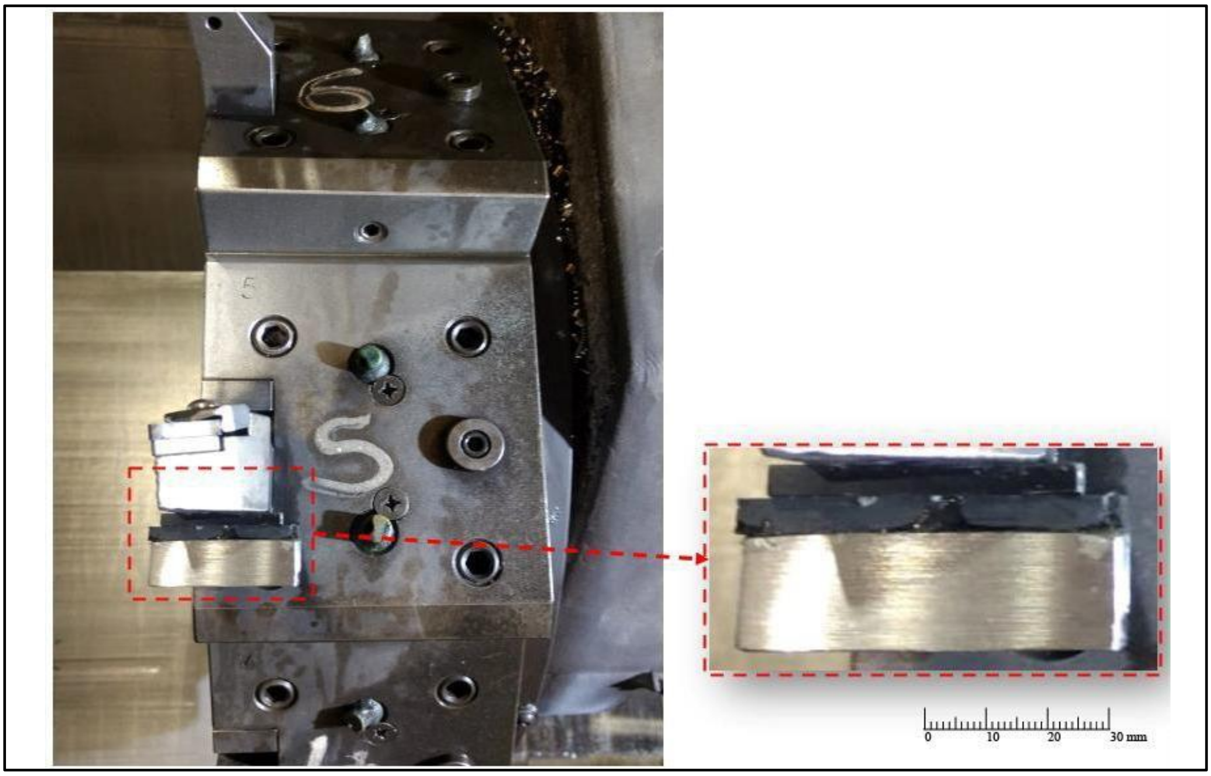

Figura 8:. VDN Fixed below the tool holder.

The use of the dynamic neutralizer in the scale thinning tool provided a significant reduction in the average and variation of the vibration amplifications, as can be explicitly seen in Figure 9, where the vibration signals are superimposed with the neutralizer in green and without the neutralizer in red, proving to be a robust solution for machining long shafts in an industrial application with high material removal rates. This technology allows controlling and mitigating the unwanted effects of vibrations during the machining process, ensuring greater stability and precision in turning.

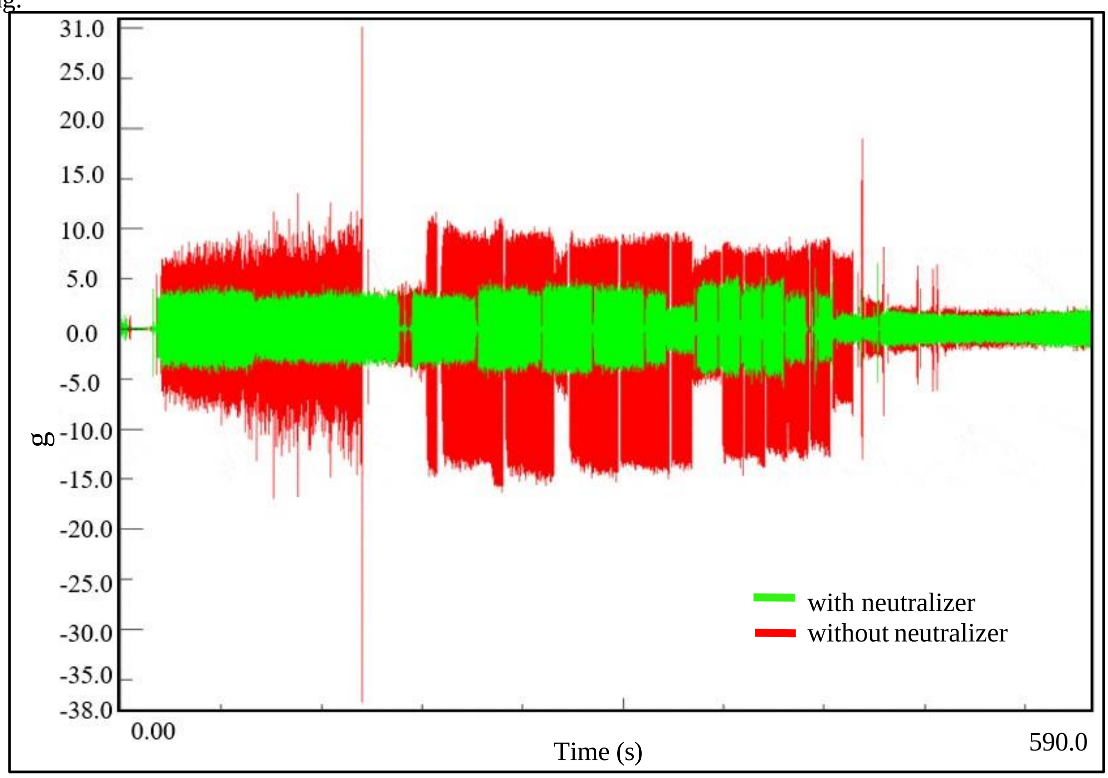

Figure 9: Superposition of two vibration signals measured during the experiments.

By applying the dynamic neutralizer, it is possible to minimize the negative impacts of vibrations, resulting in a better finish on parts, increased tool life and reduced rework. In this way, the use of the dynamic neutralizer presents itself as an effective strategy to optimize the performance and efficiency in the machining of long shafts.

6. CONCLUSIONS

This research addresses the use of viscoelastic dynamic neutralizers in the suppression of simultaneous turning vibrations that affect the quality of electric motor shafts. The effects caused by vibrations in machining processes are widely known and discussed, however current research focuses on the application of active suppression techniques and passive techniques are not so explored, which due to their low cost become viable for application. This work had as proposal the compression and control of the regenerative vibrations in which it was made and applied in a machine that performs simultaneous turning a viscoelastic dynamic neutralizer, with the purpose of minimizing unwanted vibrations of the produced parts. The use of viscoelastic dynamic neutralizers in simultaneous turning brings tangible benefits to the manufacturing industry. The application of this technique of adding passive damping resulted in the minimization of vibration amplitudes and a reduction in the noise level. The research and application of viscoelastic dynamic neutralizers in simultaneous turning represent an innovative approach to overcome the challenges caused by unwanted vibrations in the manufacturing industry.

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8. RESPONSIBILITY NOTICE

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