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Reducing chatter in turning using a piezoelectric LR passive shunt strategy

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Abstract. *The self excited vibration called chatter is a recurring problem during machining. The use of slender boring bars with the purpose of internal turning is an aggravating to the vibration that can lead to poor surface quality and excessive tool wear. In this paper, a passive control strategy is evaluated in experiments. The results are presented using frequency response functions (FRFs), in which the amplitude of vibration for the two main directions of cutting is evaluated. The FRFs are obtained using impact tests. The results are generated for four different scenarios. Firstly, the system is evaluated with no control strategy being applied. Then, the system's response to the use of piezoelectric LR passive shunts in the two main directions of vibration is analysed. The third and fourth scenarios are the ones in which the shunt is connected only to one direction. The paper presents results in which close to 20% reduction in the vibration amplitude can be seen. Numerical simulations are performed using a finite element method approach. The electromechanical coupled structure presents FRFs that are very close the experiments.*

Keywords: *Smart materials, Piezoelectric materials, Chatter, Passive shunts, Vibration control*

1. INTRODUCTION

Large relative vibrations can arise during machining operations due to complex interactions between the machine tool, tool holder and workpiece. The vibrations can be categorized as free-vibrations, forced vibrations and self-excited vibrations (Tobias, 1961). Free-vibrations can occur in machining due to collisions for instance, while forced vibrations may be caused by unbalanced bearings or can even be passed trough the work floor. These vibrations are well understood and can be avoided or significantly reduced using a wide range of methods (Quintana and Ciurana, 2011). Self-excited vibrations, however, extract energy from tool-workpiece system to grow, leading to instability and chatter.

Chatter affects the surface quality, generating unacceptable levels of accuracy; excessive tool wear; loud noise and an unsafe working environment (Wiercigroch and Budak, 2001). Although being a field of study for decades, predicting chatter's occurrence and controlling it is still a major study in the machining field (Quintana and Ciurana, 2011).

Besides being categorized as a self-excited vibration, chatter itself can also be divided into primary or secondary. Primary chatter happens as a result of inherent cutting conditions, such as thermo-mechanical effects; friction between the tool and the workpiece; and mode-coupling in the two main directions of vibration. As the proposed phenomena is studied during internal turning and boring operations, in which a long and slender tool holder is necessary for the operation, it is important to consider the mode coupling generated by the cutting and frictional forces (Quintana and Ciurana, 2011; Pratt and Nayfeh, 2001; Grabec, 1988; Tobias, 1961; Chandiramani and Pothala, 2006; Pratt, 1997; Wiercigroch and Krivtsov, 2001; Venter and da Silva, 2015). Secondary chatter is caused by the regeneration in the chip thickness, induced by modulations left in the surface from previous revolutions (Silva and Cervelin, 2013; Yigit *et al.*, 2014). The machining parameters influence the phase between successive modulations, affecting the closed-loop damping.

The stability limit is known to change proportionally to structural damping (da Silva, 2010; Silva and Cervelin, 2013; Ganguli, 2005). One can achieve a stable boring operation by carefully choosing the machining parameters or by changing the structural damping. As the first approach can lead to a conservative solution, with a negative impact on productivity, the latter presents a viable way to decrease the instability without jeopardizing the productivity.

Pursuing this path, it is possible to change the damping in the structure in a passive or active way. The increase of damping may be obtained, passivly, by the use of impact, particle and tuned mass dampers (Ema and Marui, 2000; Sims, 2007). In an active approach, several different control strategies have been already proposed (Siddhpura and Paurobally, 2012).

Piezoelectric materials can be employed not only as sensors but also as actuators due to their electromechanical coupling property (Park *et al.*, 2007). Divers active strategies that use piezoelectric materials as an actuator have been proposed and studied, as can be seen, for instance, in Wu *et al.* (2009); Yu *et al.* (2012); Min *et al.* (2002). One of the purposes of this paper is to experimentally investigate a passive strategy to reduce chatter using piezoelectric material. The numerical evaluation of this proposal has been addressed in Erturk and Inman (2008); Silva and Cervelin (2013);

Yigit *et al.* (2014). Figure 1 presents a improvement in the stability lobes obtained in da Silva (2010).

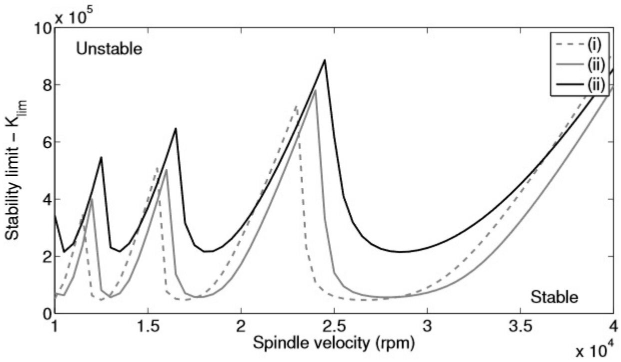

Figure 1. Comparison between stability lobe diagrams: (i) system with no piezoelectric layer, (ii) system with piezoelectric layer and open shunt circuit and (iii) system with piezoelectric layer and LR shunt, from da Silva (2010)

Although the studies present a comprehensive numerical evaluation, the models used simplify the tool-holder, using a beam structure to describe it. As addressed before, in the slender and nearly symmetrical tool-holders used in boring operations, a mode-coupling effect can be perceived, which then makes the structure vibrates in two directions. It is consequently necessary to investigate a model that accounts for two directions of movement, as well as the electromechanical coupling that occurs due to the use of piezoelectric materials.

In the present paper, experimental results that demonstrate the system dynamics are shown. Also, the proposed technique for chatter reduction is experimentally evaluated and the amplitude of FRFs are compared using different shunt configurations. At last, the current state of the new model's work is presented. The structure is being modelled using the finite element software ANSYS ®.

2. Experimental methodology and results

In order to fit in the available lathe, a specific design was created as a workpiece. The machined workpiece is made of steel AISI1020 and its dimensions are illustrated in Fig. 2.

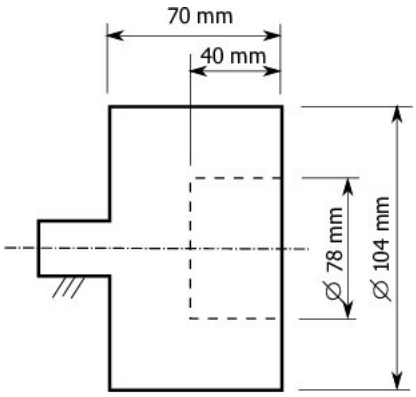

Figure 2. Workpiece's dimension

The used tool-holder was S32U-PTFNL 16-W, which is usually employed in boring operations. The tool-holder was modified to embed the piezoelectric layers. Its customized total length is 270 mm from which 40 mm is used to fix it in the machine and its section has been machined to accommodate the piezoelectric patches. The final format can be approximated by a square section cantilever beam (length: 230 mm and section: 20 mm $\times$ 20 mm). The tool TNMG 16 04 04-PF is adequate for boring operations.

Piezoelectric patches (20 mm$\times$75 mm$\times$4 mm) have been embedded to the tool-holder in the x and y directions by the use of a commercially available adhesive. The conductive surfaces have been connected to conductive copper tapes and wires. The piezoelectric layers, conductive tapes and wires, tool-holder and coordinate system are depicted in Fig. 3).

Considering the passive LR shunt in series (as seen in Fig. 4), the optimal constants can be calculated as $L = 12H$ and $R = 10k\Omega$. Being the tool nearly symmetrical, these values are adopted for both directions. This induction value requires the use of a non-commercial inductor ($L > 5H$), that have been customized. The actual shunt circuits are composed of a series of inductors and resistors as illustrated in Fig. 5a. The measured values of the induction/resistance in the x- and y-directions are $L = 11.77H/R = 8.88k\Omega$ and $L = 11.80H/R = 10.45k\Omega$, respectively.

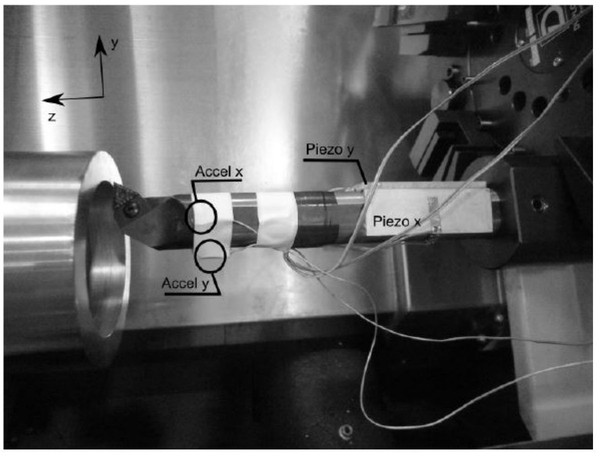

Figure 3. The Coordinate system: Workpiece, the Tool-holder, Piezoelectric layers and the Coordinate system

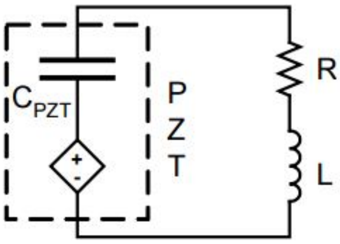

Figure 4. Schematic design of a passive LR shunt in series, adapted from Viana and Jr (2006)

Figure 5. (a) Shunt Circuit and (b) Impact Hammer and Data Acquision System

2.1 Experimental Frequency Response Functions: Setup description and Results

The Data Physics QUATTRO FFT signal analyser (see Fig. 5b) was used to acquire the signals and process the FRFs. In the first of its four channels, the reference input signal is setted to be the impact hammer input. The impact hammer used in this campaign was the a PCB Piezotronics 086C03 impact hammer with $2.39mV/N$ of sensitivity. In the second channel, the output signal of a B&K accelerometer placed in x direction (see Fig. 3) with $96.3mV/g$ of sensitivity. In the third channel, the output signal of a B&K accelerometer placed in y direction (see Fig. 3) with $95.2mV/g$ of sensitivity. The employed FRF estimator was Hv (McConnell and Varoto, 2009). The estimated FRFs are denoted by H hereafter. Its subscripts denote the place direction of the output signals.

In these experiments, the boring bar was attached to the lathe and both static experiments and dynamic ones were performed. In Fig. 6, one can see the H_{12} (Fig. 6a) and H_{13}(Fig. 6b), which depicts the estimated driving tip FRF using the output signal in the x and y direction, respectively, and the input signal in the x direction. Figure 7 depicts the estimated driving tip FRFs using the output signal in the x (Fig. 7a) and y (Fig. 7b) direction, respectively, and the input signal in the y direction. The coupling between the directions can be observed by analyzing the Figs. 6b and 7a. The output signals in a different direction of the input signal are clearly rather significant which motivate the use of piezoelectric layers in both directions. In the x direction, two approximated natural frequencies appear ($wn_{x1} = 345Hz$, $wn_{x2} = 365Hz$). In the y direction, the natural frequency can be approximated by $wn_y = 392Hz$

Figures 8 and 9 depict FRFs in four different scenarios. Figure 8 presents the estimated H_{12} FRFs for (i) open circuit,

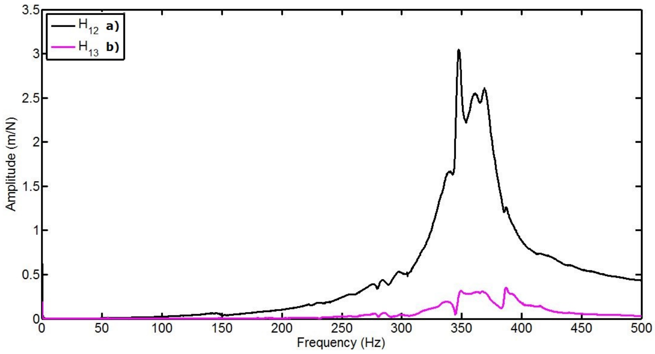

Figure 6. Estimated driving tip FRFs using the input signal in the x direction and the output signals in (a) x direction and (b) $y$direction

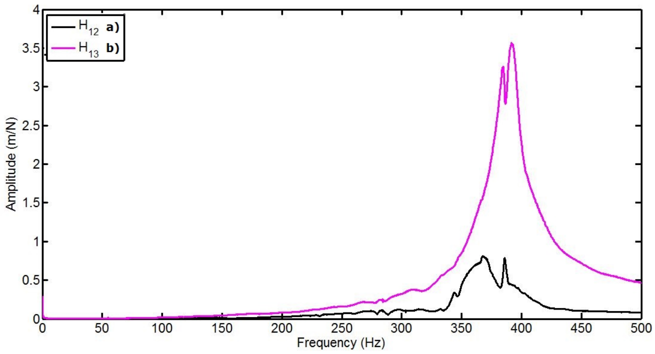

Figure 7. Estimated driving tip FRFs using the input signal in the y direction and the output signals in (a) x direction and (b) $y$direction

(ii) shunt connected to both directions, (iii) shunt conected to x direction and (iv) shunt conected to y direction, when an input was made in the x direction. Figure 9 presents the estimated H_{13} FRFs for (i) open circuit, (ii) shunt connected to both directions, (iii) shunt connected to x direction and (iv) shunt connected to y direction, when an input was made in the y direction.

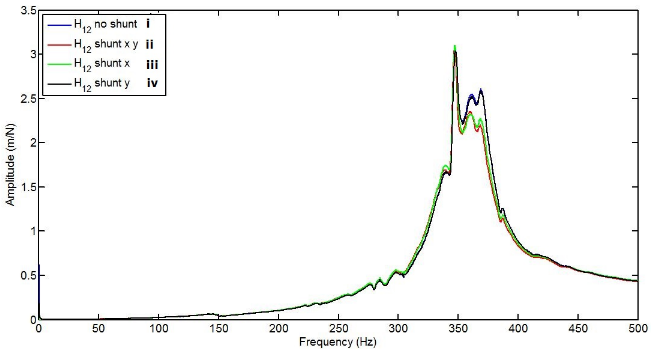

Figure 8. Comparison in estimated driving tip FRFs, input and output signals in the x-direction, i) no shunt, ii) shunt conected in both directions, iii) shunt in x direction, iv) shunt in y direction

Figures 8 and 9 show that when the input signal and the shunt circuit are in different directions, there is little change in the FRF amplitude. This fact can be observed in the H_{12} with shunt in y direction in Fig. 8 and in the H_{13} with shunt in x direction in Fig. 9. Nevertheless, a significant reduction in the amplitude occurs when the shunt circuit is in the same direction of the input signal. This fact can be observed in the H_{12} with shunt in x direction in Fig. 8iii) and in the H_{13} with shunt in $y$direction in Fig. 9iv). The use of shunt circuits in both directions promotes a significant damping reduction independent of the input signal direction. Since the cutting forces are highly dependent on the geometrical system characteristics, they are going to present components on x and y direction. Therefore, it is necessary to use shunts in both directions in boring operations. The frequency $345Hz$ in Fig. 8 was not affected with the control. One possible explanation is that this frequency is not a natural frequency of the tool-holder, but rather one that appears in the coupling with the lathe.

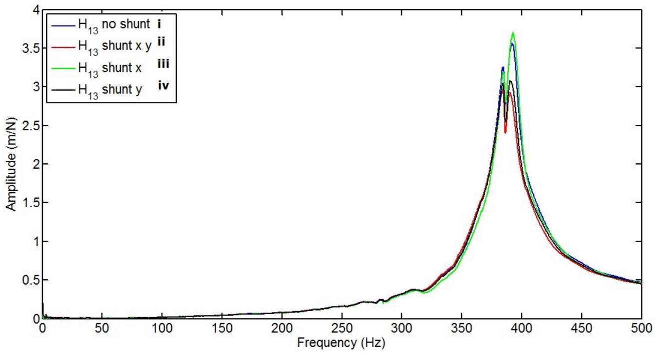

Figure 9. Comparison in estimated driving tip FRFs, input and output signals in the y-direction, i) no shunt, ii) shunt conected in both directions, iii) shunt in x direction, iv) shunt in y direction

2.2 Surface Finishing: Setup Description and Results

Two workpieces, identical in dimension as illustrated in Fig. 2, were bored using scenarios (i) and (ii). The machining parameters have been set to: depth-of-cut $0.25mm$, spindle speed $2000rpm$ and feed rate $0.1mm/revolution$. As chatter did occur, the surface finishing was then measured using a profilometer. Each workpiece surface was measured in three distinct profiles, and the results are demonstrated in Tab. 1. The average reduction on peak-to-peak values was about 30%. The machining parameters were set to yield large vibration amplitudes, therefore both pieces present poor surface quality. However, the use of passive LR piezoelectric shunts improved the surface quality by dissipating energy as expected.

Table 1. Comparison of the maximum peak-to-peak values of each profile

	No Shunt (μm)	Dissipative Shunt (μm)
Profile 1	110.0	75.0
Profile 2	100.0	85.0
Profile 3	105.0	70.0
Average	105.0	76.6

3. Numerical simulation methodology and results

The tool-holder embedded with piezoelectric patches must be designed in order to simulate as best as possible the characteristics observed in experiments. In order to do so, a simplified tool-holder was designed using SolidWorks ®as a parallelepiped with $250mm$ of length, $50mm$ in the x direction and $27mm$ in the y direction, made of SAE-AISI 8640 carbon steel. Two piezoelectric patches were also created using SolidWorks ®, and both have (25 mm×75 mm×4 mm) as dimensions. The structures were imported to ANSYS ®and coupled, as can be seen in Fig. 10. The piezoelectric bodies have been fixed in the structure $10mm$ from the C face.

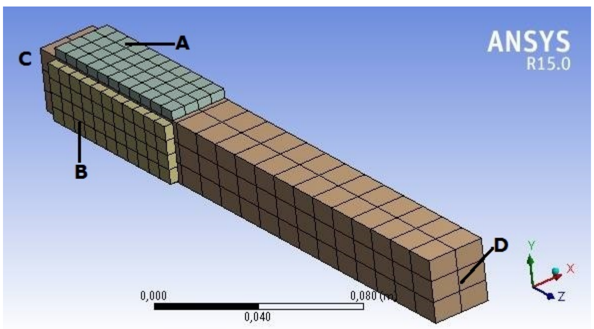

Figure 10. Simplified ANSYS ®structure

Using the Piezo ACT extension, the patches (A and B in Fig. 10) were converted to piezoelectric bodies. In order to do so, the piezoelectric constants and the polarization direction must be set, which was done using the constants provided for PZT-5A. The face C was set as a fixed support to emulate the lathe collet.

The dimensions were carefully chosen in order to emulate the same natural frequencies, in both directions of vibration, which could be found using the ANSYS R15.0 ®Workbench modal analysis tool. Adjusting the dimensions as stated provided a first natural frequency (wn_1) of $365,4Hz$ and a second natural frequency (wn_2) of $392,3Hz$, furthermore, wn_1 is related to the mode in which there is deflection in the x direction and wn_2 is related to the mode in which there is deflection in the y direction, which is precisely the expected result.

3.1 Simulated frequency response functions

As the coupled structure responded as expected in the modal analysis, one can proceed to simulate FRFs using the finite element software. The harmonic response tool, available in the ANSYS R15.0 Workbench can provide the frequency response function, when a force is provided. Two scenarios were then considered: (i) Single force as an input in the centre of face D, in the x direction; (ii) Single force as an input in the centre of face D, in the y direction.

The obtained results for scenario (i) are seen in Figs. 11 and 12

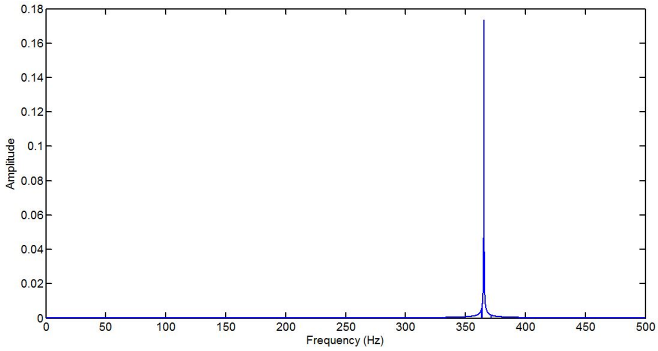

Figure 11. Simulated FRF amplitude using an input signal in the x-direction and output signal in the x-direction

In Fig. 11, there is the simulated H_{12} response, in which the input and output are in the x direction. One can see that the natural frequency appearing in the graphic is $365Hz$ which is the approximated natural frequency found in Fig. 6. It is worth stressing that there is no dynamic response in frequency $345Hz$, which meets the aforementioned conclusion that this frequency is probably regarding lathe dynamics.

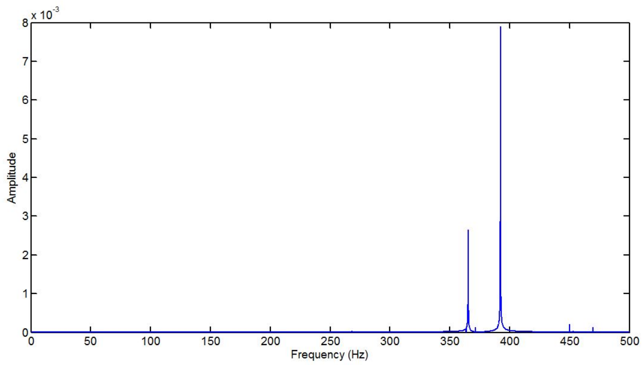

Figure 12. Simulated FRF amplitude using an input signal in the x-direction and output signal in the y-direction

In Fig. 12, there is the simulated H_{13} response, in which the input is in the x direction and the output is in the y direction. As seen in experiments, when the input is given in the x direction, the amplitude of vibration in the y direction is much smaller than the amplitude of vibration in the x direction. The two natural frequencies appear, emphasizing that the system is structurally coupled.

The obtained results for scenario (ii) are seen in Figs. 13 and 14

In Fig. 13, there is the simulated H_{13} response, in which the input and output are in the y direction. It is possible to be seen that the natural frequency appearing is $392Hz$, which is the one found in Fig. 7.

In Fig. 14, there is the simulated H_{12} response, in which the input is in the y direction and the output is in the x direction. Similarly to scenario (ii) and in order with the experimental results, the amplitude of this FRF is also smaller than the one obtained in the y direction. Not only do the two natural frequencies appear, other frequencies can also be seen in this result. The appearance of new frequencies, specially the ones in the $475Hz$ range, need to be addressed in further studies.

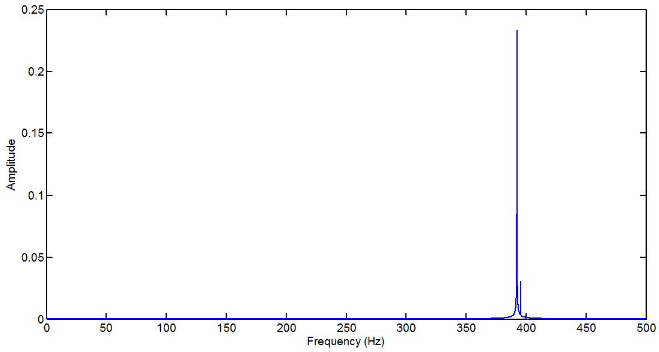

Figure 13. Simulated FRF amplitude using an input signal in the y-direction and output signal in the y-direction

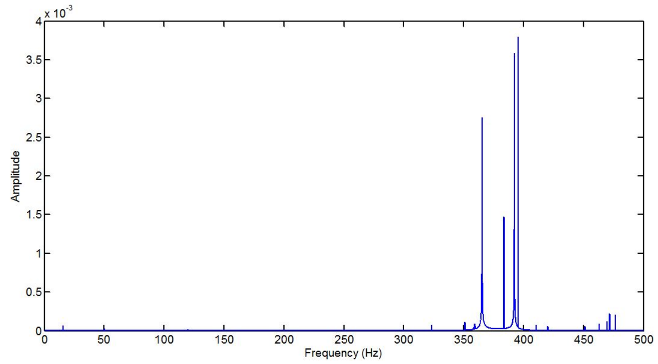

Figure 14. Simulated FRF amplitude using an input signal in the y-direction and output signal in the x-direction

4. Conclusions

In the first experimental results, it was possible to acquire the structure natural frequencies, in both main directions of vibration. It was also possible to observe that an energy input in one direction caused vibration in both directions. Therefore, the structure is coupled. The use of embedded piezoelectric materials connected to a passive shunt circuit to increase the damping in the system was, then, experimentally investigated. Driving tip FRFs in four different configurations were presented: (i) open circuit, (ii) shunt connected in both x and y directions, (iii) shunt connected in x direction and (iv) shunt connected in y direction. The presented FRFs were H_{12}, with an input in the x direction, and H_{13}, with an input in the y direction. Analysing the FRFs, it can be concluded that the damping was effectively increased when the connected shunt circuit was in the same direction as the input. The best scenario was possible to be achieved when the LR passive shunt circuit was connected to both directions of vibration, in which was possible to dimish the FRF amplitude in the x direction by 15% and in the y direction by 20%.

Since the cutting forces largely depend on the geometrical characteristics of the machining process, the use of dissipative shunt circuits in two distinct directions can be a more robust strategy to guarantee the attenuation of the vibrations. Two pieces were bored using configurations (i) and (ii) exposed above, and the surface was measured using a profilometer. The average reduction on peak-to-peak values was 30% clearly demonstrating that the proposal might be a viable solution for chatter reduction.

Having evaluated the viability of such proposal experimentally, a comprehensive model must be elaborated. The present work shows the state of this elaboration, and explores the dynamic response of such model. A simplified toolholder and the piezoeletric patches were designed in SolidWorks ®and then coupled using the finite element software ANSYS ®. Estimated FRFs were obtained for inputs in the x and y directions. The natural frequencies obtained were the same as the one encoutered experimentally. Also, the simulated FRFs show a great resemblance to the experimental ones, demonstrating that the system dynamics are correctly depicted in the model.

It is paramount that the control transfer function (TF) from LR passive shunts is incorporated in the ANSYS ®model. Only then the simulated answer can be fully evaluated. The designed model can then be used, with different TF, to evaluate distinct control strategies.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

The list of references must be introduced as a new section, located at the end of the paper. The first line of each reference must be aligned at left. All the other lines must be indented by 0.5 cm from the left margin. All references included in the reference list must have been mentioned in the text.

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