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Experimental results on chatter reduction in turning through embedded piezoelectric material and passive shunt circuits

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A B S T R A C T

Chatter instability is an important drawback concerning high precision and accurate machining operations. Suitable strategies for chatter detection and reduction should be proposed and exploited in order to ultimately improve the final quality of machined parts. It is well known that chatter instability can be reduced by increasing damping since the later presents a proportional relationship with stability limits. The main idea in the present work is to address the issue of chatter instability by proposing a vibration reduction methodology through the use of embedded piezoelectric patches in the tool-holder connected to a passive shunt electrical circuit. This circuit is responsible for energy dissipation providing extra damping to the system. The strategy is numerically and experimentally tested in turning/boring operations. A simplified electro-mechanical distributed-parameter model is briefly described and numerically evaluated in order to assess the potentiality of the proposed technique. Actual measured frequency response functions of the tool-holder with different shunt strategies are compared demonstrating how damping can be modified. Moreover, two different shunt strategies are evaluated during a boring operation. Preliminary experimental results point to a considerable improvement in the quality of the surface finishing when the proposed passive shunt circuits associated to the piezoelectric elements are used, indicating that the proposed strategy can be a promising and feasible solution for chatter reduction. Nevertheless, there are still some technical difficulties that should be overcome towards the full practical implementation of the proposed methodology.

1. Introduction

Chatter instability has been a research theme of constant interest due to its importance on the performance of high precision and accurate machining operations. It is generally characterized by intense vibration levels, loud noise, poor quality of surface finishing, excessive tool wear, among other issues. Hence, techniques for its prediction/detection and strategies for its suppression should be proposed and exploited in order to enhance the quality of machining processes. A general review on chatter in machining process has been arranged by Quintana and Ciruana [1]. Regarding turning and boring operations, Siddhpura and Paurobally [2] have summarized the status of the current research on chatter stability prediction, chatter detection and chatter control techniques.

The regeneration of chip thickness, which is related to phase between the modulations left on the surface during the successive cuts, is the most common reason behind the phenomenon of chatter instability [3,4]. In turning and boring operations, the chatter instability phenomenon is highly dependent on the spindle speed, width-of-cut and structural damping. The machining parameters, spindle speed and width-of-cut, mainly influence the phase between successive modulations which affects the damping and stiffness of the closed-loop system. It is also known that structural damping has a proportional relationship with the stability limit [5,6]. In this way, a stable process can be achieved by a conservative selection of machining parameters or by increasing the level of structural damping. The former may present a negative impact on the productivity. The latter may be pursued by the development and proposal of active or passive strategies to modify the system dynamic characteristics. Clearly, passive strategies have some advantages over active strategies since not only no extra energy is required, but also their cost is low and their implementation is arguably easy. Nevertheless, they may lack robustness and performance [2].

Among several techniques studied to increase damping through passive mechanisms, it is important to highlight the use of impact, particle and tuned mass dampers. Proposed techniques exploring

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these strategies can be found for instance in [7,8]. Similarly, in order to increase damping actively, different control strategies using a large range of sensors and actuators have been already proposed [2]. The use of active materials in chatter reduction has been treated by Park et al. [9] where authors covered the use of piezoelectric and magnetostrictive materials as well as MR and ER fluids in machining operations. Piezoelectric materials can be employed not only as sensors but also as actuators due to their electromechanical coupling property. In other words, these materials produce an electric charge under mechanical stress (sensing property) and a strain under an applied voltage (acting property) [9]. Due to these properties, they have been mainly exploited in active strategies to reduce chatter. For instance, the use of piezoelectric actuators to design a fast tool servo capable of precise machining [10,11]. Regarding turning and boring operations, several control strategies have been proposed using piezoelectric material as transducers [12]. Alternatively, the objective of this manuscript is to investigate a passive strategy to reduce chatter using piezoelectric material as shown in Fig. 1.

The use of piezoelectric shunt damping for passively improving the stability limit in turning process has been firstly investigated numerically by [13]. This investigation has been performed through the formulation of an electromechanical distributed model, evaluated along with different shunt circuits. This circuit is responsible for energy dissipation providing extra damping to the system yielding a more stable machining process. Recently, optimization strategies have been employed to properly select the electrical components of the shunt circuits by [14] and an availability study have been addressed in [5]. Nevertheless, the lack of experimental results jeopardizes the demonstration of the proposal capabilities.

In the present manuscript, experimental results demonstrate the capability of a proposed passive strategy based on piezoelectric material and shunt circuits to reduce chatter instability. The proposed technique employees piezoelectric layers embedded in the tool-holder and connected to a passive shunt circuit as illustrated in Fig. 2. In order to demonstrate the capabilities of the proposed technique, theoretical aspects are briefly introduced. Based on [6], the proportional relation between damping and stability limit is clarified in Section 2. Based on [13,15], an electromechanical model of the tool holder and the embedded piezoelectric layers is briefly introduced and numerical results access the proposal potentialities also in Section 2. In Section 3, experimental results demonstrate that the proposed passive strategy can be a feasible alternative for chatter avoidance. In this section, frequency response functions (FRFs) of the tool-holder with different shunt strategies are compared demonstrating how damping can be modified. Moreover, two different shunt strategies are exploited during a boring operation. The quality of the surface finishing are then compared and major conclusions are presented in Section 4.

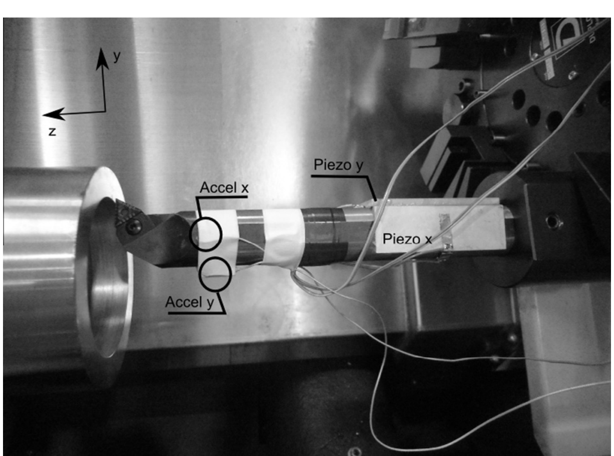

Fig. 1. The coordinate system: workpiece, the tool-holder, piezoelectric layers and the coordinate system.

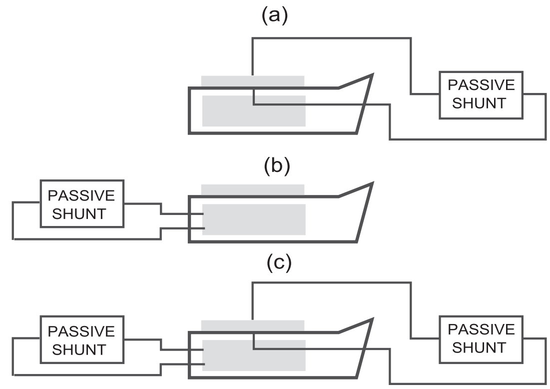

Fig. 2. Piezoelectric layers and the damping reduction strategy: (a) passive shunt at x-direction, (b) passive shunt at y-direction and (c) passive shunt at both directions.

2. Numerical methodology and results

In this section, the potentialities of the use of piezoelectric material and shunt circuits are numerically exploited. Firstly, the relation of the system stability limit and structural damping is derived. Secondly, an electromechanical model of the tool holder and the embedded piezoelectric layers is briefly introduced. Finally, numerical results demonstrate that the shunt circuits are alternatives to increase structural damping yielding a more stable machining process.

2.1. The importance of damping in regenerative chatter

For a certain combination of process parameters (e.g. depth-of-cut, spindle speed), large chip thickness variation can occur due to the modulations left on the surface during the successive cuts. This variation yields large forces and displacements promoting chatter. This regeneration process, the most common reason behind the phenomenon of chatter instability, is illustrated in Fig. 3.

For sake of simplicity, it is assumed that the tool-holder presents some flexibility in the cutting force direction allowing modulations on the surface. Nevertheless, the experimental results exploited in Section 4 clearly show that there is an important coupling factor between the different directions illustrated in Fig. 1.

Considering T as the spindle revolution period, $w(t)$ and $w(t-T)$ as the displacements at two successive cuts, h_0 as the nominal (static) depth-of-cut, the instantaneous depth-of-cut can be defined as $h_i(t) = h_0(t) + w(t-T) - w(t)$. A common hypothesis

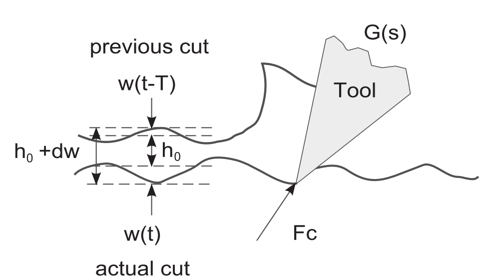

Fig. 3. The regeneration process (modified from [5]).