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Hardware-in-the-loop simulator for stability study in orthogonal cutting

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ABSTRACT

The self-excited vibrations due to the regenerative effect, commonly known as chatter, are one of the major problems in machining processes. They cause a reduction in the surface quality and in the lifetime of mechanical elements including cutting tools. Furthermore, the experimental investigations of chatter suppression techniques are difficult in a real machining environment, due to repeatability problems of hard to control parameters like tool wear or position dependent dynamic flexibility. In this work, a mechatronic hardware-in-the-loop (HIL) simulator based on a flexible structure is proposed for dimensionless study of chatter in orthogonal cutting. Such system reproduces experimentally, on a simple linear mechanical structure in the laboratory, any stability situation which can be used to test and optimise active control devices. For this purpose, a dimensionless formulation is adopted and the delay related to the phase lag of the actuator and the controller employed on the HIL is compensated.

1. Introduction

The presence of self-excited vibration, also known as chatter, in machining processes is a classic problem that limits material removal capability. The presence of these vibrations on machines is disastrous since they prevent obtaining the required surface finishes and decrease the lifetime of tools and mechanical components of the machine.

The principal reason of chatter onset is the regenerative effect, which was defined by Tobias (1965) and Tlusty and Polacek (1963) as a complex phenomenon affected by machining characteristics (spindle speed, depth of cut) and dynamic properties of the machine (stiffness and mass distribution, damping). Later on, Merrit (1965) presented the problem as a feedback loop, clarifying the understanding of the problem. All these theoretical and experimental developments were focused on continuous processes such as turning operations. More recently, studies about milling processes have been performed (Altintas & Weck, 2004; Munoa, Zatarain, Dombovari, & Yang, 2009; Quintana & Ciurana, 2011). In these investigations, the stability lobe diagrams define the limiting values for machining parameters in order to assure a stable cut. Therefore, such diagrams are usually employed to optimise the material removal rate.

Many researchers have proposed methods to avoid regenerative chatter for many years. Some of them are based on changing the spindle speed or tool geometry modification, while other authors proposed the distortion of the regenerative effect by a continuous spindle speed variation (SSV) (Altintas & Weck, 2004; Quintana & Ciurana, 2011). One of the most employed methods is to locate a tuned vibration absorber in the structure (Sims, 2007; Yang, Munoa, & Altintas, 2010). Passive devices can be appropriate in many cases, but they present limitations when dynamic characteristics can vary considerably. Active control can overcome these limitations due to its adaptability to changing conditions (Cowley & Boyle, 1970; Pan et al., 1996; Bilbao-Guillerna, Barrios, Mancisidor, Loix, & Muñoa, 2010; Munoa et al., 2013; Monnin, Kuster, & Wegener, 2014a, 2014b). Generally, such active actuators are based on the introduction of a controlled force associated to the measurement of a parameter related to the vibration. In this way, a dynamically correlated external energy is applied into the structure of the machine.

Nonetheless, the optimisation of these chatter suppression methods requires a big number of factual experiments. These tests may be very problematic, due to the large number of uncertain machining parameters (tool wear, material properties) and unavoidable cutting tests. Furthermore, the chatter characterisation process always forces the whole system to reach the stability limit and this may decrease the lifetime of several elements of the machine tool.

In this context, this work proposes the development of a

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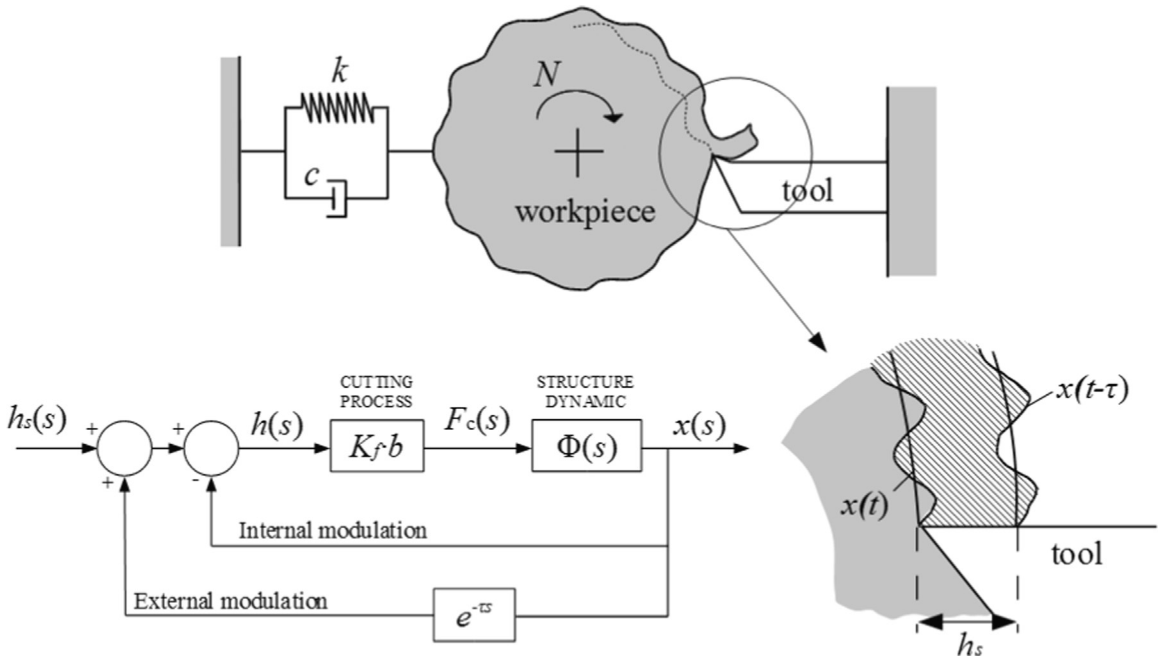

Fig. 1. Regenerative chatter vibrations in orthogonal cutting process.

mechatronic hardware-in-the-loop (HIL) system for simulating an orthogonal cutting process. In this way, such HIL simulator reproduces experimentally, on a simple mechanical structure, an equivalent cutting process where regenerative chatter can appear depending on the cutting parameters. This kind of systems can be used for testing the influence of different parameters inside the chatter formulation and active and passive chatter suppression methods can be experimentally tested and optimised by non-destructive testing. Nevertheless, such HIL simulation systems include some disadvantages. On the one hand, complex systems, where several modes can interact, cannot be reproduced accurately yet. On the other hand, only the vibration level is analysed, while other parameters such as surface finishing or chip breakage quality are not taken into account.

HIL systems have been widely employed in several industries such as automotive (Kendall & Jones, 1999). However, in manufacturing, few studies have been conducted based on such simulators. Different authors proposed the construction of different HIL simulators for reproducing machining processes (Ganguli, Deraemaeker, Horondica, & Preumont, 2005; Huyanan, 2007). However, they were built for a particular case and the delay that usually exists in mechatronic systems was neglected. The non-consideration of such delay changes drastically the regenerative effect and thus, the obtained results are not correlating properly with the theoretical stability diagrams.

The present work describes a HIL system for orthogonal cutting operations. It permits the simulation of machining process where the stability is dominated by a single mode. More complex machining operations, such as milling, could be simulated by means of a structure with more than one DOF, using more shakers to simulate complex dynamic forces in three dimensions and adapting the algorithm of the controller (Ganguli, 2005). However, the simulation of operations where more than one mode interacts in the same frequency range is a limitation for the system. In these cases, the ratio between natural frequencies and dynamic flexibilities of different modes produce intricate stability lobes diagrams (Munoa et al., 2009).

A dimensionless formulation is proposed in order to perform the dimensional analysis based on Fourier's principle of dimensional homogeneity, which states that an equation linking physical quantities must be dimensionally homogeneous (Huntley, 1967). The HIL system provides the possibility of simulating equivalent conditions of any orthogonal cutting process by adjusting the HIL relative damping to the damping of the desired system. A methodology to adjust this damping and the non-negligible delay is presented. Accurate results can be obtained and the experimental tests to optimise active control strategies can be extremely simplified.

2. Regenerative chatter in orthogonal cutting process

A brief explanation of the regenerative effect is offered in this section. First, the problem is mathematically formulated and then, a dimensionless approximation of this problem is proposed.

2.1. Formulation of the regenerative effect

Machine tool chatter vibrations result from a self-excitation mechanism in the generation of chip thickness during machining operations (Tobias, 1965; Tlusty & Polacek, 1963; Merrit, 1965; Altintas & Weck, 2004). Initially, cutting forces excite the structural modes of the machine tool–workpiece system and a wavy surface ($x(t-\tau)$) is left on the workpiece. In next revolution, this wavy surface is removed and, at the same time, a wavy surface ($x(t)$) is left owing to structural vibrations. This process is clearly shown in a groove turning operation (see Fig. 1).

Depending on the phase shift between two successive waves, the maximum chip thickness h may exponentially grow. The growing vibrations increase cutting forces $F_c(t)$, which depend on the chip thickness, and the process can become unstable. The general chip thickness can be expressed as follows:

$$h(t) = h_s - [x(t) - x(t-\tau)] \quad (1)$$

where h_s is the nominal feed per revolution, and $[x(t)-x(t-\tau)]$ is the dynamic chip thickness produced by actual vibrations ($x(t)$) and previous period vibrations ($x(t-\tau)$). It is well known that the variable cutting force $F_c(t)$ can be considered proportional to the frontal chip area, which is defined by the the chip thickness $h(t)$