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Vibration absorber design to suppress regenerative chatter in nonlinear milling process: Application for machining of cantilever plates

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ABSTRACT

In this paper, a tunable vibration absorber (TVA) is designed to suppress regenerative chatter in milling of cantilever plates. In machining industry, the majority of work-piece materials or the interaction of work-piece/cutting tool causes the cutting forces to demonstrate nonlinear behavior. The application of TVA (as a semi-active controller) is investigated for the process with an extensive nonlinear model of cutting forces. Under regenerative chatter conditions, optimum values of the absorber position and its spring stiffness are found such that the plate vibration is minimized. For this purpose, an optimal algorithm is developed based on mode summation approach. Results are presented and compared for two cases: regenerative chatter under resonance and non-resonance conditions. It is shown that the absorber acts efficiently in chatter suppression of both machining conditions, in a wide range of chatter frequencies. Moreover, using TVA leads to the great improvement in stability limits of the process. Therefore, larger values of depth of cut and consequently more material removal rate can be obtained without moving to the unstable machining conditions.

1. Introduction

One of the major machining processes is the peripheral milling. It is especially implemented in aerospace industries where the end mills are used for milling of wing parts and engine components. However, its appropriate performance may be unreachable due to existence of various types of vibrations. In machining processes, self-excited vibration or chatter is the most important type of vibration. Reduction of tool life, poor surface quality and decrease in productivity rate are the adverse affects of chatter vibrations.

Machine tool chatter is caused either by regeneration or mode coupling, as two well known mechanisms. In machining processes, the regenerative type is found to be the most important mode of chatter vibration. It occurs when the cut produced at time t leaves a wavy surface on the material regenerated during subsequent passes of cut (Fig. 1). The phase difference between the inner and outer waves and the dynamic gain of the system play a key role in stability of the cutting process. In second mechanism, when there is no interaction between the vibration of the system and undulated surface of

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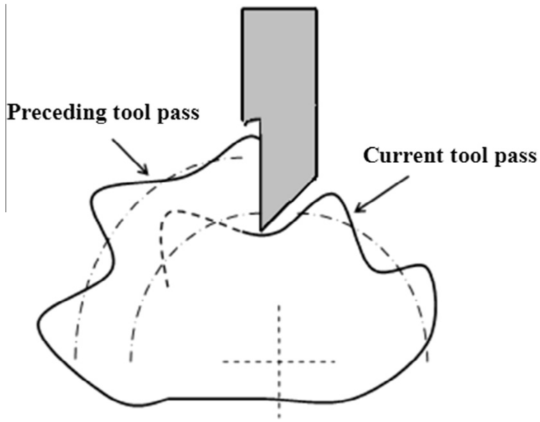

Fig. 1. Chatter instability caused by the regeneration mechanism.

the work-piece, usually mode coupling occurs. Consequently, the tool traces out an elliptic path that varies the depth of cut in such a way as to intensify the coupled modes of vibrations [1].

For the purpose of chatter prediction in high speed and high precision cutting processes, accurate models are required. To obtain dynamic equations of various milling processes and prediction of cutting forces, deflection of machine components and form errors, mechanistic approach has been extensively used [2,3]. In milling process, when the cutter has a uniform pitch, the cutting forces are periodic at tooth passing intervals (due to multiple teeth cutter).

In milling process, chatter stability has been investigated in the frequency and discrete time domains for the linear models. Also, analytical solutions have been developed for direct prediction of stability lobes in the frequency domain [4] and prediction of stability limits in high-speed milling (while multi-mode dynamics is considered) [5]. In discrete time domain and for stability analysis, various methods have been used for direct inclusion of periodically varying system parameters. Time finite element analysis (TFEA) to investigate limit cycles and bifurcation behavior [6]; semi-discretization and full-discretization methods (SDM & FDM) for determination of stability lobes diagram [7–12]; and TFEA for simultaneous predictions of stability and surface location error have been used [13].

In addition, SDM and TFEA have been used in analytical prediction of chatter stability for variable pitch and variable helix tools [14]. Also, TEFA and Chebyshev collocation methods based on harmonic balance approach have been applied for stability analysis [15]. A comparison between frequency and semi-discrete time solutions of the chatter stability [16]; and a fuzzy stability analysis for different domains have been presented [17].

Due to recent machining of materials with severe nonlinear characteristics, nonlinear modeling of the chatter phenomenon has received more attention. Considering the square and cubic polynomial terms related to the cutting forces, structural stiffness and power-law functions for cutting forces, delayed nonlinear models of the process have been governed [18–21]. Also, other sources of nonlinearity in machining processes have been recognized including the visco-elastic and hysteresis effects, variable friction, thermo-mechanical effect and intermittent engagement of the cutting tool [22].

In the previous researches [23,24], the extended nonlinear modeling of cutting forces and development of closed form expression through Fourier series expansion have been accomplished. Considering the structural and cutting forces nonlinearities, dynamics of regenerative chatter and internal resonance phenomenon was investigated [23]. In other research, nonlinear dynamics and bifurcation analysis of the milling process in the presence of tool wear, process damping and cutting force nonlinearities was studied [24].

To suppress regenerative chatter in machining processes, various passive and active control approaches have been used. Tunable vibration absorbers and tuned viscoelastic dampers for turning [25,26], boring [27,28] and milling processes have been used as some effective passive techniques [29,30]. Also, for the case of nonlinear cutting forces in milling operations, a tunable vibration absorber was designed to suppress regenerative chatter and improve stability limits of the process [12].

It should be mentioned that in the previous work [12], tunable vibration absorbers (TVAs) were designed to suppress regenerative chatter of the milling process in which the cutting tool was modeled as an Euler–Bernoulli beam (as a continuous vibrating system). That case essentially occurs when a relatively long extension part is used (in milling processes where the access to the work-piece is difficult due to work-space limitations). In [12], the work-piece dynamics was assumed to be rigid and all the structure flexibility was considered in the cutting tool. In this research (unlike [12]), the cutting tool is modeled as a lumped rigid 2DOF model (due to its short length), while all the structural flexibility is considered in the thin plate work-piece. Therefore, the scope of current research is completely different from the previous [12], both in physical implementation and engineering applications.

Moreover, to avoid chatter vibrations, the changing and selection of spindle speed have been studied [31–34]. In the category of active vibration control, various works have been developed such as active vibration absorbers [35] and model reference adaptive control to achieve constant cutting forces, e.g., [34,36]. In addition, active control systems for chatter