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Tunable vibration absorber for improving milling stability with tool wear and process damping effects

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ABSTRACT

This paper deals with the problem of chatter suppression in milling process in order to achieve higher precision, better surface quality and larger material removal rate (MRR). The peripheral milling process is modeled as a two degrees of freedom system and the effects of tool wear and process damping are considered. It is shown that when regenerative chatter develops, both tool wear and process damping act as stabilizing factors. For larger values of depth of cut and consequently higher MRR, tunable vibration absorbers (TVA) (in x–y directions) are designed to improve stability. An optimal algorithm is developed which determines the optimum values for absorbers' parameters. The effects of tool wear, process damping and absorbers on the frequency response of the system and on the stability lobe diagram of the process are investigated. It is shown that the deigned absorber set is robust against parametric uncertainties associated with the dynamic model.

1. Introduction

Peripheral milling is extensively used in manufacturing processes, especially in aerospace industry where end mills are used for milling of wing parts and engine components. The increasing demand for higher productivity and the advances in technologies related to machines and cutting tools, and high speed machining has signified the need for more productive milling processes. However, the occurrence of self-excited vibration or chatter is a hindering factor because it may cause high tool wear, tool fracture, damage to the cutting tool or spindle bearings, poor surface finish and poor dimensional accuracy of the work-piece. Therefore, it is essential to investigate this dynamic system based on more accurate modeling of the dynamics of the milling process.

In the early works related to milling dynamics, mean cutting force coefficients have been used for modeling and simulation of cutting forces [1]. This mechanistic approach was used to obtain the dynamic equations of various milling processes or to predict the deflections and form errors of the machined components [2]. In this approach, cutting force coefficients are obtained using experimental data under certain cutting conditions. Alternatively, the mechanics of cutting were used for determination of milling force coefficients. In this method, after determination of the flank forces, friction and shear angles from the orthogonal cutting test, the mechanics of the milling process was used for transforming of orthogonal data to oblique cutting conditions [3,4].

Frictional properties at the tool–workpiece interface affect the dynamic cutting force characteristics and consequently the process stability and production rate. The effect of friction on milling forces has been studied in other works. In an early work, the flank wear model for milling process was presented considering the abrasion and diffusion mechanisms, thermal fatigue effect and number of teeth [5]. Also, tool flank wear effects have been modeled through an analytic mechanistic model of milling process [6]. Various methods have been used for on-line tool wear measurement. Some of the other works, for instance, include using averaged cutting force data to predict the width of tool flank wear [7,8], application of sensor signals and developing a cutting power model for tool wear monitoring [9,10] and adaptive network based inference system for estimation of flank wear [11].

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Process damping (arisen from cutter-workpiece interaction) has a significant role on increasing stability in machining, especially at low cutting speeds. Identification of process damping from tool vibration measurements [12], dynamic modeling and mechanistic modeling of milling with process damping [13,14], and identification of cutting force coefficients and chatter stability with process damping [15] represent some of the works on process damping in recent years. More recently, a practical identification and modeling of process damping coefficients based on chatter tests has been presented that determines the indentation force coefficient responsible for the process damping through energy analysis [16]. As an alternative to the models in the frequency domain, discrete time domain models have also been used for direct inclusion of periodically varying system parameters and process damping effects in stability analysis of the milling process [17,18].

Various passive strategies have been used to suppress regenerative chatter. Among the passive techniques, tunable vibration absorbers and tuned viscoelastic dampers in turning [19], boring [20–22] and milling processes [23,24] have been used for chatter suppression. Also, change of spindle speed for the chatter avoidance and chatter prevention by acoustic signal feedback have been investigated [25,26].

Precision milling processes usually require high dimensional accuracy in spite of the tool wear and variations in cutting conditions and dynamic properties of the machine tool system. In this paper, a tunable vibration absorber (TVA) is introduced for chatter suppression in milling process considering the tool wear and process damping effects. Optimum values for the absorber parameters are determined through an optimal algorithm developed in MATLAB. Frequency responses and stability lobes diagram of the system with/without tool wear, process damping and absorber are obtained and compared. Simulation results are presented in the time domain as well as their corresponding root locus analysis. The robustness of the deigned absorber set against parametric uncertainties associated with the dynamic model is investigated.

2. Dynamics of peripheral milling with tool wear and process damping effects

Regenerative chatter is the main chatter type that hinders achieving high production rate in most machining processes. It occurs when the cut produced at time t leaves small waves in the material that are regenerated during subsequent passes of cut. Dynamics of the milling process and the milling cutter is shown in Fig. 1. The immersion angle (ϕ) is measured clockwise from the y-axis and the axial (a) and radial (w_c) depths of cut are constant. Taking the bottom end of one flute as the reference immersion angleϕ, the bottom end points of other flutes are described at angles $\phi_j(0) = \phi + j\phi_p$; $j = 0, 1,..,(N-1)$ where $\phi_p = 2\pi/N$ is the cutter pitch angle and N is the number of cutter teeth. Considering the cutting coefficients contributed by the shearing and edge actions in tangential (K_{tc}, K_{te}) and radial (K_{rc}, K_{re}) directions (neglecting force component in the axial direction in this 2D modeling), the acting cutting forces are expressed as [3]:

$$\begin{aligned} F_t\left(\phi_j\right) &= K_{tc}\, a\, h\left(\phi_j\right) + K_{te} a \\ F_r\left(\phi_j\right) &= K_{rc}\, a\, h\left(\phi_j\right) + K_{re} a \end{aligned} \tag{1}$$

where $h(\phi_j)$ is the variable total chip thickness and a is the axial depth of cut (constant). For the tooth number$j$, the component of the dynamic displacement vector in the radial (i.e. chip thickness) direction is $v_j = -x \sin \phi_j - y \cos \phi_j$ where $\phi_j(t) = \Omega t$ and Ω is the spindle speed. In the presence of regenerative chatter, the variable total chip thickness is expressed as:

$$h\left(\phi_j\right) = \left[c_f \sin\phi_j + v_{j,0} - v_j\right] g\left(\phi_j\right) \tag{2}$$

where c_f is the feed per tooth per revolution; $c_f \sin \phi_j$ is the static part of the chip thickness caused by rigid body motion of the cutter and $v_{j,0} - v_j$ is the dynamic part; produced due to vibrations of the tool at the present (v_j) and previous ($v_{j,0}$) tooth periods.

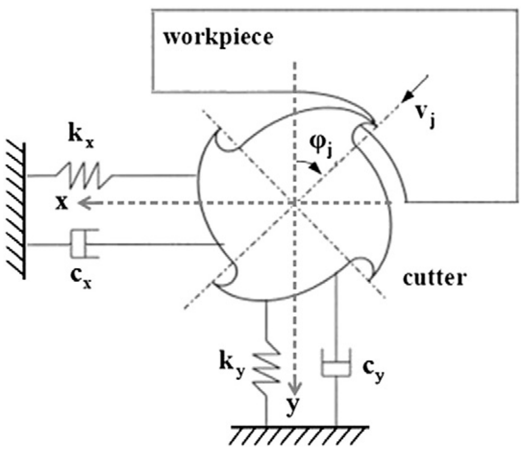

Fig. 1. Dynamics of the milling process.