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Global optimization and design of dynamic absorbers for chatter suppression in milling process with tool wear and process damping

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Abstract

Peripheral milling is extensively used in manufacturing processes, especially in aerospace industries where end mills are used for milling of wing parts and engine components. The generation of complex shapes with high quality for various types of materials is the main advantage of milling in contrast to other machining processes. During the milling process, the occurrence of self-excited vibrations or chatter may cause reduction in material removal rate (MRR), damage to the tool and spindle bearing or may result in poor dimensional accuracy and surface finish of the work-piece. In this paper, milling process is modeled as two degrees of freedom (2DOF) system in which the tool wear and process damping effects are considered. To suppress regenerative chatter (or self-excited vibrations), optimum tunable vibration absorbers (in x-y directions) are designed. A sophisticated optimization algorithm is developed to determine the optimum values of the absorber parameters (their mass and stiffness). The effects of tool wear, process damping and absorbers are investigated on the frequency response of the system. Results are presented in the time and frequency domains. According to the results, both of the tool wear and process damping play as stabilizing factors of the dynamic system; under regenerative chatter and unstable machining conditions. However, tuned vibration absorbers are implemented to achieve the global stable conditions. The robustness and efficiency of deigned absorbers are investigated for the uncertain dynamic model. It is shown that after implementation of the absorbers, higher material removal rate (MRR) can be achieved while the stability of the nominal and uncertain processes is guaranteed.

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Keywords: Peripheral milling; Process damping; Tool wear; Absorbers' optimization; Chatter suppression.

1. Introduction

In order to create complex shapes with high quality, milling process is incorporated extensively. Mechanistic approach was used to model and analyze the milling process, governing dynamics equations and prediction of the cutting forces [1].

Tool life, surface quality and productivity rate are affected adversely by self-excited vibration or chatter in machining processes. The major reasons for machine tool chatter are: regeneration and mode coupling. When the cut produced at time t leaves a wavy surface on the material during subsequent passes of cut, regeneration occurs in the process. When the tool traces out an elliptic path that varies the depth of cut and the coupled modes of vibration are bolstered, mode coupling occurs. Among the two stated reasons, the regenerative type is the main hindrance to the production rate.

To suppress the regenerative chatter, miscellaneous passive and active methods have been implemented. Tunable and optimal vibration absorbers and tuned viscoelastic dampers which have been used for chatter suppression in turning and milling processes are among the passive methods, respectively [2, 3]. Also, spindle speed regulation and acoustic signal feedback have been investigated to avoid the chatter phenomenon [4, 5]. Use of model reference adaptive control to achieve constant cutting forces as an active control method has been studied [4]. Additionally, piezoelectric active/optimal vibration control systems have been considered to suppress the chatter vibration [6, 7].

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In this paper, tunable vibration absorbers-TVAs- (in x-y directions) are designed to attenuate the chatter vibrations for the milling process. Unlike the previous works, tool wear, process damping effect (dominant at low spindle speeds) and model parametric uncertainties are considered to have a more realistic model. A multi-loops, sophisticated algorithm for determining the optimum values of absorbers parameters is developed in MATLAB environment. Frequency response of the system is obtained for the nominal and uncertain models with/without absorbers. It is observed that process damping (and similarly, tool wear) improves the stability of the nominal and uncertain processes. In the presence of uncertainties, TVAs guarantee the chatter suppression over a wide range of chatter frequencies. Finally, it is shown that TVAs improve the stability lobes diagram of the process. Through the use of the optimal absorber, production rate increases; while nominal/uncertain models are maintained in stable conditions.

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

In Fig. 1, dynamics of the milling process is represented. Assuming the reference immersion angle ϕ_0 at the bottom end of one flute, bottom end points of other flutes are at $\phi_j = \phi_0 + j\phi_p;\ j = 0,1,..,(N-1)$ where $\phi_p = 2\pi/N$ is the cutter pitch angle. Dynamic displacements for the tooth number j, in the radial or chip thickness direction is in the form $v_j = -x\sin\phi_j - y\cos\phi_j$ where $\phi_j(t) = \Omega t$ and Ω is the spindle speed. Total chip thickness can be written in the form:

$$h(\phi_j) = [c_f \sin\phi_j + v_{j,0} - v_j]\, g(\phi_j) \tag{1}$$

where c_f is the feed rate per tooth, $c_f \sin\phi_j$ and $v_{j,0} - v_j$ are respectively, the static and dynamic part of the chip thickness, caused by rigid body motion of the cutter; produced due to vibrations of the tool at the present (v_j) and previous ($v_{j,0}$) tooth periods. $g(\phi_j)$ is a unit step function which is described in terms of start (ϕ_{st}) and exit immersion (ϕ_{ex}) angles of the cutter, and determines whether the tooth is in or out of cut.

$$g(\phi_j) = \begin{cases} 1 & \phi_{st} < \phi_j < \phi_{ex} \\ 0 & \phi_{st} > \phi_j \ \text{ or } \ \phi_{ex} < \phi_j \end{cases} \tag{2}$$

The static part of the chip thickness $c_f \sin\phi_j$ has no effect in dynamic regeneration mechanism, Eq. (1) is rewritten as:

$$\begin{aligned} &h(\phi_j) = [\Delta x \sin\phi_j + \Delta y \cos\phi_j]\, g(\phi_j) \\ &\Delta x = x(t) - x(t-\tau),\ \ \Delta y = y(t) - y(t-\tau),\ \tau = 2\pi/(N\Omega) \end{aligned} \tag{3}$$

in which $[x(t), y(t)]$, $[x(t-\tau), y(t-\tau)]$ indicate cutter displacement at the present and previous tooth periods, τ is the delay time, N is the number of tool teeth and Ω is the spindle speed in (rad/s) . Tangential (F_t) and radial (F_r) forces are described in terms of the chip thickness (h) and cutting force coefficients contributed by the shearing and edge actions in tangential (ζ_1, ζ_2) , radial (η_1, η_2) directions, as [8]:

$$F_t = \zeta_1 h + \zeta_2 \ \ ; \ \ F_r = \eta_1 h + \eta_2 \tag{4}$$

Based on coordinates represented in Fig. 1, elemental forces in feed(x) and normal(y) directions are expressed as:

$$\begin{aligned} F_{xj} &= -F_{tj}\cos\phi_j - F_{rj}\sin\phi_j \\ F_{yj} &= +F_{tj}\sin\phi_j - F_{rj}\cos\phi_j \end{aligned} \tag{5}$$

Substituting Eqs.(3) and (4) into Eq.(5), yields (for tooth j):

$$\begin{cases} F_x = -\Upsilon_1 [\Delta x \sin\phi + \Delta y \cos\phi] + \Upsilon_2 \\ F_y = \Upsilon_1' [\Delta x \sin\phi + \Delta y \cos\phi] + \Upsilon_2' \\ \Upsilon_i = \zeta_i \cos\phi + \eta_i \sin\phi;\ \ \Upsilon_i' = \zeta_i \sin\phi - \eta_i \cos\phi;\ i = 1,2 \end{cases} \tag{6}$$

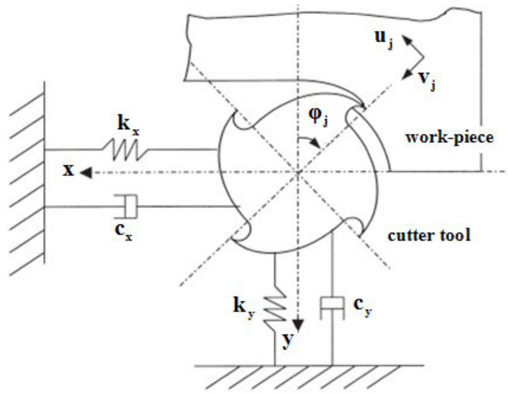

Fig. 1. Dynamics of the milling process as two degrees of freedom system (Source: [7]).

The matrix form of Eq. (6) is in the form:

$$[F_x \ \ F_y]^T = [\mathrm{M}(\phi)]\{\Delta x, \Delta y\} \tag{7}$$

Eq. (7) is rewritten in the matrix form, in time domain as,

$$\{F(t)\} = [\mathrm{M}(t)]\{\Delta t\}$$

because angular position varies with time ($\phi_j = \Omega t$). Since $[\mathrm{M}(t)]$ is periodic at tooth passing frequency, it can be expanded into Fourier series as:

$$\begin{aligned} &[\mathrm{M}(t)] = \sum_{r=-\infty}^{\infty} [\mathrm{M}_r] e^{irN\Omega t} \\ &[\mathrm{M}_r] = (1/\tau) \int_0^{\tau} [\mathrm{M}(t)] e^{-irN\Omega t}\, dt \end{aligned} \tag{8}$$

The number of harmonics ($\bar{r}$) of tooth passing frequency ($N\Omega$) which must be considered for a precise reconstruction of $[\mathrm{M}(t)]$, is found based on the immersion conditions and the number of teeth in cut. Since half immersion up-milling with four teeth is considered as a case study here, the average components of the Fourier series expansion ($\bar{r} = 0$) is sufficient [9]. In this case:

$$[\mathrm{M}_0] = (1/\tau) \int_0^{\tau} [\mathrm{M}(t)]\, dt \tag{9}$$

For any other machining condition, in which the cutting force signals are measured, the same procedure can be implemented. Since $[\mathrm{M}_0]$ is valid when $g_j(\phi_j) = 1$, it equals the average value of $[\mathrm{M}(t)]$ on cutter pitch angle as:

$$[\mathrm{M}_0] = (1/\phi_p) \int_{\phi_{st}}^{\phi_{ex}} [\mathrm{M}(\phi)]\, d\phi \tag{10}$$

The average cutting force is independent of the helix angle, as a result $[\mathrm{M}_0]$ is valid for both helical end mills and those with zero helix angle [9]. Following out the integral of Eq. (10) on F_x, F_y, given by Eq. (6), while using Eq. (7) yields:

$$F_x = -\frac{N}{2\pi}(\alpha\,\Delta x + \beta\,\Delta y + \gamma)\ ;\ F_y = \frac{N}{2\pi}(\alpha'\,\Delta x + \beta'\,\Delta y + \gamma') \tag{11}$$