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Cumulative Surface Location Error for milling processes based on tool-tip Frequency Response Function

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Abstract

In milling processes, the desired machined surface cannot be perfectly achieved even in case of chatter-free machining due to the thermally induced errors, the trajectory following errors and the most significant one: the cutting force induced vibration errors. In case of vibration, the error is represented by the so-called Surface Location Error (SLE), which is the distance between the machined and the required surface position. In case of roughing operations, these errors can have a significant impact on the surface position due to the interaction between the subsequent SLEs. The machined surface depends on the previously resulted SLE through the variation of the radial immersion. In this paper, the series of the consecutive SLEs are investigated in a multi-degree-of-freedom model. The dynamical behaviour of the milling tool is described by frequency response functions. The variation of the SLE values is governed by a discrete map, which may lead to an unpredictable final surface position. The parameter range where this unpredictable final SLE occurs is presented together with the traditional stability chart representing the chatter-free domains of cutting parameters. With the proposed methods, the traditional stability chart can be improved, from which chatter-free and CSLE-stable technological parameters can be selected.

1. Introduction

In industry, milling is a widely used manufacturing method. This machining process may induce harmful vibrations which are responsible for unacceptable surface quality. These vibrations are classified into two groups [1]. One of them is the self-excited vibration that is due to the loss of stability typically related to the surface regeneration effect [2]. This effect can be modelled with delay-differential equations (DDE) [3]. The other type of vibration is the large amplitude forced vibration near to resonant spindle speeds [4]. These forced vibrations lead to the so-called *Surface Location Error* (*SLE*), which is the largest deviation between the machined and the desired surface.

The so-called stability chart [5] presents the chatter-free (stable) parameter domain which is usually illustrated in the plane of the spindle speed and the axial immersion. It can be calculated by means of methods in frequency domain or in time-domain [6-10]. The stability boundary has pockets between the so-called stability lobes typically around the resonant spindle speeds. The most productive chatter-free parameter regions are located in these pockets, however, large amplitude vibrations occur there due to the resonant excitation of the periodic milling force, which leads to substantial *SLE* [11]. The stability chart is useful during the roughing operations. Due to the fact that *SLE* is relevant at finishing operations [12], its effect is usually neglected in the model of roughing operations. Despite this, the *SLE* can still have significant impact on the surface quality in case of consecutive immersions during roughing, which is used to remove the oversize of a workpiece.

At each immersion, the machined surface differs from the desired one due to the Surface Location Error. This current offset error modifies the next radial immersion and generates different cutting force, which leads to a modified *SLE* at the subsequent immersion. During this process, the *SLE* can be
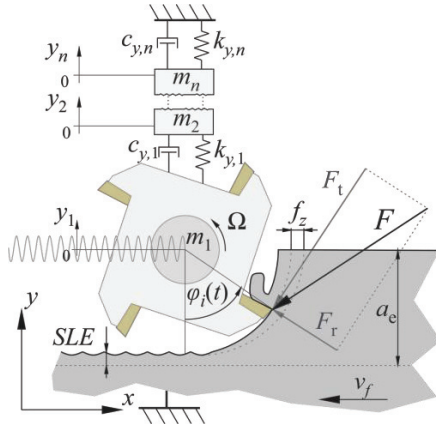
Fig. 1. Mechanical model of the milling process and representation of the *Surface Location Error* (*SLE*)

accumulated immersion-by-immersion which converge to a certain value, which is called *Cumulative Surface Location Error* (*CSLE*) [13, 14].

In this paper the evaluation of the series of *SLE* values is investigated in milling operations by means of a multi-degree-of-freedom model with multiple modes based on measured tool-tip frequency response functions (*FRF*).

2. Forced vibration

In what follows, the main steps of the *SLE* computation are summarised based on [15]. The quality of the machined surface, specifically, the Surface Location Error (SLE) is determined numerically in case of a straight fluted tool.

In the mechanical model, the workpiece is considered as a rigid body and the cutting tool is modeled as shown in Fig. 1. This assumption is valid for long thin peripheral milling tools. The *SLE* is influenced by the vibration perpendicular to the machined surface only, hence, the modes are projected to the y direction. The stable (chatter-free) forced vibration of the tool centre can be described by a non-homogeneous ordinary differential equation in the following form:

$$\mathbf{M\ddot{y}}(t) + \mathbf{C\dot{y}}(t) + \mathbf{Ky}(t) = \mathbf{Q}(t) \tag{1}$$

where the generalized coordinates are arranged in the column vector $\mathbf{y}(t) = [y_1(t), y_2(t),…, y_n(t)]^T$, the dynamical parameters of the tool are defined in the modal matrices $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$, and the resultant cutting-force acting on the tool-tip is included in the general force $\mathbf{Q}(t) = [F_y(t), 0, …, 0]^T$. In the applied model, the linear force model [5] is used to describe the cutting force, where the magnitude of the resultant force is linearly proportional to the current chip thickness and chip width [15]:

$$F_y(t) = \sum_i^N a_p f_z \sin(\varphi_i(t)) \cdot g_i \cdot (\varphi_i(t)) \cdot (K_r \cos(\varphi_i(t)) - K_t \sin(\varphi_i(t))) \tag{2}$$

where N is the number of teeth, a_p is the axial immersion, f_z is the feed per tooth, $\varphi_i(t)$ is the angular position of the ith cutting edge, $g_i(\varphi_i(t))$ is the screen function which indicates that the ith edge is in contact with the material ($g = 1$) or not ($g = 0$). K_r and K_t are the radial and tangential cutting force coefficients, respectively. The current angular position of the ith cutting edge is

$$\varphi_i(t) = \Omega t + \frac{2\pi \cdot (i-1)}{N} \tag{3}$$

where Ω is the angular spindle speed in rad/s. The intermittent cutting force leads to periodic force excitation. The resulting forced vibration is copied to the surface during the cutting processes and creates surface errors.

The periodic motion of the tool is determined after the Fourier transformation of the equation of motion (Eq. (1)):

$$\mathbf{\Psi}(\omega) = \left(-\omega^2 \mathbf{M} + i\omega \mathbf{C} + \mathbf{K}\right)^{-1} \cdot \mathbf{\Phi}(\omega) \tag{4}$$

where $\mathbf{\Phi}(\omega)$ and $\mathbf{\Psi}(\omega)$ are the Fourier transforms of the general force $\mathbf{Q}(t)$ and displacement vector $\mathbf{y}(t)$, respectively.

During the numerical implementation, $\mathbf{\Phi}(\omega)$ is approximated by the Fast Fourier Transformation (*FFT*) of $\mathbf{Q}(t)$ defined by Eq. (2), and $\mathbf{y}(t)$ is calculated by means of the inverse Fast Fourier Transformation (*iFFT*) of the resultant $\mathbf{\Psi}(\omega)$ from Eq. (4). For the *SLE* computation, only the forced periodic vibration $y_1(t)$ of the tool-tip is needed in time domain. This scalar component can be defined based on the Measured tool-tip *FRF* ($H_{11}(\omega)$):

$$y_1(t) = iFFT\{H_{11}(\omega) \cdot \Phi_i(\omega)\}. \tag{5}$$

3. Surface Location Error

The surface contour is defined by the motion of the cutting edges and their forced vibrations, synchronized with the tooth passing frequency which lead to a constant offset error. The *Surface Location Error* (*SLE*) is the maximum distance between the milled and desired surface (see Fig. 1.) defined by:

$$Up - mill. : SLE = \min_i \left(-\frac{D}{2} \cos\varphi_i(t) + y_1(t) \right) + \frac{D}{2} \tag{6}$$

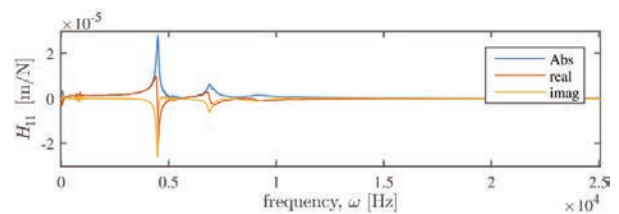$$Down - mill. : SLE = -\left(\max_i \left(-\frac{D}{2} \cos\varphi_i(t) + y_1(t) \right) - \frac{D}{2} \right) \tag{7}$$

Fig. 2. Measured FRFs at the tool-tip