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Chatter stability prediction in milling using speed-varying cutting force coefficients

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Abstract

Chatter prediction accuracy is significantly affected by reliability of data entry, i.e., cutting force coefficients and frequency response, both influenced by spindle speed. The evaluation of specific cutting force coefficients in High-Speed Milling (HSM) is challenging due to the frequency bandwidth of commercial force sensors. In this paper specific cutting coefficients have been identified at different spindle speeds: dynamometer signals have been compensated thanks to an improved technique based on Kalman filter estimator. The obtained speed-varying force coefficients have been used to improve the reliability of stability lobe diagrams for HSM, as proven by experimental tests.

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Keywords: Cutting Force Coefficients; HSM; Chatter; Dynamic compensation.

1. Introduction

Milling is the most common and versatile technology for machining process characterized by a wide range of metal cutting capability, that places it in a central role in manufacturing industry. Chatter vibration is one of the main limitation of milling process performance [1]. The occurrence of this unstable regenerative phenomenon produces poor surface finish, tool wear and breakage. In the last decades chatter has been widely investigated and different predictive models have been developed [2-4]. These models lead to a chart known as Stability Lobe Diagram (SLD), used to select stable machining parameters. Even if literature counts several complex and accurate predictive models generally based on time domain simulations (e.g., [3]), the most widely used method still refers to zero-order analytical approach [4] because its simplicity and efficient SLD evaluation.

Stability lobes diagrams accuracy is strongly affected by reliability of data entries, i.e., machine dynamics at the tool-tip and coefficients for cutting forces prediction. Both these parameters are influenced by spindle speed [5-10]: this is an issue for High-Speed Milling (HSM), where the cutting speed could change significantly. Moreover accurate SLD are useful especially in HSM: increasing spindle speed, typical diagram lobes are more spaced creating stable zones at high depth of cut that can be exploited for increasing productivity. Therefore investigation of tool-tip dynamics and cutting force coefficients dependence on cutting speed becomes crucial to improve milling performance.

Machine tool dynamics generally is identified as frequency response function (FRF) at the tool-tip by means of impact test on non-rotating tool. At high speed, tool-tip dynamics could change because of influence of gyroscopic effects and centrifugal forces. This aspect has been studied in literature [5-7] leading to conflicting results. These studies are focused mainly on FE modeling of spindle under operation condition. Increasing spindle speed Cao's [5] model predicts a shift in natural frequency and an increasing of damping in FRF reflecting in a slight change of the SLD; in the same way Gagnol et al. [6] confirm, in their model based stability, that lobe diagram generated from the non-rotating transfer function underestimates the allowable depth of cut, but in

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their study the difference between stationary and rotating is more significant. Furthermore Mañé [7] presents an integrated method to identify chatter stability considering workpiece dynamics and spindle dependent tool-tip FRF, in his work frequency shift between stationary and rotating FRF results quite considerable.

On the other hand Rantalo [8] built a contactless dynamic spindle testing (CDST) instrument in order to experimentally identify tool-tip FRF at high spindle speed: the results of his research show a slight increase on depth of cut limit in stability lobe diagram, suggesting an increase of damping on the FRF without notable differences on natural frequencies.

For what concerns coefficients, cutting process and chip formation mechanics change as cutting speed varies, thus reflecting in a change of cutting coefficients. This trend has been presented in [9,10], and it's relevant especially for tangential forces: according to these studies coefficients are high at low speed, showing a decrease and then increasing again in HSM area. There are mainly two ways to identify cutting force coefficients: coefficients obtained using the mechanics of cutting or specific coefficients from experimental results. For the first approach one of the most used method is the one developed by Budak et al. [11] and named orthogonal to oblique transformation: a general approach that could identify cutting force coefficients for different cutting tool and operation from data extracted from orthogonal cutting tests. The coefficients obtained using the mechanics of cutting are more general, they can be applied to any different tool geometry thanks to the orthogonal to oblique transformation; nevertheless this transformation implies some approximation errors. On the other hand there are different options related to the second approach to obtain the specific cutting coefficients from the experimental results, among them, the most advanced are based on average forces measurements per revolution in slot milling tests [1,12] but there are some methods based on simulation [13] and instantaneous coefficients. Specific coefficients are consistent only for the particular material and tool used in the experimental tests but this approach results more accurate. The evaluation of such coefficients with high speed milling tests is challenging due to the limited frequency bandwidth of commercial force sensors that results inadequate for high rotational speeds (dynamometer's natural frequency limits measurements to low speed).

The aim of the presented study is to improve the reliability of chatter prediction implementing a speed-dependent stability lobe diagram starting from analytical prediction theory [4]. This work is focused on cutting force coefficients influence and its variation with cutting velocity. Variation of FRF in the spindle range is negligible in this study. Milling tests at different speed have been carried out to identify cutting force coefficients without cutting mechanics approximation. In order to overcome dynamometer dynamics issues an improved compensation technique, based on Kalman filter estimator [14] was employed, as already used by authors in [15].

Based on cutting speed dependent force coefficients, a method to create analytical SLD has been developed, taking into account different cutting coefficients changing continuously with spindle speed. The reliability of obtained stability lobe diagram for HSM has been proved by experimental tests.

2. Cutting coefficients

Cutting force model proposed by Altintas [16] has been used for the evaluation of cutting forces. This model computes the force components by means of 6 coefficients as expressed in equation (1) where db and dl are the chip width and length for an infinitesimal section of the chip respectively.

$$\begin{aligned} dF_t &= K_{tc}t_n db + K_{te}dl \\ dF_r &= K_{rc}t_n db + K_{re}dl \\ dF_a &= K_{ac}t_n db + K_{ae}dl \end{aligned} \tag{1}$$

Identification of these coefficients has been carried out by average cutting force method [1] performing full-immersion (i.e., slotting) milling experiments to simplify identification. The average cutting forces can be expressed as a linear function of the feed rate, therefore average forces at different feed rates are measured and coefficients are estimated by data linear regression.

3. Speed-varying stability lobe diagram

Analytical chatter stability considering zero-order approximation [4] has been applied including speed-varying coefficients. Chatter critical depth of cut is:

$$a_{\lim} = -\frac{2\pi\Lambda_R}{NK_{tc}}(1+\frac{\Lambda_R}{\Lambda_I}) \tag{2}$$

where N is number of flutes, K_{tc} is tangential cutting force coefficient, Λ_R Λ_I are real and imaginary parts of the eigenvalues calculated from the stability Nyquist criterion:

$$\det\left[[I]-\frac{1}{2}K_{tc}a(1-e^{-i\omega_c T})[A_0(K_r)][\Phi(i\omega_c)]\right]=0 \tag{3}$$

where ω_c is chatter frequency, Φ is the directional FRF matrix and A_0 is the directional cutting coefficient matrix.
A_0 matrix is dependent on K_r, relative coefficient calculated as:

$$K_r = \frac{K_{rc}}{K_{tc}} \tag{4}$$

Consequently the depth of cut limit (2), needed to create SLD, is dependent on K_{tc} and K_{rc}. Chatter stability changes as these parameters vary.

In the case of spindle-speed-varying coefficients different approaches can be applied to build an accurate SLD. Cao [5] proposed a method based on the same stability theory but for FRF varying with spindle speed, his basic idea is to check stability (3) for discrete spindle speeds while increasing depth