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Technical note

Speed-varying cutting force coefficient identification in milling

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ABSTRACT

Accurate simulation of the machining process is crucial to improve milling performance, especially in High-Speed Milling, where cutting parameters are pushed to the limit.

Various milling critical issues can be analyzed based on accurate prediction of cutting forces, such as chatter stability, dimensional error and surface finish. Cutting force models are based on coefficients that could change with spindle speed. The evaluation of these specific coefficients at higher speed is challenging due to the frequency bandwidth of commercial force sensors. On account of this, coefficients are generally evaluated at low speed and then employed in models for different spindle speeds, possibly reducing accuracy of results.

In this paper a deep investigation of cutting force coefficient at different spindle speeds has been carried out, analyzing a wide range of spindle speeds: to overcome transducer dynamics issues, dynamometer signals have been compensated thanks to an improved technique based on Kalman filter estimator. Two different coefficients identification methods have been implemented: the traditional average force method and a proposed instantaneous method based on genetic algorithm and capable of estimating cutting coefficients and tool run-out at the same time.

Results show that instantaneous method is more accurate and efficient compared to the average one. On the other hand, the average method does not require compensation since it is based on average signals. Furthermore a significant change of coefficients over spindle speed is highlighted, suggesting that speed-varying coefficient should be useful to improve reliability of simulated forces.

1. Introduction

Milling process has been improved in the last decades thanks to new tooling systems, technologies and control, leading performance to a higher level. The increasing use of high speed machining (HSM) has led to new challenges for the machine tool manufacturers and users. Simulation of cutting processes has become crucial on production optimization: accurate prediction of machining effects is nowadays needed to improve milling performance [1].

Many aspects of cutting process, such as tool-workpiece vibrations, chatter stability [2], dimensional errors [3], milled surface generation [4] are mainly influenced by cutting force originating in the tool-workpiece interface. As a consequence various cutting force models have been developed on this purpose and presented in literature [5–7]. Despite the differences between the existing force models, it is practically universally assumed that cutting forces are related to uncut chip area, through dynamic cutting force coefficients that could be obtained by means of experimental tests. The accuracy in cutting force prediction, and consequently in process simulation, is mainly related to the accuracy achieved in identifying such coefficients.

There are mainly two ways to identify cutting force coefficient: using the mechanics of cutting and tool geometry or specific coefficients from direct experimental results. Regarding the first approach, the most used method is the one developed by Budak et al. [8] and known as "orthogonal to oblique transformation": a general approach that allows the identification of cutting force coefficient for different cutting tools and operations from data extracted from orthogonal cutting tests. Coefficients obtained using the mechanics of cutting are more versatile, since they can be applied to any different tool geometry thanks to the orthogonal to oblique transformation; nevertheless some relevant approximations are included in this approach. On the other hand, there are different options to obtain specific cutting coefficients from experimental results; among them, the most common are based on average force measurement per revolution in slot milling tests [5,9], but other methods based on simulation and instantaneous forces [10–12] have been presented in addition. In instantaneous approaches, force coefficients are identified using an inverse method by fitting simulated and measured forces in time domain.

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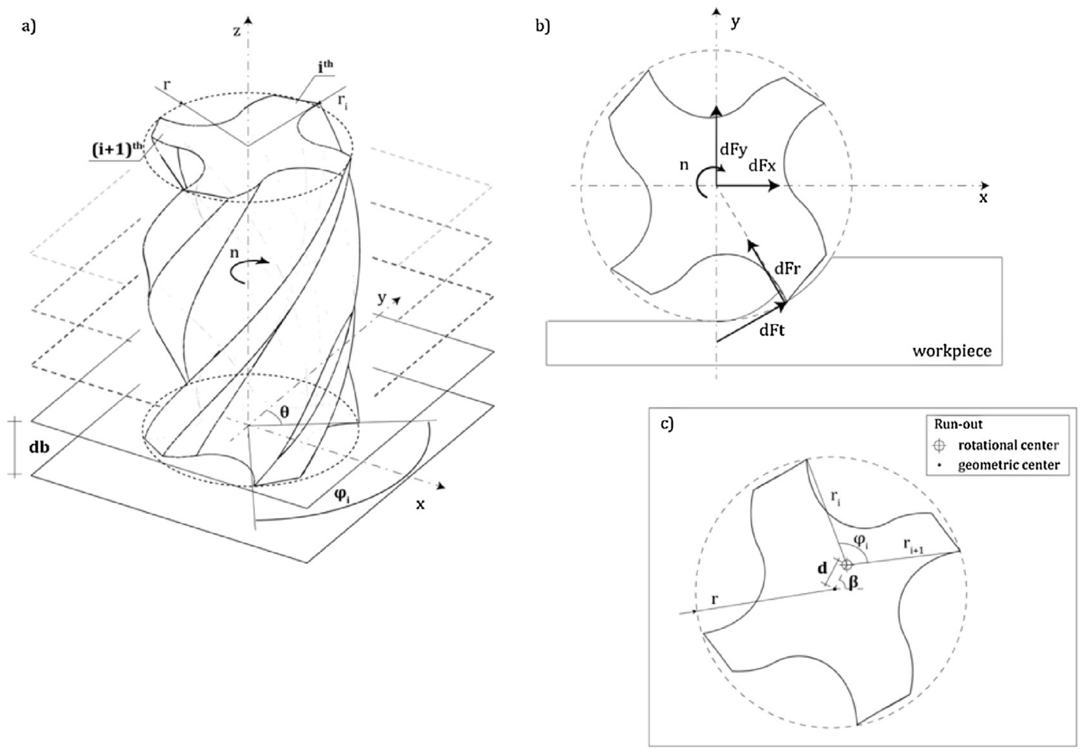

Fig. 1. Tool scheme: (a) variables, (b) force components, (c) run-out formulation.

Specific coefficients are consistent only for the same tool-material combination used in the experimental tests, but accuracy achieved with this approach is higher.

General approach to specific cutting force coefficient identification is based on low speed experiments to limit the dynamic issue of cutting force measurement devices. The main drawback of this approach is that the so-identified coefficients are employed in simulation of a general machining operation at different spindle speeds. This could be an issue considering that cutting process and chip formation mechanics change with varying cutting speed, suggesting a change in coefficients as well.

Speed dependence of cutting force coefficients has not been widely investigated in literature; showing partial and conflicting results. In Refs. [13,14] a variation of cutting coefficients with speed is presented and this trend appears relevant especially for tangential forces. According to these studies coefficients are higher at low speed, showing a decrease and then increasing again in high speed area. On the contrary according to Wang et al. [15] cutting coefficient is constantly varying with cutting velocity, but only a limited range of speeds has been tested (10–30 m/min). Anyhow all these analyses are affected by uncertainties and errors derived from measuring cutting forces at high rotational speeds. Evaluating coefficients with high speed milling tests, in fact, is challenging due to the frequency bandwidth of commercial force sensors that is inadequate for high spindle speeds (dynamometer's frequency response limits measurements to low speed).

In this paper an improved approach to identify specific speed-varying cutting force coefficients is presented, overcoming dynamometer dynamics issues by means of an improved compensation technique, based on the Kalman filter estimator [16]. With this technique a more reliable estimation of specific cutting forces coefficients has been carried out by means of milling tests over a wide range of speed (1000–30,000 rpm).

Using compensated measurements both average and instantaneous methods have been applied to identify coefficient for a linear force model, in order to compare the methods' reliability and compensation influence on results.

An improved instantaneous coefficients identification approach is proposed and implemented: a trochoidal cutting edges path for chip thickness identification has been chosen as already presented in Ref. [10] but a more accurate analytical formulation [17] has been used including run-out in order to better correlate the measured forces with simulated ones. The fitting procedure has been performed by means of genetic algorithm (GA): this way all the coefficients and run-out values can be obtained from one set of force measurements, properly compensated, with reasonable computational effort. Differences between the two identification methods have been presented both in coefficients values and fitting curves, analyzing compensation effects on cutting force prediction reliability.

Experiments have been conducted on Aluminum 6082-T4 alloy, employing nine different spindle speeds: cutting speed influence on cutting force coefficient for linear force model has been consequently evaluated. Through this investigation, cutting speed dependency of specific coefficient is highlighted and the effectiveness of the improved identification technique validated.

2. Proposed approaches

Proposed approaches allow the estimation of cutting force coefficients at various spindle speeds in order to improve reliability of cutting force simulation.

2.1. Cutting force model

Coefficient estimation is based on the linear cutting force model presented by Altintas in [5] where cutting force is expressed by