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Title: Accurate and fast measurement of specific cutting force coefficients changing with spindle speed

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Title

Accurate and fast measurement of specific cutting force coefficients changing with spindle speed

Abstract

Prediction of cutting forces is essential to simulate dynamic effects of the milling process, and optimize process parameters to reduce detrimental vibrations. Cutting forces are conventionally modeled by assuming a dependence on uncut chip thickness using dedicated coefficients, to be experimentally identified. These coefficients are proven to vary significantly with spindle speed, causing the need of a time-consuming experimental phase to achieve an accurate simulation of cutting forces in a wide range of spindle speeds. This paper presents a method to efficiently identify the specific cutting force coefficients in the entire speed range by a single milling test, in which spindle speed is ramped-up. During the test, the forces signals are acquired and then processed to identify the speed-varying cutting force coefficients. The method was applied to the identification of Aluminum 6082-T4 coefficients in a wide range of speeds and results were validated through traditional approach, proving the efficiency and effectiveness of the proposed technique. In addition, an application of the obtained coefficients to chatter prediction is presented and validated through chatter tests.

Keywords: Milling, Cutting force, Coefficients, Chatter, Spindle speed

1. INTRODUCTION

The actual trend of milling process is the continuous increase of the cutting parameters (i.e., spindle speed and feed) to enhance Material Removal Rate (MRR) [1]. However, the achievable improvement in productivity is still limited by the influence of the system dynamics, becoming increasingly critical due to the higher inertia and forces involved in the process. Prediction of these effects is nowadays crucial to optimize process parameters and reduce detrimental vibrations occurrence. In particular, cutting forces must be taken into account in every dynamic simulation, such as chatter vibration prediction [2], surface finish estimation [3], process time-domain evolution [4] and thin-walled machining optimization [5]. In the last decades several cutting force models have been developed [6,7,8]. Despite the differences, every model generally assumes the dependence of cutting forces on uncut chip thickness by means of dedicated coefficients, the accuracy of which is essential to achieve a reliable simulation of cutting forces.

Since the coefficients are identified via experiments, the actual research progress is focused on the development of identification methods both accurate and fast. Indeed, reducing the time required by the experimental phase will foster the application of predictive models in industry. Two main identification approaches are pursued, classified on the basis of the tests required: orthogonal cutting or direct milling tests. The first technique, known as “orthogonal to oblique transformation”, was firstly presented by Budak et al. [9] and allows to identify the coefficients for different tool geometries, starting from a set of experimental results on orthogonal cutting. Although the approach allows to build a database of materials to be used for different milling configurations, the approximations assumed by the method affect the accuracy of the results, especially in case of tools with complex geometry [1].

On the other hand, milling tests can be performed to extract directly the specific coefficients, ensuring higher accuracy but requiring dedicated tests for every couple tool-material. The most common approach is based on average cutting forces per revolution. Even thought it needs simple set-up and signal processing, it requires multiple tests at different feed rates to be implemented. Recently, methods based on instantaneous forces were presented [10]. In these approaches the force coefficients are identified by fitting measured and simulated

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forces in time-domain. They require fewer experimental tests but more complex signal processing techniques.

In the last years, extensive investigations on cutting force coefficients have been carried out, highlighting their dependency on several variables, such as feed rate and cutting speed [11]. The latter parameter appears as the most critical, since a significant influence is underlined in several works [11–13]: coefficients are high at low speed, and increasing speed a general downward trend is found. However, the coefficients are commonly identified at low speed to reduce dynamics influence on measurement [14] and then used for high speed simulation, overestimating cutting forces. To avoid this issue, an investigation of the speed-varying cutting force coefficients should be carried out, as proposed in recent works [11,12]. This procedure is time-consuming, since a large number of tests is required, especially if a wide range of spindle speeds has to be analyzed.

This paper presents a new method to overcome this issue, the specific cutting force coefficients are identified in the entire spindle speed range of interest through a tailored procedure, based on a fast experimental test and the instantaneous identification approach. The main advantage of the proposed approach is to reduce the number of tests generally required without affecting the identification accuracy. This novel approach exploits a fast and easily implementable test, able to return the required measured data (forces and spindle speeds) in few seconds. A dedicated identification procedure automatically processes the data to compute the required coefficients to ensure an accurate cutting force simulation in a wide spindle speed range. In the paper the experimental phase is firstly presented, including signal processing procedure. Then, the identification method based on instantaneous technique is described. Lastly, the experimental implementation is shown: the speed-varying coefficients are computed for end-milling on Aluminum 6082-T4 and results are validated via traditional approach and applied to chatter prediction.

2. PROPOSED TEST

The proposed method is based on a fast experimental test, able to scan the entire spindle speed range of interest. This test is called Spindle Speed Ramp-up (SSR) and was presented in [15], applied for chatter detection purpose. The test aims at drastically reducing the large number of tests at different spindle speeds generally required, by concentrating them in a single test. Indeed, during SSR spindle speed is increased continuously, while feed per tooth and depth of cut are kept constant, hence investigating the entire spindle speed range with only one test. Force signals are collected and then post-processed to identify the speed-varying coefficients. The testing procedure is very fast (one test can be performed in few seconds) and can be programmed via a simple NC code (in this work generated by a Matlab routine).

2.1 Signal Processing

Once the SSR test is performed and the cutting forces are acquired, a signal processing procedure is required in order to apply the proposed identification method and compute the cutting force coefficients.

First of all, spindle speed data are obviously needed. This information could be measured during the test via a tachometer or acquired by accessing machine encoders. However, this would imply an operation on the machine tool. A more industrial-oriented approach is here proposed to extract spindle speed information via post-processing the forces data, without the need of any modification on the machine. A simple speed extraction technique based on order analysis, borrowed by rotordynamics field is adopted. The basic idea is to analyze the signal in time-frequency domain and extracting at each time step the tooth pass frequency (i.e., order frequency), that is correlated with spindle speed according with:

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$$v\,[rpm] = ftp * 60/z \tag{1}$$

where v is the spindle speed, ftp the tooth pass frequency and z the number of teeth. The method to compute spindle speed, proposed here, can be applied to different force signals and in any condition (e.g., spindle speed range). Tooth pass frequency is generally the dominant contribution of chatter-free cutting forces, easily to identify even in case of run-out or high number of teeth (in this case Eq. 1 is changing accordingly).

The second step of the signal processing phase is the definition of the cutting sections. The force signals are divided in several sections and the cutting force coefficients are computed for each of them. A constant spindle speed is assumed within the sections; therefore, small sections are preferred to investigate the speed variance of the coefficients. On the other hand, large sections ensure a correct and accurate application of the identification technique (at least one tool rotation should be analyzed). In this work the sections are created every 2 rounds, ensuring both a high spindle speed resolution and the effectiveness on the application of the identification method.

3. PROPOSED IDENTIFICATION METHOD

The force signals, clustered in the different sections, are then analyzed to compute the specific cutting force coefficients at different spindle speeds. In this work, an instantaneous approach is proposed. The method computes the coefficients by fitting measured and simulated forces, therefore a cutting forces simulation in time domain and a fitting method are needed.

3.1 Cutting force model

In this work, the mechanistic force model [1] is used: the three cutting force components are described by six specific coefficients:

$$\begin{aligned} dF_t &= K_{tc}hdb + K_{te}dl \\ dF_r &= K_{rc}hdb + K_{re}dl \\ dF_a &= K_{ac}Hdb + K_{ae}dl \end{aligned} \tag{2}$$

where Ft, Fr, Fa are the tangential, radial and axial components of cutting force respectively, h is the uncut chip thickness, dl the cutting edge discretization, db the chip width. Each of the force component is described by two coefficients, one related to material shearing and proportional to the chip thickness (Ktc, Krc, Kac), and the other related to friction and ploughing (Kte, Kre, Kae).

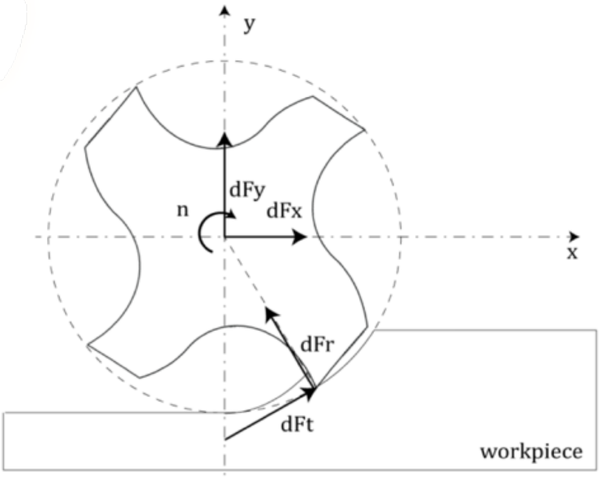

Fig. 1 Cutting forces in milling, x-y section

Since tangential and radial directions are changing during the milling process respect to the machine coordinate system (Fig. 1), the cutting forces are generally transformed on X (feed), Y (normal) and Z (axial) directions to be compared to the measured ones. This transformation is performed according to Eq.3.

$$\begin{Bmatrix} dF_x \\ dF_y \\ dF_z \end{Bmatrix} = \begin{bmatrix} -\cos(\varphi) & -sin(\varphi)sin(\kappa) & -sin(\varphi)cos(\kappa) \\ sin(\varphi) & -cos(\varphi)sin(\kappa) & -cos(\varphi)cos(\kappa) \\ 0 & cos(\kappa) & -sin(\kappa) \end{bmatrix} \begin{Bmatrix} dF_t \\ dF_r \\ dF_a \end{Bmatrix} \tag{3}$$

where κ is the approach angle of the cutting edge and φ is the spindle rotation. In order to take into account helix angle, tool is discretized in planes and the forces on each of them are integrated to compute the total force.

3.2 Cutting force simulation

Cutting forces simulation (Eq.2) requires uncut chip thickness computation (h). In this work an advanced analytical formulation[16] is used, including both trochoidal tool motion and run-out. Milling tooth path is described by Eq. 4.

$$x_i = \rho\theta + r_i \sin(\theta + \varphi_i) \quad y_i = r_i \cos(\theta + \varphi_i) \tag{4}$$

where xi and yi are the motion of the i-th tooth on the two directions, ρ=Vf/n is the radius of the circle that defines the trochoidal motion of the tooth (Vf the feed rate, n the spindle speed). θ is the instantaneous cutter angle, and φi is the angle between θ and the i-th tooth. The related chip thickness formulation is:

$$H_i = r_i - \sqrt{\rho^2(\theta_0 - \theta)^2 + 2\rho \cdot r_{i+1}(\theta_0 - \theta)sin(\theta_0 + \varphi_i) + {r_{i+1}}^2}$$

where $\theta_0 = \theta - \frac{\varphi_{i+1} - \varphi_i}{(\rho/r_{i+1})\cos(\theta + \varphi_i) + 1}$ (5)

Eq. 5 allows the computation of the chip thickness in time domain and included in Eq. 2 returns the simulated forces.

3.3 Fitting strategy

The six specific cutting force coefficients are identified by fitting measured data with simulated forces. Genetic Algorithm (GA) fitting strategy, as used in other works, was applied for this purpose. The six cutting force coefficients (Ktc, Kte, Krc, Kre, Kac, Kae), are computed, minimizing the fitting function (fo) presented in Eqs. 6-9:

$$fox = |F_x - F_{x\_mes}|/|F_{x\_mes}| \tag{6}$$
$$foy = |F_y - F_{y\_mes}|/|F_{y\_mes}| \tag{7}$$
$$foy = |F_z - F_{z\_mes}|/|F_{z\_mes}| \tag{8}$$
$$fo = (fox + foy + foz)/3 \tag{9}$$

where F_x, F_y, F_z are simulated forces using Eqs. 2-3, while F_{x_mes}, F_{y_mes}, F_{z_mes} are the measured ones.

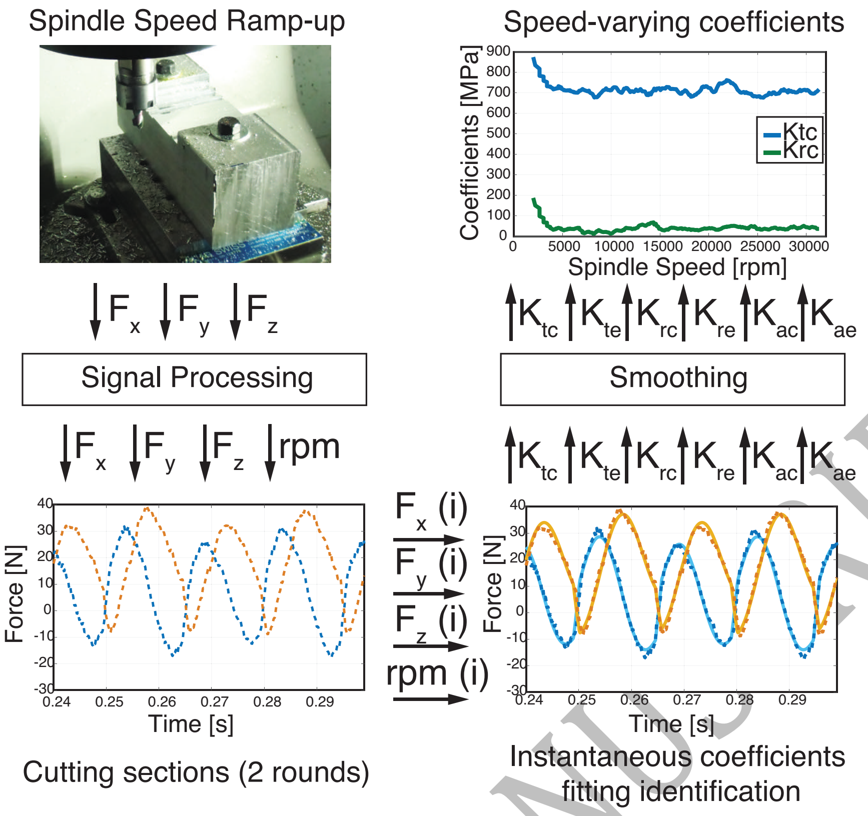

Fig. 2 Scheme of the proposed identification method

Fitting is performed for each forces section to obtain the overall trend of the cutting force coefficients with spindle speed. A smoothing strategy based on moving average is then proposed to analyze cutting coefficients evolution, mitigating noise in the result, as discussed in the following sections. The whole proposed identification cycle is schematized in Fig. 2.

4. EXPERIMENTAL IMPELEMENTATION

The proposed method was experimentally applied to investigate cutting force coefficients of Aluminum 6082-T4 in a wide range of spindle speed.

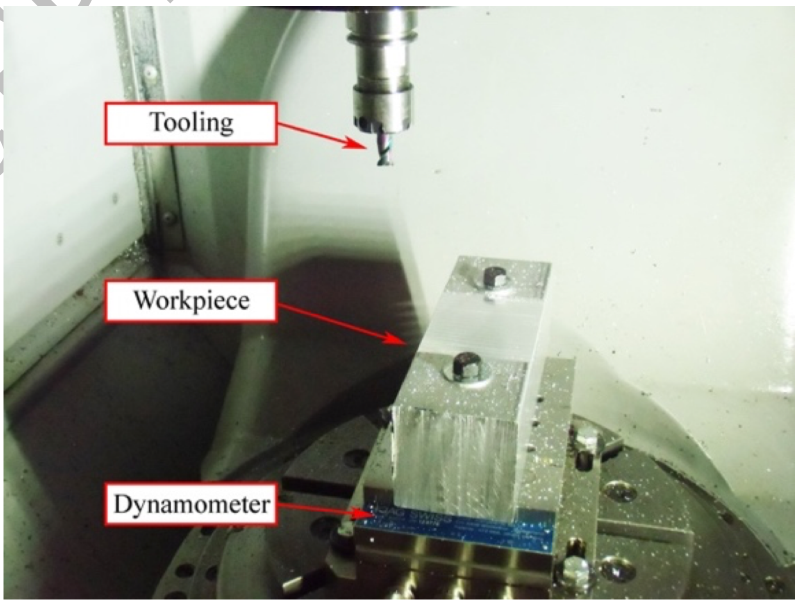

Fig. 3 Test set-up

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4.1 Set-up

Test set-up is presented in Fig. 3. Cutting tests were performed on a Mori Seiki 5-axis milling machine, NMV 1500 DCG, equipped with high speed spindle. The workpiece was rigidly clamped to a three-component Kistler dynamometer type 9257A. A two flutes 8 mm end mill (Garant 201770) clamped on a HSK32ER20 collet holder with 20 mm overhang was selected as tooling system.

4.2 Dynamic analysis

Before performing cutting tests, a dynamic analysis was carried out to study the influence of vibrations on the measured data. First, an experimental modal analysis through hammer testing was performed on the tooling via LSM Scadas III acquisition system and LMS Test.Lab software using a Brüel & Kjaer Type 8202 impulse hammer and a PCB 352C22 accelerometer. Frequency response functions (FRFs) of tool is presented in Fig. 4. Tooling system shows a symmetric behavior with two main modes at about 5,000 Hz and 11,600 Hz. The measured FRFs were used to predict chatter vibration occurrence and select cutting parameters to avoid instability. Stability Lobe Diagram (SLD) computed by analytical solution [17] based on on Zeroth Order Approximation (ZOA) is presented in Fig. 5. The limiting depth of cut is about 2 mm, a conservative depth below 2 mm will be selected in the testing to avoid the influence of chatter vibration on the measured data.

The influence of dynamometer and system dynamics on the measured cutting forces is a well-known issue14 that could lead to unwanted frequency content in the measured data. To analyze this issue, a dynamic analysis of workpiece/dynamometer system was performed via hammer testing. Transfer functions for all the three directions were measured and reported in Fig. 6.

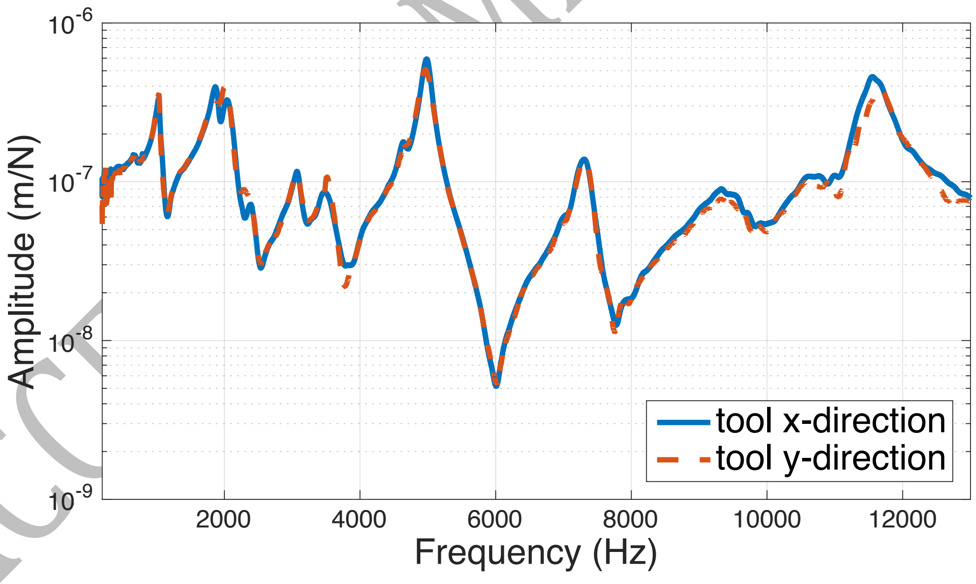

Fig. 4 FRFs of the tooling system

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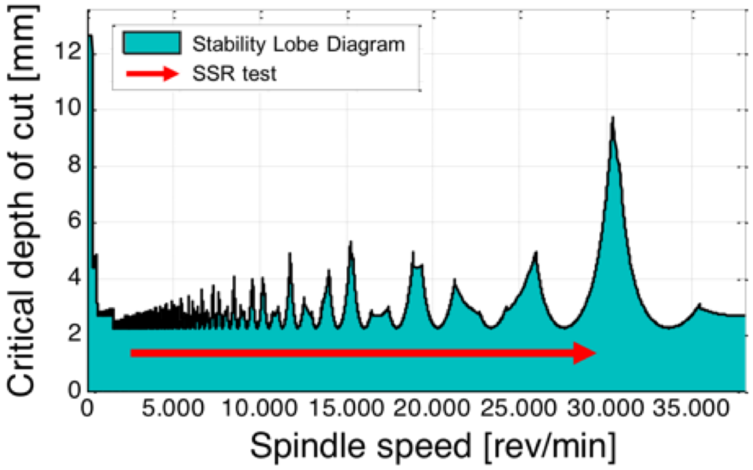

Fig. 5 SLD and depth of cut selection for SSR test

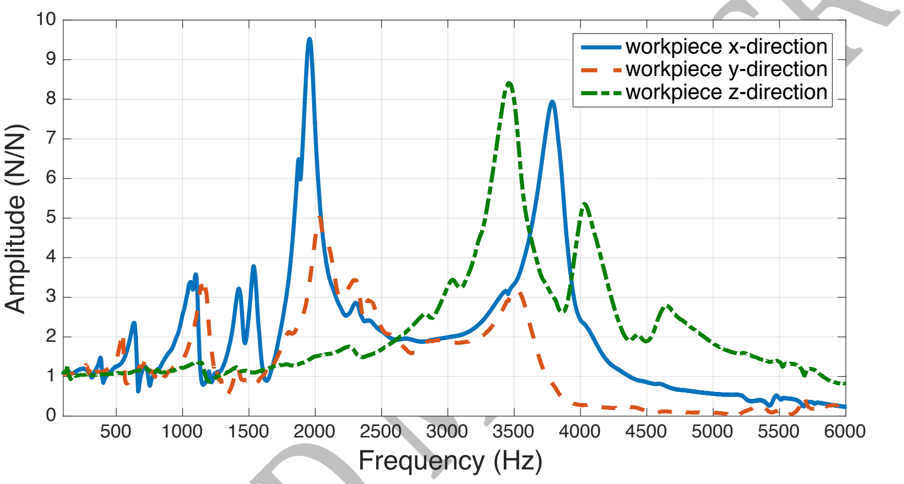

Fig. 6 FRFs of the workpiece/dynamometer system

The system shows dominant modes at about 2,000 Hz in x and y directions and at about 3,500 Hz in z. However, especially for x and y direction, other significant contributions are identified even below 1,000 Hz. These dynamic contributions could lead to a distorted measurement of cutting forces and affect the results. Therefore, based on the transfer functions, a compensation technique tailored for table dynamometers [18], was implemented in this study to filter measured cutting forces and compensate the influence of system dynamics. The proposed coefficients identification technique was applied to the filtered data.

4.3 Signal Processing

A single SSR test was performed to compute cutting force coefficients in the spindle speed range: 2,000-31,000 rpm. The test was carried out in stable condition at 1.5 mm depth of cut (Fig. 5) in slotting operation (i.e., full immersion), 0.03 mm feed per tooth was used according to tool manufacturer suggestions. A spindle acceleration of about 8,000 rpm/s was set for the test, resulting in 3.5 s cutting. Forces signals were acquired by a LMS Scadas III and elaborated in LMS Test.Lab software. Spindle speed time history was computed by post-processing force signals according to the proposed identification based on the tooth pass frequency. Sampling frequency was set to 25,600 Hz and order analysis was performed with 10 Hz frequency resolution and time step equal to 3 ms. The resulting waterfall diagram for force signal in Z direction is presented in Fig. 7, as a colormap (force amplitude in color).

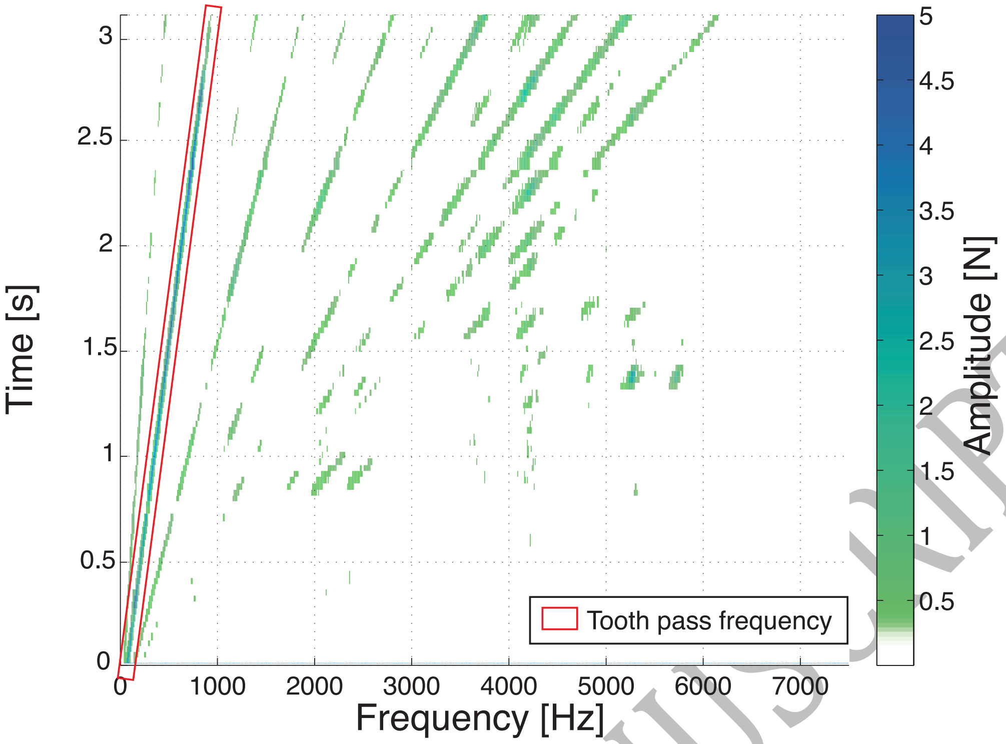

Fig. 7 Colormap of FFT waterfall (force Z) for speed detection

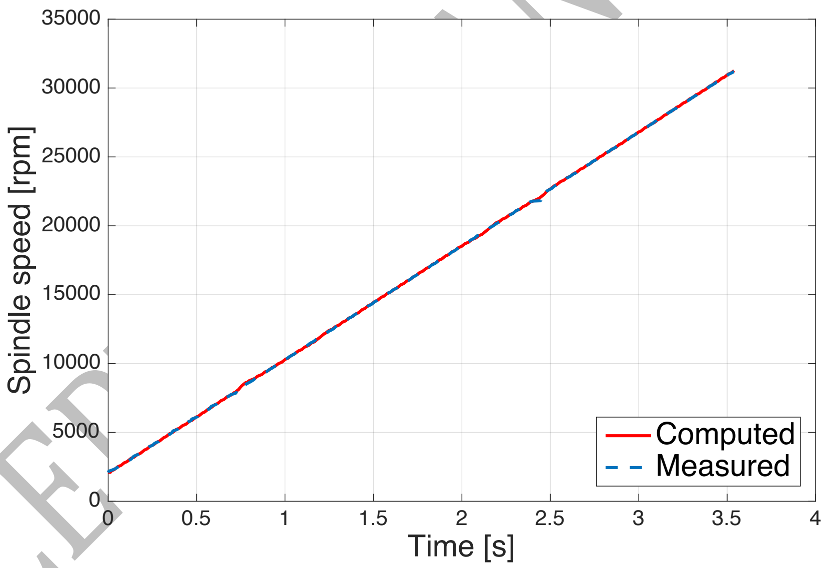

Fig. 8 Spindle speed during SSR computed by proposed method and measured via optical tachometer

The waterfall diagram shows frequency content of force signal changing during an SSR, i.e., increasing spindle speed. Tooth pass frequency and its harmonics are clearly shown in the diagram as diagonal lines due to their linear increase with spindle speed. Isolating tooth pass frequency is straightforward, since in stable condition it is dominant in the spectra. Moreover, the test parameters (i.e., spindle speed range, spindle acceleration) support the detection, avoiding identification errors. Indeed, if the tooth pass frequency is confused with one of its harmonics, the resulting spindle speed range, computed by Eq. 1, will be far higher of smaller than the spindle speed range programmed in the machine. This will help the identification also in case of a high number of flutes or high run-out. The method is hence valid in general and can be adapted to any cutting conditions or tool parameters.

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In order to validate the proposed technique, the extracted spindle speeds were compared to the signal measured by an optical tachometer, acquired by the same acquisition system (LMS Scadas III) and using the same sampling parameters (i.e., spindle speed is measured at 3 ms time step) to ensure the required synchronization. Comparison results, reported in Fig. 8, prove the accuracy of the proposed technique to identify spindle speed information without the need of additional sensors.

4.4 Results

The force signals were clustered in sections of 2 rounds each (in total 231 sections), and the identification of the coefficients was performed.

For the sake of clarity, the analysis will be focused on the two main cutting force coefficients, essential in many applications (e.g., chatter prediction): Ktc and Krc. In Fig. 9 the identified coefficients are presented before and after the smoothing phase. Thanks to the proposed approach, cutting force coefficients in the entire spindle speed range can be obtained. The smoothing phase allows to mitigate noise in the data and return the general trend. Increasing spindle speed a downtrend until about 10,000 rpm is found, then the coefficients slightly increase. Coefficients trend is in good agreement with results previously published [11,12], and with the physics of the process: a general initial decrease is expected due to the thermal softening of the material [11].

The computed speed-varying coefficients can be used for accurately predict cutting forces at the different spindle speeds. Using the obtained coefficients, the cutting forces during SSR test were simulated and compared to the measured ones. Results, presented for low spindle speed (average value around 2,000 rpm) in Fig. 10 and high spindle speed (20,517 rpm) in Fig. 11, shows the accuracy of the speed-varying coefficients. As found for the coefficients, forces at low speed are higher than the ones at high speed. At 2,002 rpm measured forces are fitted more accurately since the influence of dynamics is reduced. On the contrary, at high speed, measured forces are altered by high frequency oscillations probably due to the tooling vibrations. Nevertheless, the overall comparison between measured and simulated forces using identified coefficients is quite good with errors (fo in Eq. 9) less than 8%.

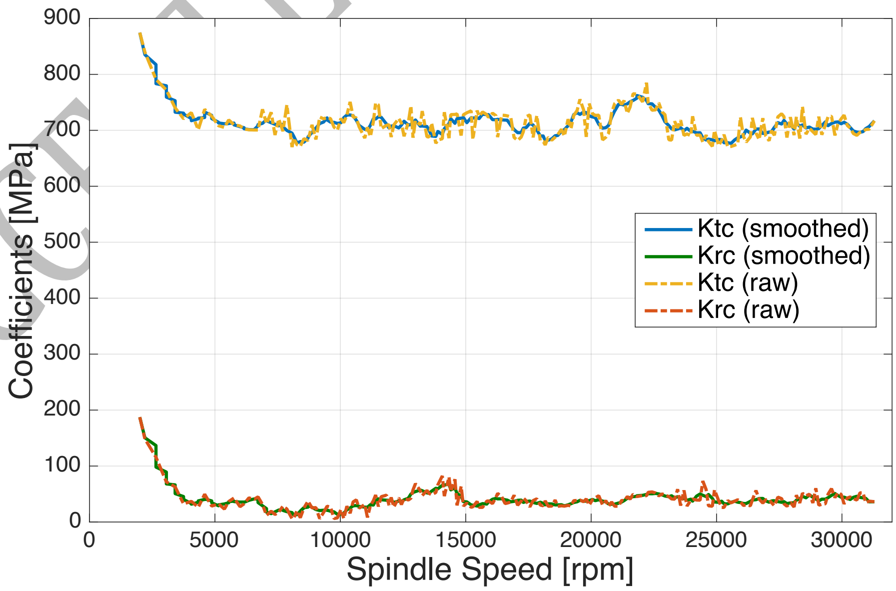

Fig. 9 Identified speed-varying cutting force coefficients

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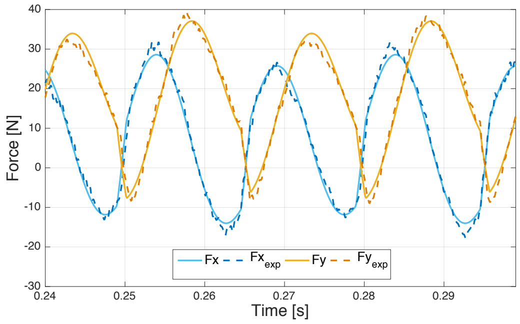

Fig. 10 Simulated and measured forces at 2,002 rpm

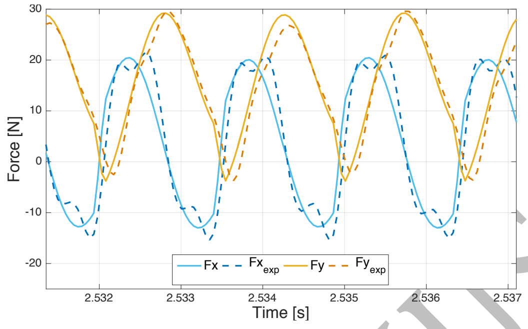

Fig. 11 Simulated and measured forces at 20,517 rpm

5. VALIDATION

The proposed identification approach was validated via two different experimental procedures. First, the speed-varying cutting force coefficients obtained by the proposed method were compared with the ones computed using state of the art approach at different spindle speeds. Secondly, the speed-varying coefficients were used to predict Stability Lobe Diagram (SLD) and outcomes were validated through chatter tests, showing the potential application of the method.

5.1 Coefficients

For validation purpose, cutting force coefficients were evaluated at different spindle speeds using state of the art approach. Average force method is adopted in this work, as the most widely used technique to compute specific cutting force coefficients. The method is based on the assumption that average cutting forces can be expressed as linear functions of the feed rate. Therefore, to apply the method 5 different feeds per tooth were tested with the same set-up (Fig. 3a) and coefficients were estimated by linear regression on the data. Slot milling tests were preferred to simplify the procedure. The average force method was performed for 9 different spindle speeds, to investigate the entire spindle speed range. Cutting parameters are summarized in Table 1.

Table 1 Cutting parameters for coefficients estimation

Spindle Speed [rpm]	995	3,979	7,958	11,937	15,916
	19,894	23,873	27,852	31,831	
Feed per tooth [mm]	0.02	0.025	0.03	0.035	0.04
Axial depth [mm]	1.5		Radial depth	Slotting	

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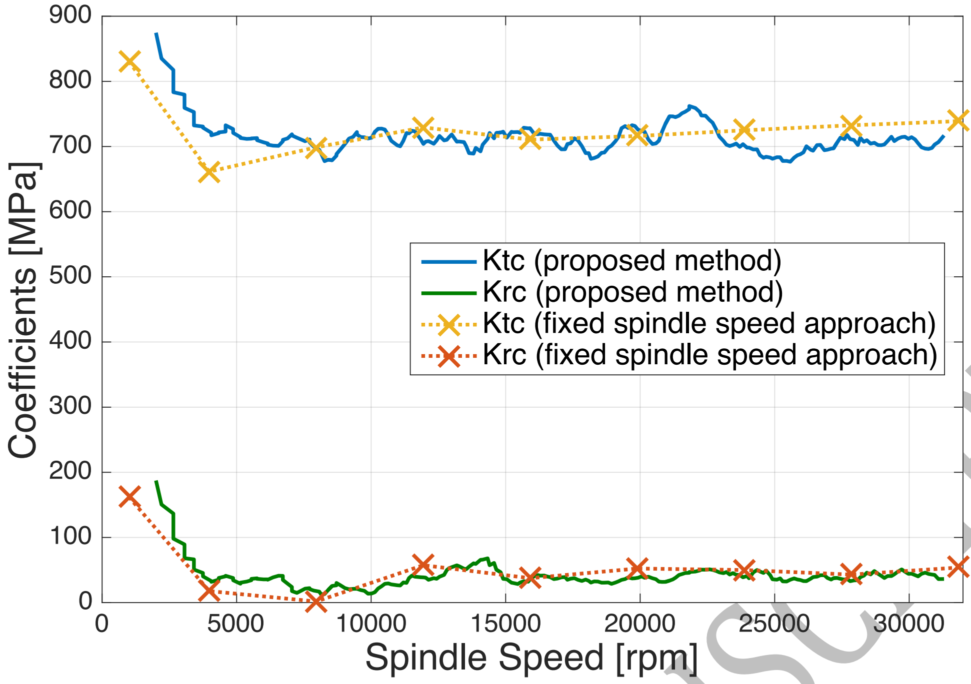

Fig. 12 Coefficients validation compared to fixed spindle speed

In Fig. 12 Ktc and Krc coefficients extracted by fixed spindle speed tests are compared to the speed-varying coefficients obtained by the proposed method.

Results show a good agreement between the two approaches (maximum of 9% error on Ktc at 4,000 rpm), proving the effectiveness and efficiency of the proposed method. The technique based on SSR test is able to accurately predict force coefficients in a wide range of spindle speed with only one test, while a traditional approach required 45 distinct tests.

5.2 Chatter stability

One of the main application of cutting force coefficients is simulation of the dynamics of milling process to predict the occurrence of instability, known as chatter. In this work the computed speed-varying coefficients were used to assess their accuracy in chatter prediction application. The chatter theory based on ZOA was implemented in this work.

The same material and tool were used while a different overhang (36.5 mm) was applied to the tooling system to increase the compliance of the structure and hence the occurrence of vibrations. System flexibility was measured through impact testing (Brüel & Kjaer Type 8202 impulse hammer and a PCB 352C22 accelerometer). Modal parameters of the first two dominant modes on both x and y directions are reported in Table 2.

Table 2 Modal parameters for the chatter stability test set-up

	Natural frequency [Hz]	Damping ratio [%]	Dynamic stiffness [N/mm]
1st X direction	4267	1.39	12,100
1st Y direction	4247	1.35	9,310
2nd X direction	6248	1.38	26,100
2nd Y direction	6219	1.40	21,300

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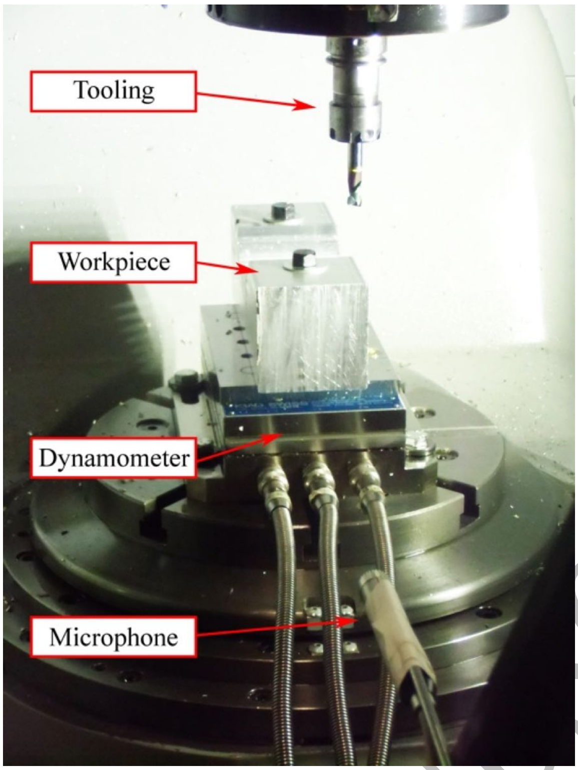

Fig. 13 Chatter identification set-up

Stability Lobe Diagram was computed using ZOA approach and validated with experimental results. In particular, 20 different cutting tests with fixed cutting parameters in the range 19,500-25,000 rpm were performed. In addition to dynamometer, the machine was equipped with a microphone (Bruel & Kjaer type 4165) installed inside the cutting chamber, close to the cutting zone (Fig. 13). Chatter occurrence was assessed by checking chatter frequency evolution on the microphone signals spectra as in [19].

An example of chatter detection results is shown in Fig. 14, where microphone spectra for a stable unstable cutting test are presented.

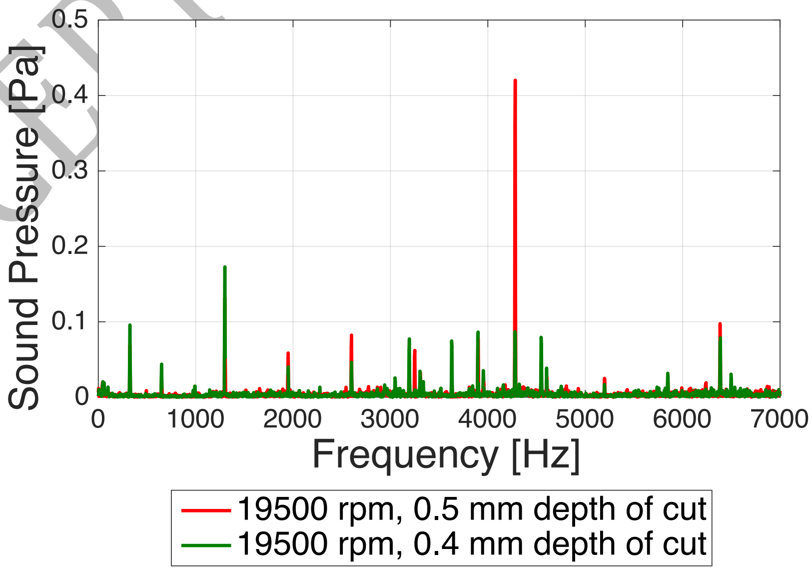

Fig. 14 Microphone spectra in stable and unstable tests

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In case of stable cutting (0.4 mm depth) no dominant frequency but tooth pass frequency and harmonics is found in the spectrum. On the contrary, increasing the axial depth of cut to 0.5 mm, chatter is detected, since a frequency, close to the natural frequency of the tooling, is found dominant in the spectrum. Using this procedure, the 20 experimental results are extracted. These conditions are used to validate SLD computed by speed-varying coefficients, as presented Fig. 15. In the same figure, SLD obtained using coefficients at low speed (2,000 rpm) is reported (dashed line) to show the importance of speed dependent coefficients.

In general, cutting force coefficients are computed at low speed to avoid measurements issue, neglecting the influence of spindle speed. However, by doing so cutting forces are overestimated, leading to a wrong prediction of limiting depth of cut values, as clear from the results in Fig. 15. On the other hand, the SLD obtained using the speed-varying coefficients, return accurate results.

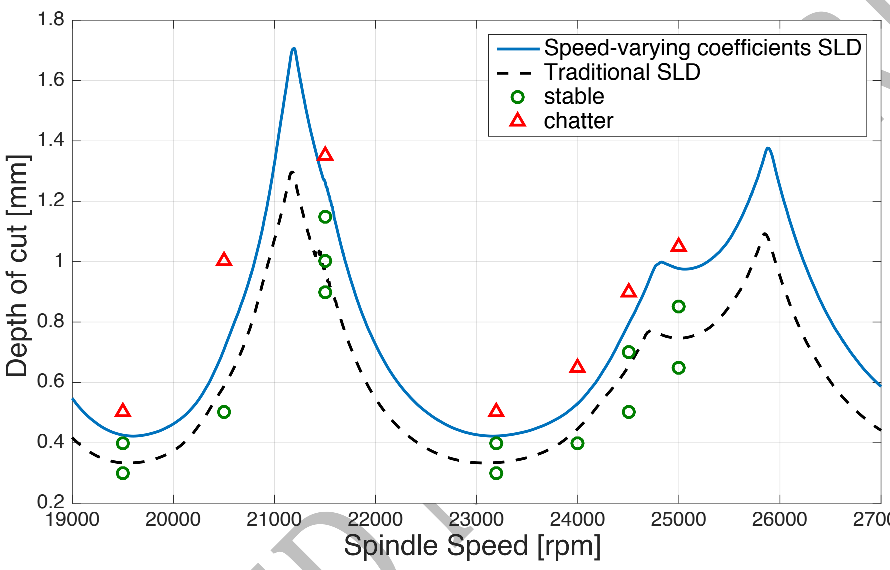

Fig. 15 SLD validation with experimental results

6. CONCLUSIONS

Cutting force coefficients variation with spindle speed is crucial to improve cutting process simulation accuracy. In this paper an efficient way to accurately compute speed-varying cutting force is presented. The novelty of the proposed approach is the extraction of cutting force model coefficients in a wide spindle speed range in few seconds. Indeed, a fast test, called Spindle Speed Ramp-up, is used to scan the entire spindle speed range. Cutting force signals acquired are used to compute the coefficients through a tailored signal processing procedure and fitting algorithm. The proposed method is able to compute the speed-varying coefficients with a single test increasing the accuracy of cutting force simulation, without affecting the testing time required.

The following conclusions can be drawn:

1. The proposed method can be performed in few seconds with simple implementation; measurement of spindle speed is not needed, since this information can be extracted by measured forces.
2. The proposed method is able to return accurate speed-varying coefficients in line with the ones obtained by state of the art approach (less than 10% error), but it drastically reduces testing time required (40 times faster in the specific application).
3. Using coefficients evaluated at low spindle speed, for high speed simulation (e.g., chatter prediction) could lead to inaccurate results. The proposed method overcomes

this limitations providing the coefficients for the entire spindle speed range, without further affecting machine downtime.

The proposed method simplifies the identification of cutting force coefficients varying with spindle speed, compressing a large number of tests in a single one. Reducing the testing time and improving the accuracy, the method could foster cutting process simulation in industry. A big limitation to the diffusion of cutting force coefficients identification still relies on the use of expensive force sensors (i.e., dynamometer), requiring complex set-up. However, to overcome this limitation the proposed method could be coupled with force measurement technique based on sensors embedded on the machine tool, as proposed in the last years [20]. Future works will be focused on extending the validation to different tooling system (e.g., higher number of teeth), type of operation (e.g., face milling) and workpiece materials (e.g., steel). The method should be valid in any condition since it is based on the same theory of the other method for coefficients identification.

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