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Speed-varying cutting force coefficient identification in milling

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HIGHLIGTHS

- Speed-dependency of cutting force coefficients is investigated and highlighted
- A robust approach to identify speed-dependent force coefficients is described
- Improved compensation technique is used to extend dynamometer measureable bandwidth
- Proposed instantaneous method including run-out and average method are tested
- Efficiency and accuracy of the developed instantaneous approach is shown

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.

Keywords: Milling; Cutting Force; Genetic algorithm; Dynamic compensation.

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 are 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. 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 [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 (1.000-30.000 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 [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 three components (tangential, radial and axial) and six different specific coefficients as shown in Eq. 1.

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

where dl is the edge length of each discrete element in which cutting edge is discretized, H is the underformed chip thickness, db is the chip width. Eq. 1 describes each component by two contributions: one related to material shearing and the chip flowing along the tool rake face, which is proportional to chip thickness, given by K_{ic}, and the other related to friction and ploughing, given by K_{ie} coefficients (where i refers to tangential, radial, or axial).
The tangential, radial and axial components are then transformed to the X (feed), Y (normal) and Z (axial) directions by the transformation [5] in Eq. 2:

$$\begin{Bmatrix} dF_X \\ dF_Y \\ dF_Z \end{Bmatrix} = \begin{bmatrix} -\cos(\varphi) & -\sin(\varphi)\sin(\kappa) & -\sin(\varphi)\cos(\kappa) \\ \sin(\varphi) & -\cos(\varphi)\sin(\kappa) & -\cos(\varphi)\cos(\kappa) \\ 0 & \cos(\kappa) & -\sin(\kappa) \end{bmatrix} \begin{Bmatrix} dF_t \\ dF_r \\ dF_a \end{Bmatrix} \tag{2}$$

where φ is the spindle rotation angle and κ is the approach angle of the cutting edge.
Forces are calculated for each plane in which the tool is discretized (Figure 1a) and integrated to obtain the total force components acting on the tool.

2.2 Average method

The fastest and most widely used technique for calibrating specific cutting force coefficients from milling tests is called the average force method [5] which requires a set of milling tests at different feed rates, but at constant axial and radial immersion. The average cutting forces can be expressed as linear functions of the feed rate. Therefore, average forces at different feed rates are measured and coefficients are estimated from this data by linear regression.
Slot-milling tests are generally performed to simplify identification, in this case cutting force coefficients are calculated as shown in Eq. 3 [5].

$$K_{tc} = \frac{4\underline{F}_{yc}}{Na} \qquad K_{te} = \frac{\pi \underline{F}_{ye}}{Na}$$
$$K_{rc} = \frac{-4\underline{F}_{xc}}{Na} \qquad K_{re} = \frac{-\pi \underline{F}_{xe}}{Na} \tag{3}$$
$$K_{ac} = \frac{\pi \underline{F}_{zc}}{Na} \qquad K_{ae} = \frac{2\underline{F}_{ze}}{Na}$$

where $\underline{F}_{ic}$ is the proportional contribution and $\underline{F}_{ie}$ is the offset calculated by linear regression from the data related to the feed rate. In this work slotting operations have been performed at five different feed rates and repeated at different spindle speeds, in order to collect data for cutting coefficient identification at each cutting velocity.

2.3 Instantaneous method

Another approach for obtaining specific cutting force coefficients is based on fitting measured and simulated forces in time domain. In this paper, this approach is called the "instantaneous method" [10]: it is more complex than the average method because it implies hypothesizing a formulation to simulate cutting forces in time domain and a fitting method. On the other hand it requires only one set of measurements for coefficients estimation.

2.3.1 Chip thickness formulation

Undeformed chip thickness calculation is required to calculate cutting forces as presented in Eq. 1. Different approaches are presented in literature, the most used method entails a circular tool-path approximation [18], neglecting the actual trochoidal tool motion. To reach a more accurate simulation, trochoidal motion is considered in this paper (as in [10]), in addition specific run-out formulation has been implemented. This feature, not yet implemented in usual cutting coefficient identification techniques, could represent a sensible advantage in accurately identifying both the cutting force coefficients and run-out parameters by means of a single experiment.
A particular analytical formulation for chip thickness simulation presented by Kumanchik and Schmitz in [17] has been applied to the proposed approach. In their work, the trochoidal path of the i-th tooth in a milling cut is described as:

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

where $\rho = V_f/n$ is the radius of the circle that defines the cycloidal motion of the tooth, V_f the linear feed rate, n is the rotational speed of the tool, r_i is the radius of the i-th tooth including run-out, θ the instantaneous cutter angle, and φ_i is the angle between θ and the i-th tooth (Figure 1a).

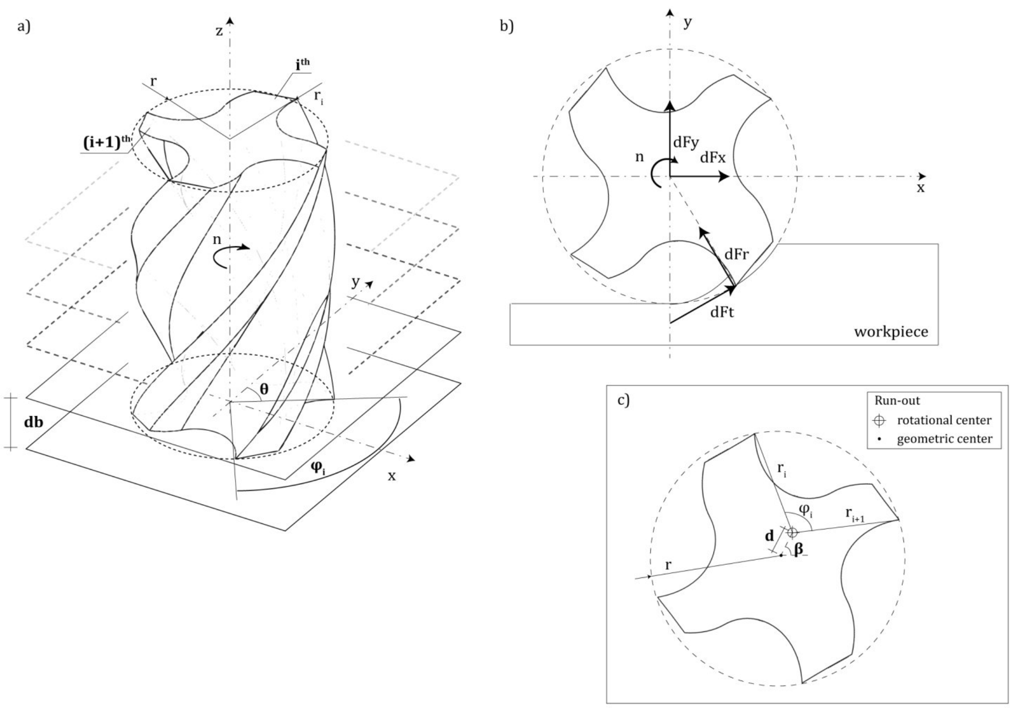

Figure 1: Tool scheme: a) Variables, b) Force components, c) Run-out formulation

Starting from this, chip thickness formulation is calculated as:

$$H_i = r_i - \sqrt{\rho^2(\theta_0-\theta)^2 + 2\rho\cdot r_{i+1}(\theta_0-\theta)\sin(\theta_0+\varphi_i) + r_{i+1}{}^2} \tag{5}$$

where:

$$\theta_0 = \theta - \frac{\varphi_{i+1}-\varphi_i}{(\rho/r_{i+1})\cos(\theta+\varphi_i)+1} \tag{6}$$

Using this formulation, the true trochoidal path is analytically computed, thus improving the accuracy of simulated forces. Circular approximation, in fact, entails errors in the chip thickness calculation as shown in Figure 2, where trochoidal (2a) and circular (2b) tool-paths are compared (a two flute tool is considered as the example).

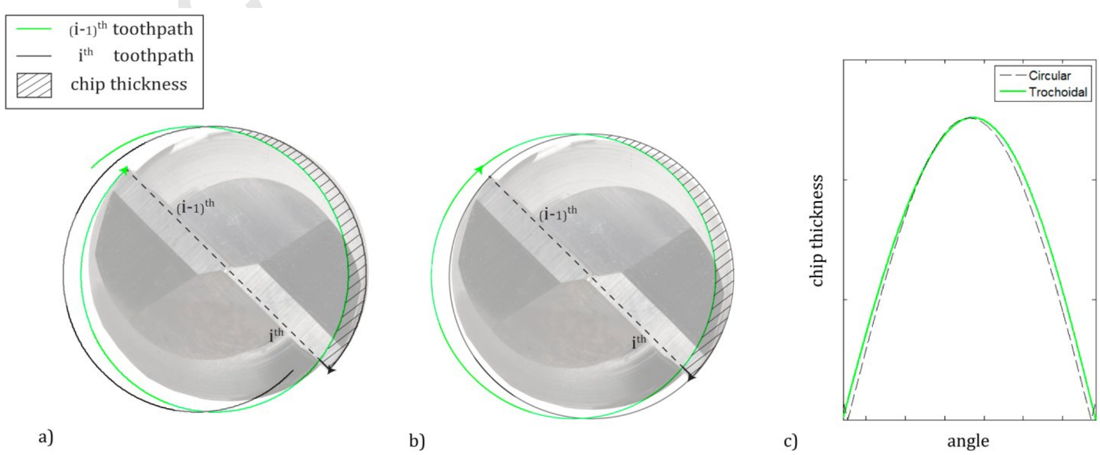

Figure 2: Trochoidal tool-path (a) compared to circular (b) for chip thickness identification (c)

2.3.2 Run-out

As already mentioned, with the improved chip thickness formulation also run-out can be taken into account: any cutting edge, in fact, can be characterized by radius (r_i) and angle (φ_i). To consider valid values for run-out, a correlation between cutting edges' radii and angles has been implemented. The effect of run-out has been included considering the position of rotational center shifted with respect to tool geometric center.

Therefore cutting the edges' parameters have been calculated by the distance (d) from geometric center and the angular position (β) of rotational center as shown in Figure 1c.

This formulation allows us to introduce run-out by two variables, excluding non-physical values, which is a very useful feature in the parameter fitting application.

2.3.3 Fitting method

Once forces are simulated starting from chip thickness formulation, a fitting method is required to identify optimal cutting force coefficients. In this paper Genetic Algorithm has been used to optimize fitting of simulated and measured forces. Genetic algorithms are efficient search algorithms based on the mechanics of natural genetics. They imitate nature with their "survival-of-the-fittest" approach, performing a fitting procedure in a very efficient way compared to more-conventional search techniques.

GA is nowadays widely used to solve optimization problems in different research fields, including machining [19]-[21]. In this paper, the simple genetic algorithm based on least mean square (LMS) curve fitting [21] is implemented.

Nine variables are considered:

- Six cutting force coefficients (K_{tc}, K_{te}, K_{rc}, K_{re}, K_{ac}, K_{ae});
- Two parameters for run-out presented above (d and β)

Considering the cutting configuration and tool parameters, and these nine variables, chip thickness and forces are simulated and compared with measured ones.

Fitting has been performed by minimizing the fitness function in equation 7:

$$fo = \left|F_{sim} - F_{xp}\right|^2 / \left|F_{xp}\right|^2 \qquad (7)$$

The fitting procedure has been performed for the three components (X, Y, Z) at the same time. The resulting fitness function is the sum of the three specific functions.

2.4 Compensation

Measuring cutting forces at higher spindle speeds entails acquiring signals characterized by frequencies components that could approach the transducer resonant frequency or even exceed it. This could result in appreciable distortion of the measured force signals in general applications.

Although this is a known issue, just a few references in literature can be highlighted regarding specific compensation of force transducers, outlining three major approaches. The most intuitive technique is based on identifying the transfer functions (TFs) between measured and applied forces, hence reconstructing the original signal by multiplying the measured force signal with the identified transfer function matrix inverse. Such technique has been presented by Ricardo Castro et al. [23] and latter by Girardin et al. [24], including crosstalk contributions. This technique shows two major drawbacks since existence of the TF matrix inverse is not always ensured and small errors in TF identification could result in measurement noise amplification.

An alternative technique, generally referred to as "accelerometrical compensation", is based on measuring dynamometer cover plate accelerations and removing inertial force contributions by estimating an equivalent mass, as presented by Lapoujoulade et al. [25], [26]. This technique revealed some accuracy problems and limited compensated bandwidth, moreover it requires a number of additional sensors (accelerometers).
The most promising technique seems to be the one based on Kalman filter estimation, as presented by Albrecht et al. [16] and later by Chae and Park [27], where an hybrid formulation contemplating the implementation of additional accelerometrical signals is described. This technique seems to be more robust and accurate since it requires no direct matrix inversion and it should be less influenced by measurement noise, as a consequence of the Kalman filter formulation.
In this work an improved technique has been developed following the technique described in [16] but including some adjustments that have been needed to overcome numerical limitations and extend the compensation bandwidth over a wider frequency range, as imposed by the wide spindle speed range used for in experiments in this work.

2.4.1 Improved compensation technique

As should be clear by analyzing the work of Albrecht et al. [16], a crucial process in determining global and local accuracy of these techniques is fitting the measured FRFs into mathematical TF formulations to numerically compute the compensation filters. Instead of using a modal identification approach, as in [16] and [27], a technique mainly based on the rational fraction polynomial method (RFP) [28] has been implemented. This technique allowed better global accuracy, even if still not adequate over some specific frequency ranges as shown in Figure 3. Some evident accuracy improvements have hence been achieved by using the results obtained with this technique as initial estimates for a fitting algorithm based on the damped Gauss-Newton method for iterative search [29]. This approach ensured adequate accuracy is maintained over the entire frequency range and revealed to be computationally efficient.
This second technique has demonstrated to be sensibly more accurate and has been preferred to the modal curve fitting techniques, given that earlier interest was put in modal parameter identification techniques, and the accuracy was found to be definitely not adequate, at least in this specific application. Figure 3 shows a comparison between the fitting results obtained using the two described fitting techniques over one of the experimentally identified FRFs.

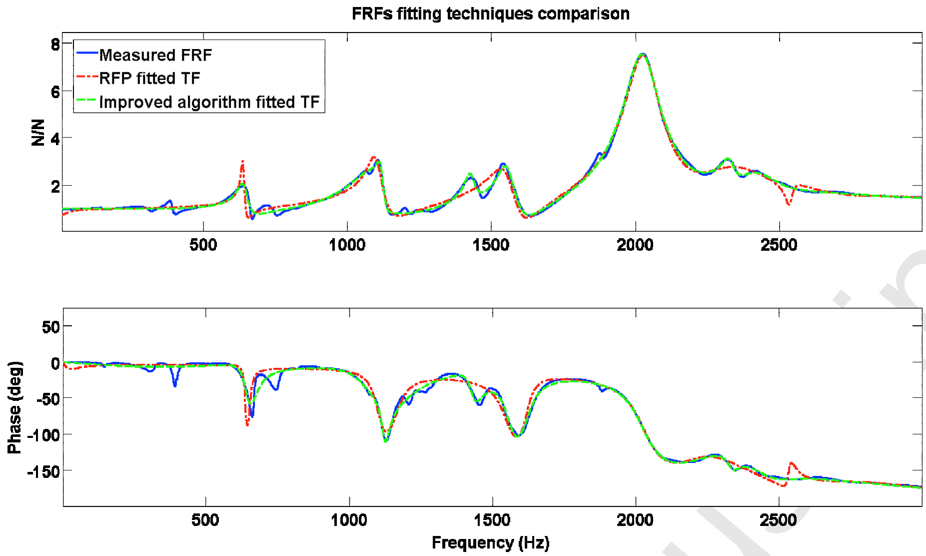

Figure 3: FRF fitting techniques comparison over the 0-3000 Hz frequency range, using 21st order polynomials.

Figure 3 exemplifies that sufficient fitting accuracy could be achieved only using high order TF polynomials, even if the superior algorithm is used.

As highlighted in [16] and [27], the curve fitted TF generally leads to ill-conditioned system matrices and this issue gets more relevant as the polynomial order increases, actually preventing numerical filter computation in this specific application. Approaches such as system rescaling or similarity transformations, like the one used in [16], could only partially solve the problem when the interest is put in compensating dynamic behavior over a wide frequency range with FRFs presenting many modes, as the one measured in this work. Hence to effectively extend the compensation bandwidth while maintaining adequate accuracy over the entire frequency range a specific approach has been developed and allowed to extend the implementation of the described compensation technique to most practical applications, even in HSM if needed.

Since the polynomials used could not exceed a given order without determining numerical limitations, the maximum allowable polynomial order has been imposed for the fitting algorithm and the fitting frequency range has been reduced as much as needed to ensure adequate accuracy over the desired range. By doing so accuracy is maximized for the chosen frequency range overcoming numerical limitations. On the other hand, the resulting compensation bandwidth would be way too narrow for general applications.

To extend the compensation bandwidth as much as needed, while maintaining sufficient accuracy over the entire frequency range of interest, a sort of "parallel elaboration" approach has been developed following [30]. This approach is based on computing different compensation filters for specific discrete frequency ranges over the entire range of interest, maximizing accuracy without exceeding polynomial order limitations. The measured force signals could hence be frequency-partitioned over those frequency ranges using zero-phase band-pass filters; the single frequency contributions could then be processed with the specifically developed compensation filters, finally the compensated force signal could be reassembled by summing the single compensated contributions together. The "parallel elaboration" approach is exemplified in Figure 4.

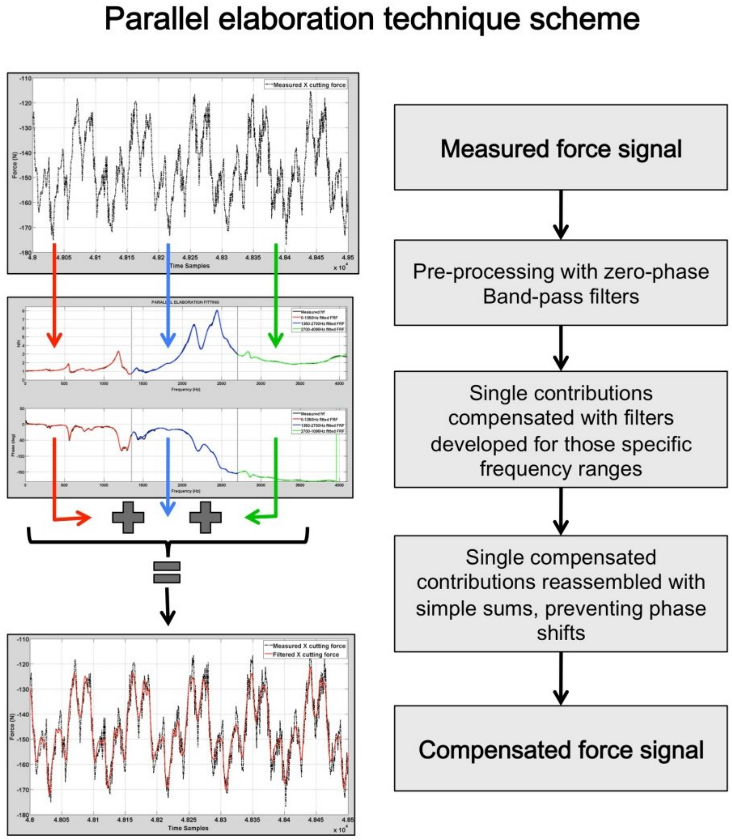

Figure 4: Parallel elaboration technique scheme.

This method allows the avoidance of most of the limitations experienced, but its effectiveness and accuracy mostly depend on the pre-process filtering phase that could become computationally demanding if complex filters are used. Nevertheless in this specific application good results in term of accuracy have been achieved even using computationally efficient 8th order Butterworth filters.

The successive steps necessary for filter computation have been accomplished in accordance with the method reported in [16]. Results obtained by the compensation techniques in cutting coefficient estimation will be fully discussed in a following paragraph.

The improved compensation technique has been validated by means of experiments and supporting results have been obtained in terms of accuracy and effectiveness.

3. EXPERIMENTAL VALIDATION

To investigate the identified cutting coefficients' speed-dependence, using both the average and instantaneous force methods, cutting experiments have been conducted. Slot milling operations were chosen, in order to simplify the average force method implementation.

3.1 Set up

Experimental cutting force coefficient identification has been carried out using a CNC vertical machine, a Mori Seiki NMV1500DCG. The material used for the machining tests was Aluminum 6082-T4 alloy.

The workpiece used was a bar of 60x60x150 mm^3 clamped to a dynamometer with two screws (Figure 5b). A three-component Kistler dynamometer type 9254 A, has been mounted on the machine table and the coordinates system has been set to level with the force sensor surfaces (Figure 5a). LMS Scadas III frontend and LMS Test.lab 11A software have been used to acquire the signals.

The tool has been chosen to ensure stable depth of cut in slotting operations. Different tools and overhangs have been tested. Indentifying tool-tip FRF and calculating Stability Lobe Diagram (SLD) with coefficients measured by the authors in [13] at low speed: a two flute Garant 201770 cutter with 8 mm diameter has been selected and mounted with 20mm overhang on an HSK32ER20 tool-holder (Figure 5c). In Figure 6, the stability diagram is presented. 2.5mm minimum critical depth of cut is identified. Slot milling of 1.5mm was performed considering an adequate uncertainty margin.

In order to determine the average cutting force coefficients, cutting forces have been measured during slotting at different spindle speeds (Figure 5d). For each speed, five different feed rates have been tested to improve data quality for computing linear regression in the average force method. Cutting and tool parameters are summarized in Table 1. Feed rates have been chosen in accordance to the one suggested by cutting tool manufacturer (0.03 mm).

Table 1. Cutting and tool parameters

Tool parameters					
Diameter (mm)	8		Helix angle	45°	
Flutes number	2		Material	Carbide	
Cutting parameter for milling tests					
Spindle speed (rpm)	995	3979	7958	11937	15916
	19894	23873	27852	31831	
Feed per teeth (mm)	0.02	0.025	0.03	0.035	0.04
Axial depth (mm)	1.5		Radial depth	Slotting	

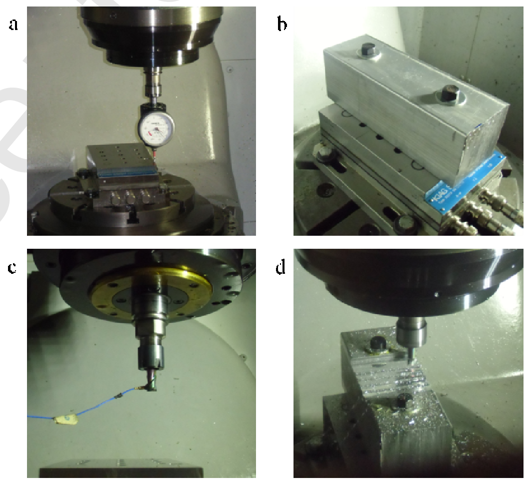

Figure 5: Tests set-up (a) dynamometer (b) workpiece (c) tool (d) slotting tests

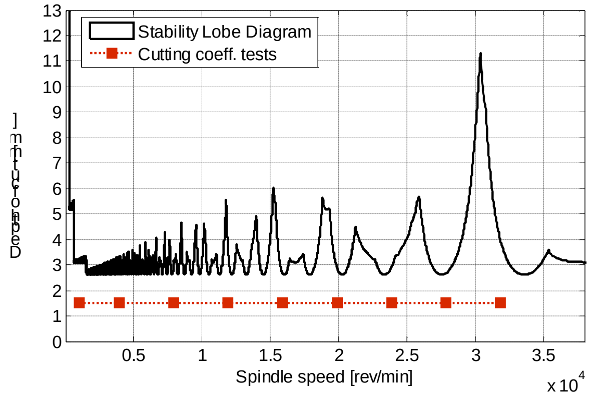

Figure 6: Stability Lobe Diagram for tests of coefficients identification

3.2 Compensation

To investigate cutting coefficient estimation using the instantaneous force method at various spindle speeds, the compensation technique described in Section 2.4 has been used.
Kistler reports a resonant frequency around 2.5kHz for the dynamometer used, as shown in Table 2.

Table 2: Kistler 9257A Table dynamometer technical datasheet.

Measuring range (Fx, Fy)	N	± 5000
Measuring range (Fz)	N	± 10000
Overload capacity	%	50
Resolution	N	0.1
Sensitivity Fx, Fy	pC/N	-7.5
Sensitivity Fz	pC/N	-3.5
Rigidity (x, y direction)	N/μm	1000
Rigidity (z direction)	N/μm	2000
Resonant frequency (z direction)	kHz	≅ 3.5
Resonant frequency (x, y direction)	kHz	≅ 2.5
Linearity	%	< ± 1
Crosstalk	%	< 2
Working temperature range	°C	0…70
Weight	kg	6.9

Referring to Kistler documentation about 5% amplitude rise can be expected at approximately 1/5 of the resonant frequency (f_n). So the expected usable frequency range of this dynamometer should be around 0 – 500 Hz, actually limiting the employable spindle speeds for cutting tests. In Figure 7 this aspect is illustrated.

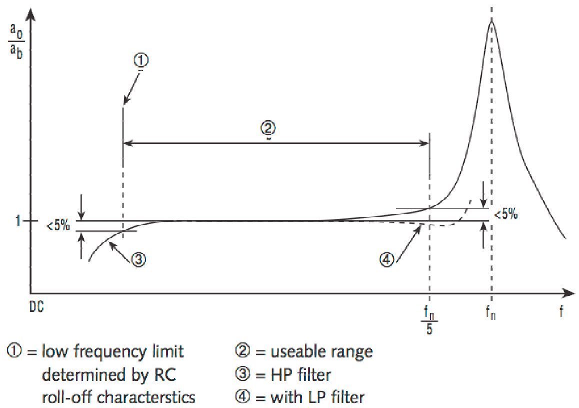

Figure 7: Typical frequency response curve (source: Kistler document 20.290e-05.04).

To estimate the actual measurement bandwidth of the Kistler 9257A table dynamometer used some impact modal tests have been conducted using a Brüel & Kjaer Type 8202 impulse hammer, LMS Scadas III frontend and LMS Test.lab 11A software. In Figure 8 the measured FRFs for each of the three dynamometer axis are reported.

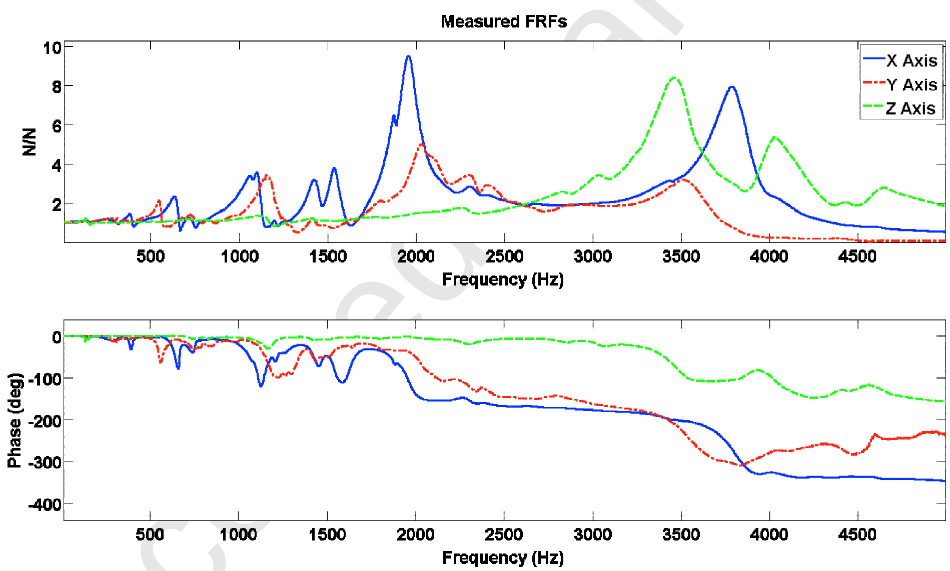

Figure 8: Measured Transmissibility FRFs for each of the Kistler 9257A dynamometer axis.

As shown even in the 0 – 500 Hz range some appreciable modes are presents, reducing the actual measurable bandwidth and confirming again the need of an effective and accurate compensation technique to extend the range of investigable cutting velocities. As a matter of fact, if no compensation is used, the highest spindle speed employable for the experimental tests could not exceed 3000rpm, resulting in around 100Hz tooth passing frequency with a two-teeth mill such as the one used in the experiments. The range of cutting velocities of interest would hence not be sufficient for defining a general trend of cutting coefficients' speed-dependency.

As anticipated, the compensation technique effectiveness mostly depends on the FRF's measurements accuracy, but these FRFs could change over time due to workpiece material removal. It should be clear that this aspect is only relevant for table dynamometer.

To ensure accuracy of the compensation technique is maintained over the entire set of cutting test, the FRFs have been measured at three different times during the milling tests. In Figure 9 the results obtained for the X-axis of the dynamometer in the three different impact tests are shown.

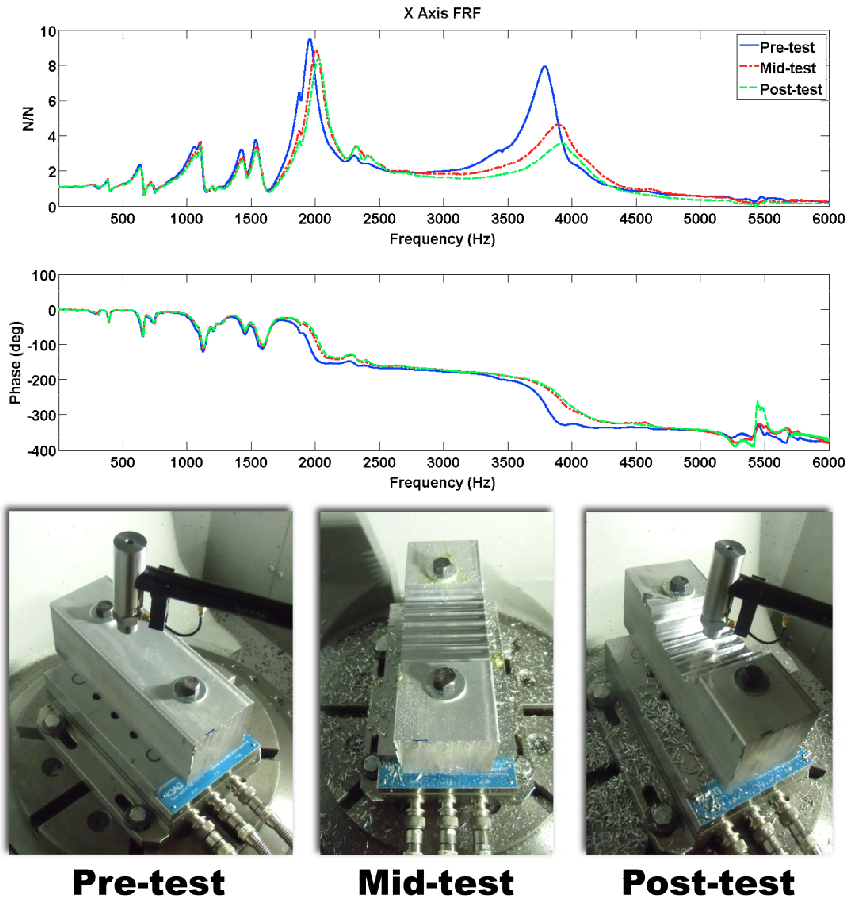

Figure 9: Measured transmissibility FRF-X in different times.

By doing so, the compensation filters could be developed on experimentally measured FRFs that more closely represent the actual system dynamics during the specific cutting tests, ensuring that accuracy and effectiveness of the compensation technique is maintained over the entire experimental data. As shown in Figure 9, the changes in the measured FRFs are appreciable, especially below the transducer resonant frequency, confirming that neglecting the FRFs evolution would result in misleading compensated forces and not reliable coefficient estimation.

As should be expected by analyzing the FRFs, the errors induced in force measurements by the system dynamics are appreciable and for some milling tests the difference in cutting force magnitude was as high as 60%, when the measured and compensated force signals were compared. This confirms, again, that an accurate and effective compensation technique is an absolute requirement if interest is focused on cutting force measurements, even at relatively low spindle speeds.

In Figure 10 a comparison of measured and compensated forces for some of the milling tests is shown both in time domain (Figure 10a) and frequency domain (Figure 10b).

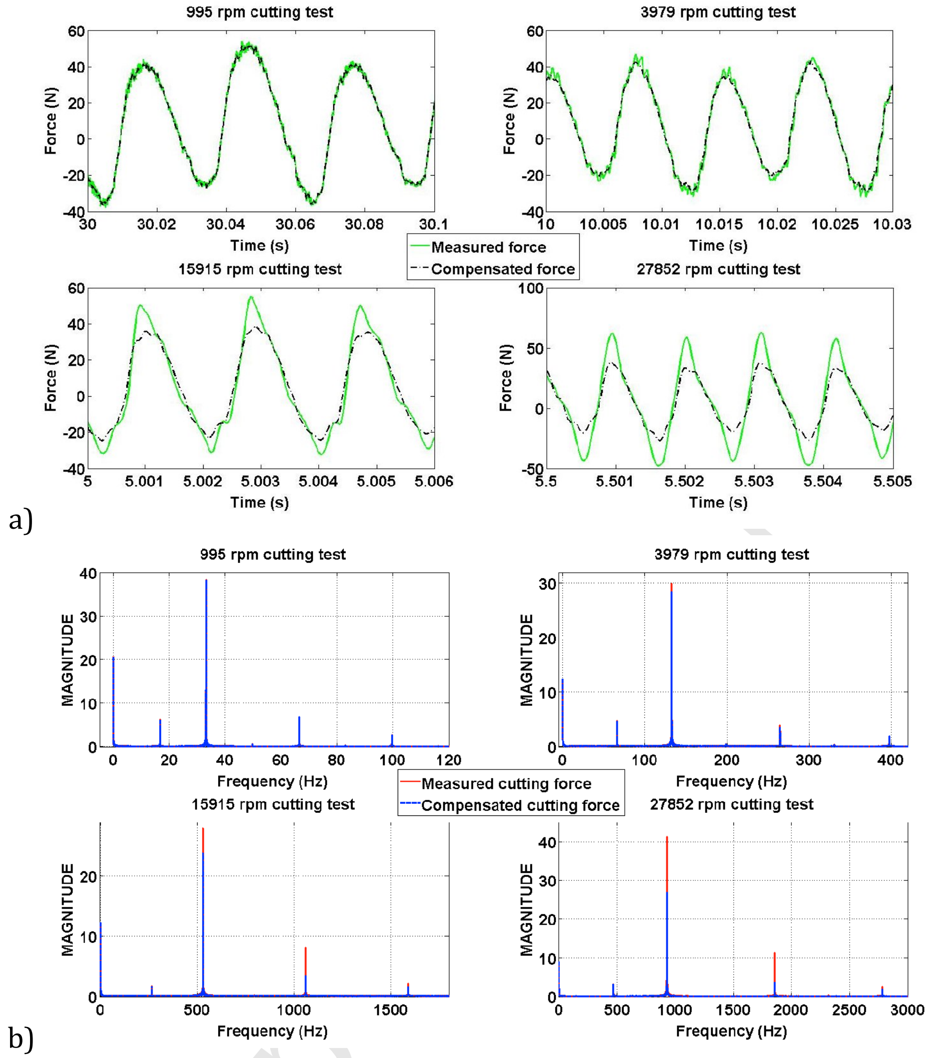

Figure 10: Compensated and measured force signals for four different spindle speeds the along X-axis of the dynamometer, Time domain (a) Frequency domain (b).

Effects of the compensation technique are highlighted in Figure 11, where a comparison between measured and compensated forces is shown over the measurement FRF.

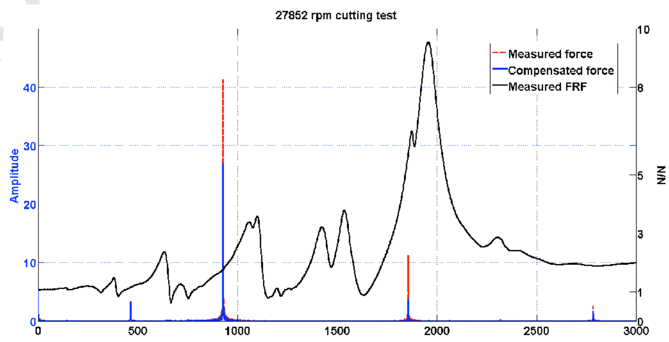

Figure 11: Detailed Frequency domain force signals related to measured transmissibility FRF

As reported in the figure the errors on the measured force signal are in accordance with the distortion imposed by system dynamics.

Even if the differences between measured and compensated forces are appreciable, it should be pointed out that no real need exists in compensating the force signals if the average force method for cutting coefficient estimation is used, since the mean force results will not to be affected by system dynamics. This effect could be explained by pointing out that cutting force signals are actually composed of a mean constant (i.e., 0 Hz) contribution and some frequency contributions related to the tooth passing frequency and its harmonics [5]. While the frequency contributions could be affected by errors induced by system dynamics, as already shown in Figure 9 and Figure 10, the constant contribution should not be distorted by any dynamic effect, since the FRFs should have a magnitude of one and zero phase at 0 Hz, for physical reasons (i.e., rigid motion frequency). This aspect is exemplified by Figure 12, where a comparison between measured and compensated mean forces for one of the experiments is shown.

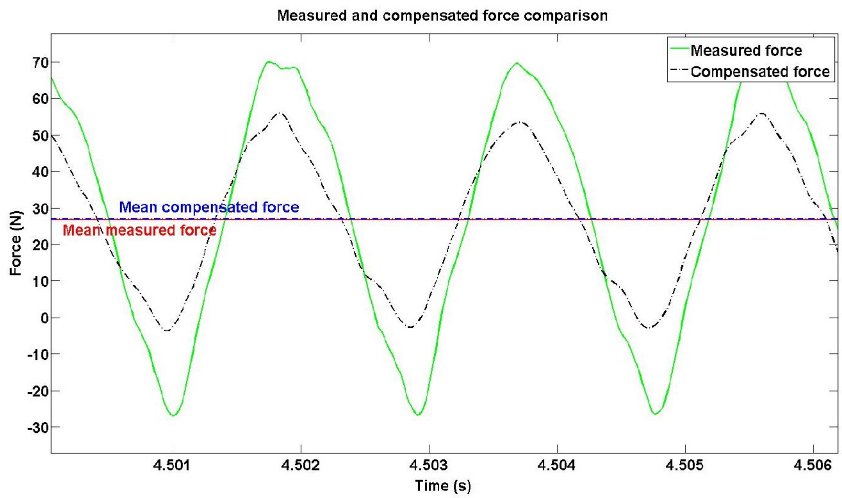

Figure 12: Mean compensated and mean measured forces comparison

On the other hand, if interest is put in implementing the instantaneous force method, the effects of the compensation technique are definitely appreciable, as will be discussed more in detail in the results section.

3.3 Implementation of the Proposed Method

On the basis of force signals acquired in the cutting tests, average force method has been applied to obtain cutting force coefficients. For each spindle speed, average forces at the five feed rates have been calculated, linear regression of the data has been performed to identify cutting coefficients as presented in Section 2.2. Having chosen slotting operations, y direction force has been used to identify tangential coefficients, x for radial and z for axial (e.g. in figure 13).

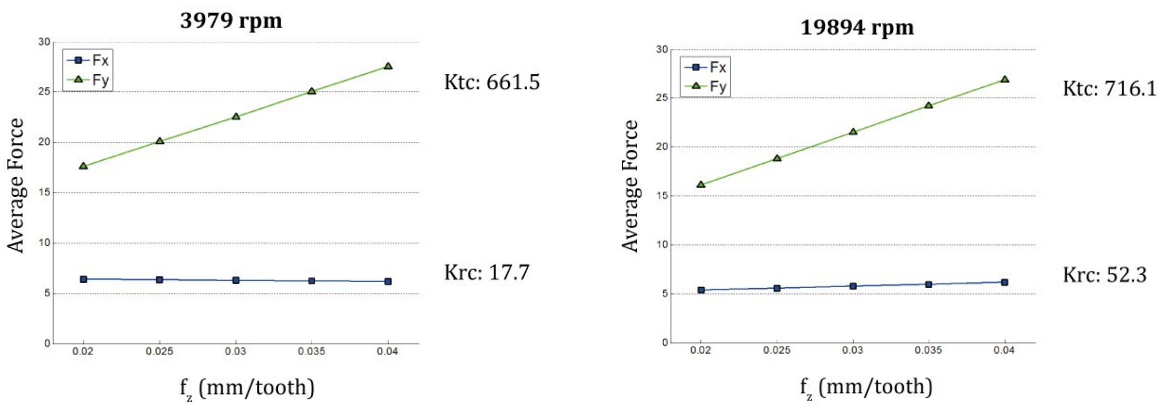

Figure 13: Linear fitting for average method

This procedure has been repeated for each spindle speed: by doing so speed-varying coefficients have been estimated.
In the implementation of the instantaneous force method, coefficients have been calculated for a single feed rate, the one suggested by the tool manufacturer (0.03 mm/tooth). For each spindle speed, a genetic algorithm has been implemented to match simulated and measured forces. This fitting has been applied to a small part of the force signal, consisting of only one tool revolution.
In order to reduce influence of possible local measurement errors in the acquired force signals that could result in misleading coefficient estimation, different samples of each single measured force signal have been selected at different acquisition times. The identified samples have then been averaged to smooth the potential effects of local measurement errors.

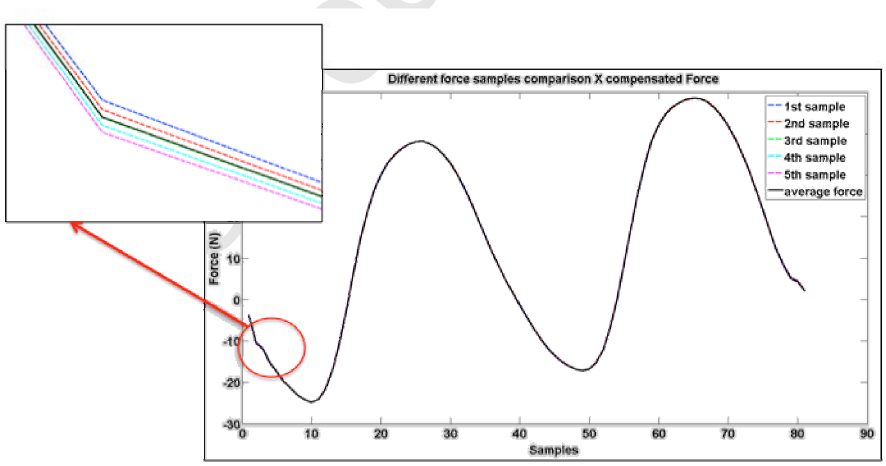

Figure 14: Comparison of five different cutting force samples and average cutting force.

Analogous results have been obtained for all the measured cutting force signals.
As a matter of fact in this specific application the effects of measurement errors could have been neglected, as shown in Figure 14.

3.4 Coefficient identification methods and compensation results

In this section, resulting cutting force coefficients are presented highlighting the influence of compensation on the identification procedure and their dependence on cutting speed.
Coefficients have been calculated for each spindle speed both with average and instantaneous methods using uncompensated and compensated measurements. As already pointed out in

Section 3.2, compensation does not influence the average method, thus only the instantaneous method has been applied to both compensated and non-compensated measurements.
In addition as an added advantage, made possible in the instantaneous force approach, the run-out value has been estimated around 1 µm for all the experiments.
In Figure 15, force measurements at two different spindle speeds (low speed: 3979 rpm and high speed: 27852 rpm) are shown as an example compared to simulated forces using cutting force coefficients obtained by the different methods. Significant variables are presented in the figure (coefficients K_{tc} and K_{rc} and Least Mean Square fitting error between the curves).

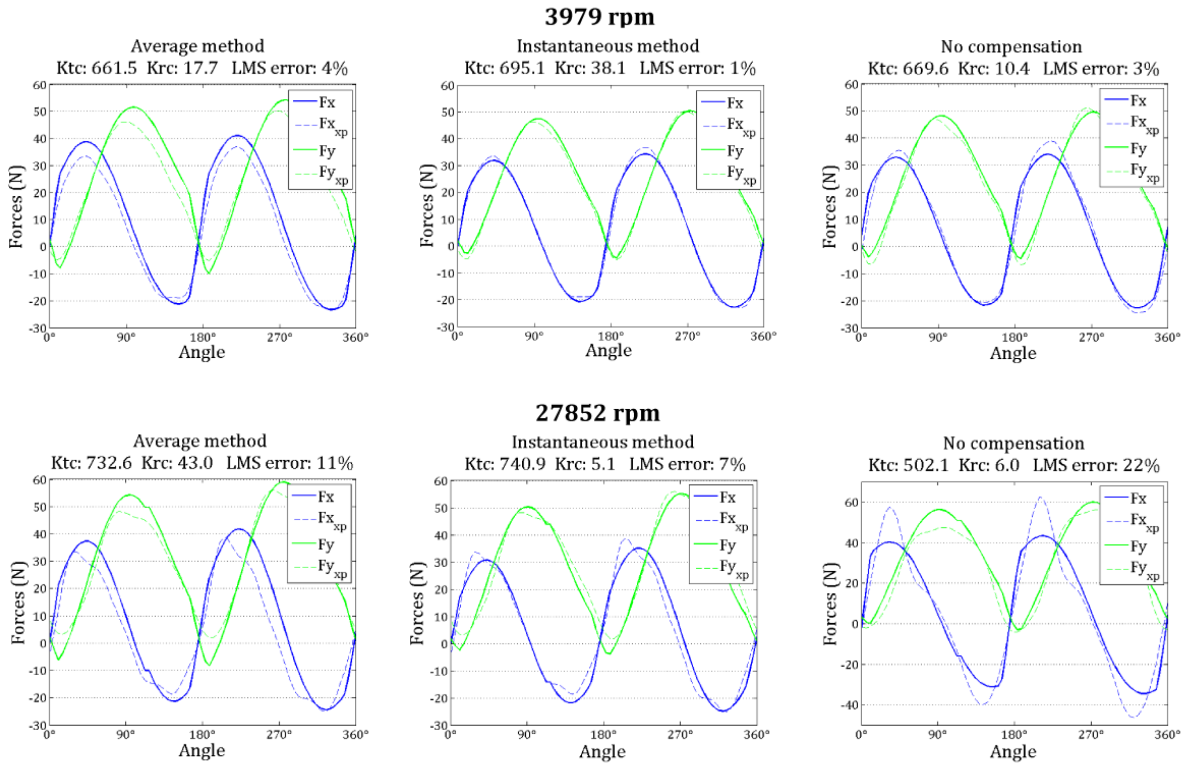

Figure 15: Comparison between cutting forces simulated with coefficients obtained by different methods and experimental forces

As shown in Figure 15, cutting coefficients applied to simulated chip thickness by means of improved formulation including run-out effect lead to more accurate results.
Comparing the two estimation approaches, the instantaneous method is more accurate compared to the average method. However, at high speed compensation is essential to return proper results following the instantaneous approach: at 27852 rpm force signals are sensibly distorted and identification of coefficients from these signals would lead to significant errors.
This is even clearer examining spindle-speed-varying coefficients presented in Figure 16, limiting the analysis to the two more significant coefficients for cutting force model applications, K_{tc} and K_{rc}.

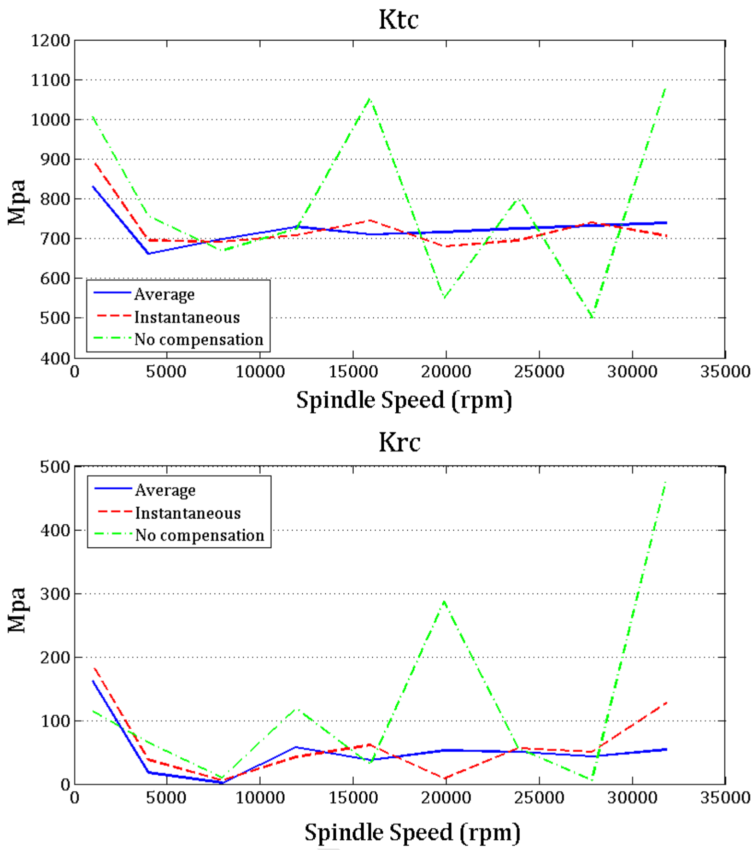

Figure 16: Cutting force coefficients Ktc and Krc varying with spindle speed

Instantaneous method applied to non-compensated force signals becomes unreliable with increasing spindle speed. Average force method and instantaneous method applied to compensated signals result in similar coefficients and similar trends. Coefficient variations with spindle speed range tested are appreciable: estimated coefficients are, in fact, higher at low speed decreasing quickly then increasing again at higher speed.

It is important to point out this trend: generally cutting force coefficients are evaluated only at low speed to avoid transducers dynamics influence and they are used even in higher speed applications. This approach could lead to significant errors, reducing reliability of higher speed simulation.

Moreover, it should be pointed out that speed-dependent coefficients identification can be investigated by means of the average force method, since results obtained by this approach are not affected by transducer dynamics. Therefore, for this technique no real need exists for limiting experiments to low speed, such as generally suggested if interest is put in cutting force simulation at higher speed; given that otherwise misleading results could be obtained.

On the contrary for the more complex and accurate method, as the instantaneous one presented in this paper, distorted force signals influence coefficient identification. Thus a compensation technique as the one proposed is definitely needed.

3.5 Speed varying cutting force coefficients: results and discussion

In this section, the trend of force coefficients, changing with cutting velocity, is highlighted for the average method. In order to improve robustness and investigate repeatability of the resulting coefficients, the cutting tests have been repeated 13 times in the same configuration and parameters. Based on these tests, error bars for each spindle speed and coefficient have been considered in accordance with [31]. Particularly 95% confidential intervals have been computed and presented in Figure 17 as error bars for shearing and edge force coefficients.

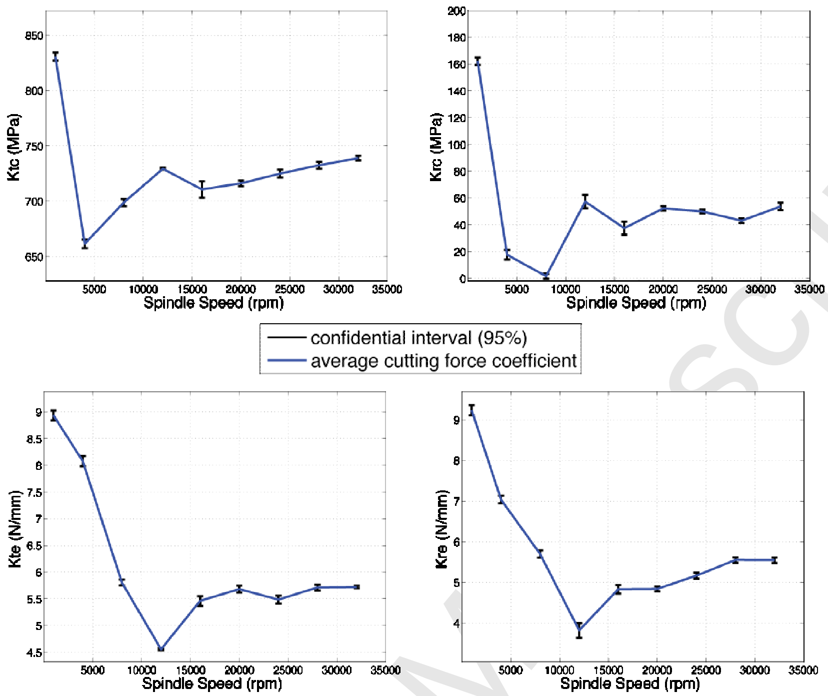

Figure 17: Error bars of average cutting force coefficients varying with spindle speed

As shown in Figure 17, both shearing and edge coefficients change significantly over spindle speed. With these error bars, robustness of the presented results is highlighted: calculated coefficients at different velocities are quite repeatable, the low statistical low statistic spread is identified confirming coefficients' dependency on cutting speed.

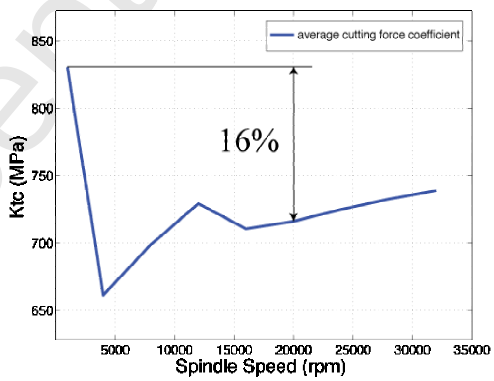

Figure 18: Estimation of coefficient K_{tc} error for 19894 rpm

Cutting force coefficients are traditionally evaluated at low speeds to avoid influence of dynamometer dynamics. These coefficients are considerably different respect to the ones at high speed, reducing reliability of simulated forces. For example 16% error on K_{tc} is committed considering coefficients identified at 995 rpm to simulate forces at 19894 rpm, 8% considering coefficients identified at 3979 rpm, as exemplified in Figure 18.

4. CONCLUSIONS

Cutting force simulation is essential to analyze several aspects in the field of machining, such as chatter stability, dimensional errors, milled surface generation, and trajectory optimization. Cutting force models are generally based on experimentally estimated coefficients, the accuracy of which is crucial to accurately simulate cutting forces.

In this paper a deep investigation of cutting force coefficients at different spindle speeds has been carried out. These coefficients are generally evaluated at low speed to avoid the influence of dynamometer dynamics on measurements. To overcome this limitation an improved compensation technique is presented and experimentally implemented.

Specific cutting force coefficients have been evaluated by means of both average and instantaneous methods resulting in similar values. An advanced instantaneous method has been developed by the authors to reduce the computational effort by means of a genetic algorithm and including tool run-out, by applying an improved chip thickness formulation.

The main conclusions of this investigation are:

1) Cutting force coefficients change appreciably with spindle speed as mechanics of cutting change. This is an issue especially for HSM. Using cutting force coefficients evaluated at low speed for higher speed simulations could lead to significant errors. In some applications, speed-varying coefficients should be useful to improve the reliability of simulated forces.
2) Speed-varying cutting coefficients can be computed without compensating dynamometer dynamics in case of the average cutting force method, but this technique requires four-five measurements at different feed rates to ensure reliable results.
3) Only one series of measurements is needed for the instantaneous force based methods, but an effective compensation technique, as the one presented here, must be applied. Instantaneous force method is more accurate than the average force method. Moreover, in case of using an improved formulation for chip thickness in the fitting approach, also run-out values can be estimated with the same procedure.

   On the other hand, a specific compensation filter is needed for each application, if the workpiece or fixture is changed. Nevertheless this approach is more time-efficient once the compensation algorithm is developed; than the average force approach since fewer experimental data is needed.

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