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ORIGINAL ARTICLE

Mechanistic cutting force model parameters evaluation in milling taking cutter radial runout into account

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Abstract The simulation of the cutting process becomes a key aspect on production optimization. The search for optimal cutting parameters by simulation can be a very effective way of reducing the tuning time of the process and can demonstrate potential cost reduction. As the simulation of the microscopic behavior of the cut is still difficult to perform, most of the prediction techniques are based on mechanistic models of the cutting forces, whose parameters are deduced from experimental tests. The runout of the tool can be a parasite effect that lowers the precision of the identification of the cutting forces parameters. This paper shows the improvement of an identification algorithm given by the modeling of radial runout effect on the undeformed chip thickness. Two different models of cutter runout have been used and tested on experimental measurement performed on a static dynamometer. The adequacy between simulation and experiment is good and allows reliable prediction of cutting forces for different cutting conditions.

Keywords Machining simulation · Cutting forces modeling · Experimental identification · Tool runout

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1 Introduction

Such as many other production techniques, machining process can be optimized by mean of simulation. Various models were developed to study and control parasite effects such as chatter [1–3]. At least three mathematical models must be studied for accurate simulation: the geometry of the chip, the dynamic behavior of the system, and the cutting forces. One of the most difficult points is to find out a reliable model for cutting force simulation. Two main paths have been intensively explored in the literature.

The first one is a complete modeling of physic phenomena during machining at the microscopic scale. Finite elements methods are intensively used to predict chip morphology and cutting forces. These simulations use complex constitutive models of material behavior [4–6] and are, most of the time, limited to the prediction of the cutting forces for orthogonal cutting tests [7, 8]. The simulation of operations with a complex cutting tool is time consuming, so these models are still often unsuitable for practical use on the shop floor [9].

The second approach is a simplified modeling of the machining process based on mechanistic models. The complex cutting tool is divided on slices along its axis, and the cutting forces are locally modeled as a simple analytical law. This is the most common method used in the literature to predict cutting forces for milling [10–12]. The drawback of this method is that the input parameters of the cutting force model are often difficult to find from intrinsic properties of the materials, such as Young's modulus, yield strength, or hardness.

Identification methods must be used to deduce cutting force parameters from experimental tests. A procedure has been developed by Altintas [1], where the cutting constants for a given machined material are identified during orthogonal cutting test. An "orthogonal to oblique" transformation is performed to obtain the cutting constants for practical application (milling, for example).

The aim of this paper is to develop an identification method that is able to identify the cutting coefficient and the runout parameters directly from the measurement of the efforts from milling operation when radial runout is experienced. Moreover, this method only needs one measurement to identify all the data needed to simulate cutting forces for a given operation.

2 Radial runout in milling

The radial runout of the milling tool is defined as the state of a cutter rotating about an axis parallel but not identical to the axis of its geometrical center [13]. As a result, the radial positions of the different teeth of the cutter are slightly different. This phenomenon is caused by a combination of three main sources: the tool itself, the adaptation of the tool into the toolholder, and the position of the toolholder in the spindle. Several technological solution has been developed to minimize this effect, but a common value around 5 μm is often experienced. The runout of the cutter mainly influences the surface finish (the roughness of a surface is often mainly given by one tooth). Schmitz demonstrated that runout can also affect stability of the process [14].

2.1 Modeling the effect of radial runout

Modeling the effect of the cutter runout on the evaluation of the actual chip thickness is important for reliable estimation of the cutting forces. The runout of the cutter can be defined by two values: the shift of the cutter ρ, which is the distance between the center of the cutter and the center of rotation, and the angular position of the center of rotation λ (measured from the position of an arbitrary chosen cutting edge, see Fig. 1).

Sutherland and DeVor [15] and Wang and Liang [16] developed an iterative algorithm to compute the chip thickness with cutter runout using this definition.

As the effect of the radial runout is mainly a shift of the radial position of the teeth, Kline and DeVor [17] developed a simplified model based on a different feed for each tooth. Li and Li [18] developed a model based on the reconstruction of the trochoidal path of the cutter. Those two models are considered for this paper.

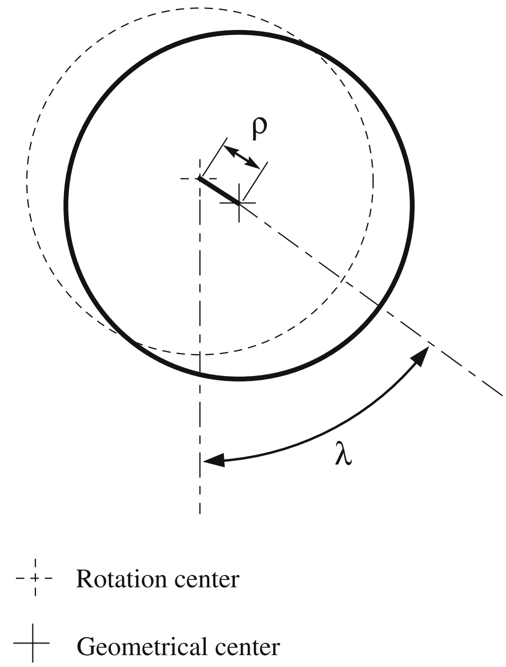

Fig. 1 Definition of the parameters for the radial runout

2.1.1 Simplified model

The simplified method [17] models the effect of the runout as a change in the feed per tooth. It considers that the feed per tooth (f_z) for tooth i is the programmed feed per tooth plus the difference of the radial shift for the tooth in cut i and the previous one $i-1$:

$$f_{z,i} = f_{z,th} + RAD_i - RAD_{i-1} \tag{1}$$

The undeformed chip thickness h is computed using the classical formula (θ is the immersion angle of the tooth):

$$h = f_{z,i} \sin\theta \tag{2}$$

This model is not totally exact, but it allows simple approximation of the actual undeformed chip thickness while the runout of the cutter is small compared to the feed per tooth.

2.1.2 Improved model

Kline and DeVor [17] demonstrated that the runout of the cutter also modifies the entry and exit angle of the cutter into the workpiece. A more precise value of the undeformed chip thickness can be obtained by the reconstruction of the exact trochoidal path of the tooth as in [18].

Points c and i are, respectively, the position of the centre of the cutter and of the cutting edge at time t (see

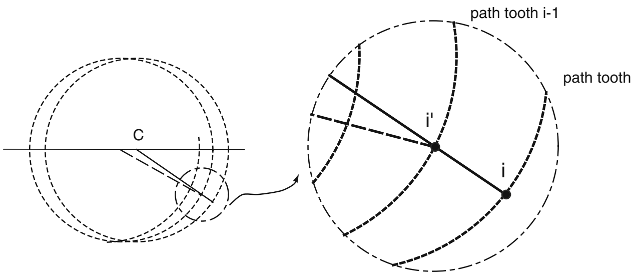

Fig. 2 Trochoidal toolpath

Fig. 2. The coordinate of those points can be computed as follows:

$$\begin{cases} x_c = \dfrac{f_t \cdot n_f \cdot \theta}{2\pi} \\ y_c = 0 \end{cases} \tag{3}$$

$$\begin{cases} x_i = \dfrac{f_t \cdot n_f \cdot \theta}{2\pi} + R_i \sin\theta \\ y_i = R_i \cos\theta \end{cases} \tag{4}$$

R_i is the actual radial position of the edge (taking runout into account) and n_f is the number of cutting edges of the cutter.

The actual chip thickness is given by the distance between point i and point i'. If the runout is small compared to the feed, i' is the intersection between line $|ci|$ and the toolpath of previous teeth. The coordinates of point i' can be found by the following equation:

$$\begin{cases} x_{i'} = \dfrac{f_t \cdot n_f \cdot \theta'}{2\pi} + R_i' \sin\left(\theta' + \theta_p\right) \\ y_{i'} = R_i' \cos\left(\theta' + \theta_p\right) \end{cases} \tag{5}$$

R_i' is the actual radial position of the previous edge, θ' is the immersion angle while the previous edge was on point i', and θ_p is the pitch angle between the tooth in cut and the tooth that left the previous mark on the surface. As points c, i, and i' are collinear, the following relationship can be written:

$$\frac{x_i - x_c}{y_i - y_c} = \frac{x_i - x_c}{y_i' - y_c}; \tag{6}$$

the combination of Eqs. 3 to 5 into Eq. 6 leads to:

$$\frac{R_i \sin\theta}{R_i \cos\theta} = \frac{\dfrac{f_t \cdot n_f \cdot \left(\theta' - \theta\right)}{2\pi} + R_i' \sin\left(\theta' + \theta_p\right)}{R_i' \cos\left(\theta' + \theta_p\right)} \tag{7}$$

$$\sin\theta \cos\left(\theta' + \theta_p\right) - \cos\theta \sin\left(\theta' + \theta_p\right) = \frac{f_t \cdot n_f \cdot \left(\theta' - \theta\right)\cos\theta}{R_i' 2\pi} \tag{8}$$

$$\sin\left(\theta - \theta' - \theta_p\right) = \frac{f_t \cdot n_f \cdot \left(\theta' - \theta\right)\cos\theta}{R_i' 2\pi} \tag{9}$$

If the variable X and the constant A are defined as $X = \theta - \theta'$ and $A = \dfrac{f_t \cdot n_f \cdot \cos\theta}{R_i' 2\pi}$, the equation to solve is as follows:

$$\sin\left(X - \theta_p\right) + A \cdot X = 0 \tag{10}$$

Coefficient A is often small (always less than one). Equation 10 is transcendental so a numerical solving method must be used. If the runout of the tooth is smaller than the feed per tooth, the previous mark on the surface has been left by the previous tooth so the value of X that solves equation 10 is close to θ_p (see Fig. 3). A dichotomic root finding method is sufficient to solve accurately the equation in few iterations.

When the value of X is computed, the position of points c, i, and i' can be easily deduced from Eqs. 3 to 5. The undeformed chip thickness is given by the distance between point i and i'. If the computed value is negative, the chip thickness is set to zero.

$$h = \left|ii'\right| = |ci| - |ci| \tag{11}$$

$$|ci| = \sqrt{\left((x_c - x_i)^2 + (y_c - y_i)^2\right)} \tag{12}$$

$$|ci| = \sqrt{\left(\left(x_c - x_i'\right)^2 + \left(y_c - y_i'\right)^2\right)} \tag{13}$$

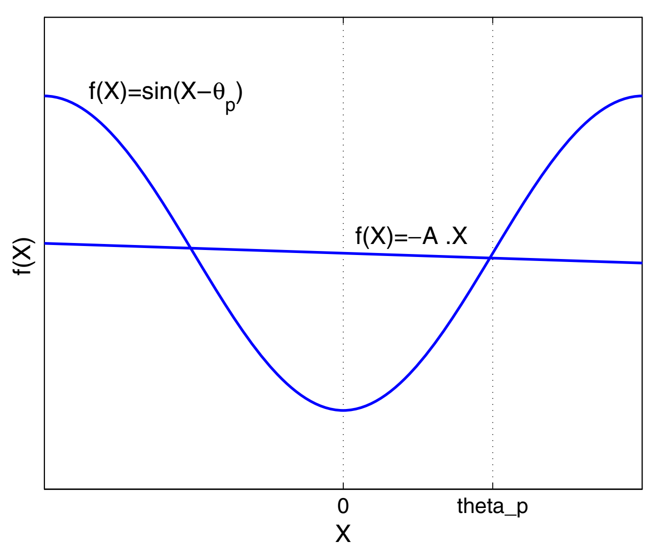

Fig. 3 Localization of the first root of $f(X) = \sin\left(X - \theta_p\right) + A \cdot X$

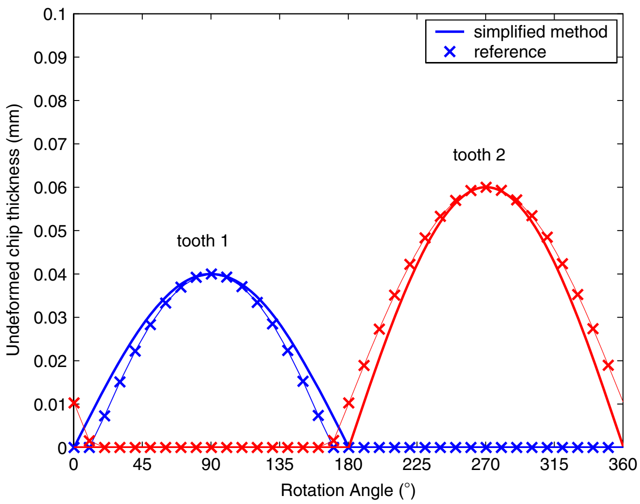

Fig. 4 Comparison between simplified method and the reference case for the undeformed chip thickness

2.2 Simulation example

This example shows the comparison of both methods with the exact toolpath computed with time domain simulation of the milling process performed by an in-house software [19]. The example of a cylindrical cutting tool (diameter 10 mm, two flutes) performing slot cutting is simulated. The feed is 0.05 mm per tooth, the runout of the first tooth is 10 μm.

The comparison shows that the simplified method (Fig. 4) only gives approximate evolution. The improved method is able to reproduce the modification of entry and exit angle (see Fig. 5).

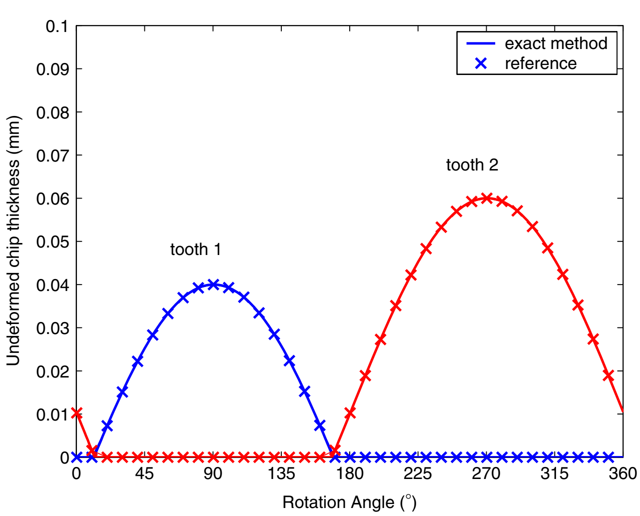

Fig. 5 Comparison between exact method and the reference case for the undeformed chip thickness

3 Cutting force parameters evaluation from measurement

The extraction of parameters of a cutting force model is a key factor for reliable simulation of the machining process. Altintas [1] developed a method based on orthogonal cutting tests followed by mathematical transformation to get the parameters for oblique cutting. This method gives good results but needs to find out the same couple tool/material in orthogonal cut (commonly on a lathe) and in milling operation.

To avoid the use of two different tools, a method to predict cutting force parameters from the measurement of the efforts during milling tests has been developed [20]. This method is summarized, and then the improvements given by the modeling of the runout are developed.

3.1 Theoretical considerations

Mechanistic cutting forces models are based on the mathematical relationship between cutting forces and macroscopic quantities such as chip section or cutting edge length. In order to model the complex geometry of the cutter, a common approach developed by Line and DeVor [17] is to divide the tool into small slices along its axis to study the efforts locally. The approach of this paper for the estimation of the cutting force is the model developed by Altintas [1, 11]. This approach is similar to the developments of Kline and DeVor for a cylindrical cutter [17] or Ko and Cho for ball end mills [12], but the definition of the cutter is more general and allows modeling any geometry of solid cutter.

The elementary efforts on each slice are projected on a global frame and added to get the global effort. For each slice, three directions of projection are defined: along the cutting speed direction (index t), along the local normal to the cutter (index r), and along a third direction (index a) to create an orthogonal frame (see Fig. 6). For this paper, the elementary efforts are computed using the following model proposed by Altintas [1]:

$$\begin{cases} dF_t = K_{te} \cdot \mathrm{dS} + K_{tc} \cdot h \cdot \mathrm{db} \\ dF_r = K_{re} \cdot \mathrm{dS} + K_{rc} \cdot h \cdot \mathrm{db} \\ dF_a = K_{ae} \cdot \mathrm{dS} + K_{ac} \cdot h \cdot \mathrm{db} \end{cases} \tag{14}$$

h is the undeformed chip thickness, db is the projected length of an infinitesimal cutting flute in the direction along the cutting velocity, and dS the local cutting edge length. The coefficients $K_{.c}$ (linked to the shearing of the chip) and $K_{.e}$ (linked to the edge forces) must be identified. The identification method rewrites Eq. 14 into a matrix relationship between cutting forces and cutting coefficients:

$$\begin{Bmatrix} dF_t \\ dF_r \\ dF_a \end{Bmatrix} = \left[A\right] \cdot \overbrace{\begin{Bmatrix} K_{tc} \\ K_{rc} \\ K_{ac} \\ K_{te} \\ K_{re} \\ K_{ae} \end{Bmatrix}}^{\{K\}} \tag{15}$$

$$\left[A\right] = \begin{bmatrix} h\cdot \mathrm{db} & 0 & 0 & \mathrm{dS} & 0 & 0 \\ 0 & h\cdot \mathrm{db} & 0 & 0 & \mathrm{dS} & 0 \\ 0 & 0 & h\cdot \mathrm{db} & 0 & 0 & \mathrm{dS} \end{bmatrix} \tag{16}$$

The efforts are projected in the reference frame of the measurement device. The classical transformation matrix $[B]$ performs the projection (κ is the axial immersion angle, see Fig. 6) .

$$\begin{Bmatrix} dF_x \\ dF_y \\ dF_z \end{Bmatrix} = [B] \cdot \begin{Bmatrix} dF_t \\ dF_r \\ dF_a \end{Bmatrix} \tag{17}$$

$$[B] = \begin{bmatrix} -\cos\theta & -\sin\theta\cdot\sin\kappa & -\sin\theta\cdot\cos\kappa \\ \sin\theta & -\cos\theta\cdot\sin\kappa & -\cos\theta\cdot\cos\kappa \\ 0 & -\cos\kappa & -\sin\kappa \end{bmatrix} \tag{18}$$

The immersion angle θ takes three parameters into account:

- Rotation of the tool ($\Omega \cdot dt$ with Ω the spindle speed)
- Shift of each cutting edge around the tool ($\frac{2\pi}{N}$ for a tool with N edges and uniform pitch)
- Shift of the cutting edge due to helix angle ($\frac{2z\tan i}{D}$ for a cylindrical mill, see [11] for other geometries);

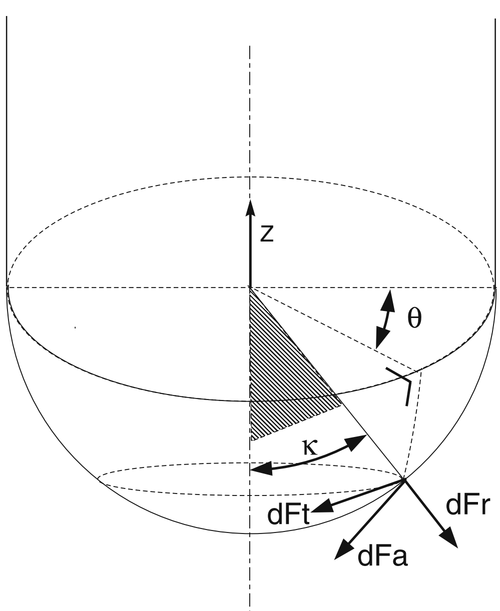

Fig. 6 Orientation of the cutting forces with respect to the tool

These relationships are then added for each tooth and each slice to perform numerical integration along the cutting edges:

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix} = \sum_{i=1}^{n_d}\sum_{j=1}^{n_t} \begin{Bmatrix} dF_x(i,j) \\ dF_y(i,j) \\ dF_z(i,j) \end{Bmatrix} = \overbrace{\left(\sum_{i=1}^{nd}\sum_{j=1}^{nt} [B]\cdot\left[A\right]\right)}^{[C]} \cdot \{K\} \tag{19}$$

Matrix $\left[C\right]$ (dimension 3×6) links cutting coefficients to cutting forces. At each time step, a matrix $\left[C^k\right]$ can be built (k is the index of the current time step).

This method is similar to the work of Ko and Cho [12], but instead of finding the cutting coefficients for each time step, all the matrices are $\left[C\right]$ assembled to get a global system:

$$\overbrace{\begin{Bmatrix} F_x^1 \\ F_y^1 \\ F_z^1 \\ F_x^2 \\ F_y^2 \\ F_z^2 \\ \vdots \end{Bmatrix}}^{[F]} = \overbrace{\begin{bmatrix} C^1 \\ C^2 \\ \vdots \end{bmatrix}}^{[D]} \cdot \{K\} \tag{20}$$

The cutting force parameters can be computed by filling the vector $\{F\}$ with the measured forces and by applying least square fitting method to solve the overdetermined system:

$$[K] = \left([D]^T\,[D]\right)^{-1} \cdot \left([D]^T\,[F]\right) \tag{21}$$

$[K]$ is the matrix containing the six unknown coefficients, $[D]$, the assembly of all $\left[C^k\right]$ matrix and $[F]$ the measured cutting forces.

While the cutting coefficients are obtained, the cutting forces can be simulated and the quality of the fitting can be estimated by the root mean square (RMS) error between computed (F_c) and measured effort (F_m):

$$\mathrm{RMS}_{\mathrm{error}} = \frac{\sqrt{\sum\limits_{i=0}^{\mathrm{npoints}} \left(\left(F_c^i - F_m^i\right)\cdot\Delta\theta\right)^2}}{\theta_{\mathrm{end}} - \theta_{\mathrm{begin}}} \tag{22}$$

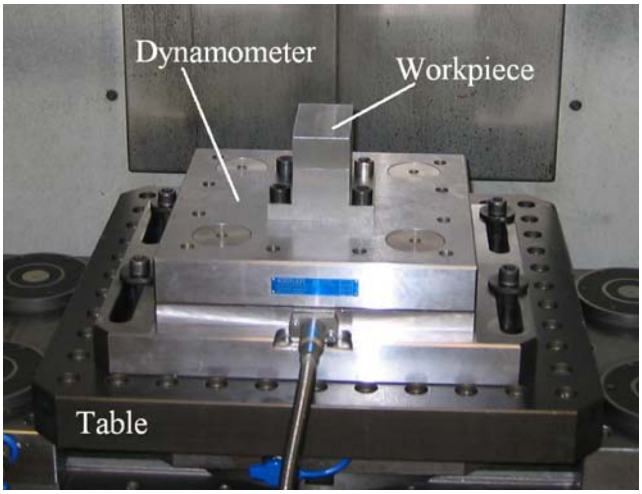

Fig. 7 Test piece on the dynamometer (Kistler 9255B)

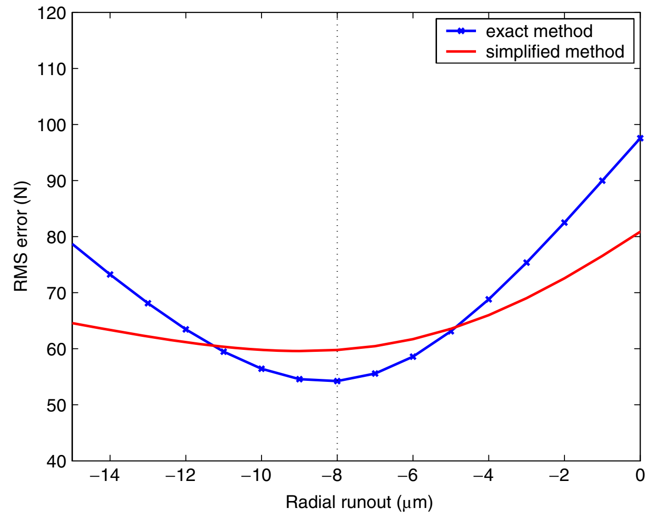

Fig. 9 Evolution of the RMS error with respect to the runout of the second tooth

The actual runout of the cutter is obtained by a minimization of the RMS value for different values of the radial runout of the cutter. This is an advantage of the method as the actual measurement of the runout directly on the spindle could be very difficult due to dynamic effect [21].

The optimization of the RMS value for a given operation has also been successful to predict the parameters of more complex cutting force models with parameters having a nonlinear impact on the cutting forces [22].

3.2 Experimental validation without taking runout into account

A set of measurements were made on a Kistler 9255B dynamometer (see Fig. 7) using a high-speed steel cylindrical cutter (two flutes, diameter 8 mm) to perform slot cutting on St 52-3 steel blocks (50 mm width, 90 mm length, 60 mm height). The cutting parameters were chosen around nominal values of cutting speed (20 m/min) and feed (0.04 mm/tooth). Three different axial depth of cut were used (1.2 and 3 mm).

The reference example for this article is a slot milling test performed with a spindle speed of 875 rotations per minute (RPM), a feed rate of 0.04 mm/tooth, and an axial depth of cut of 2 mm. Figure 8 shows the result of the best fit (for two revolutions of the tool) when the runout of the cutter is not taken into account. The RMS error is of 89 N. It can be clearly seen that the

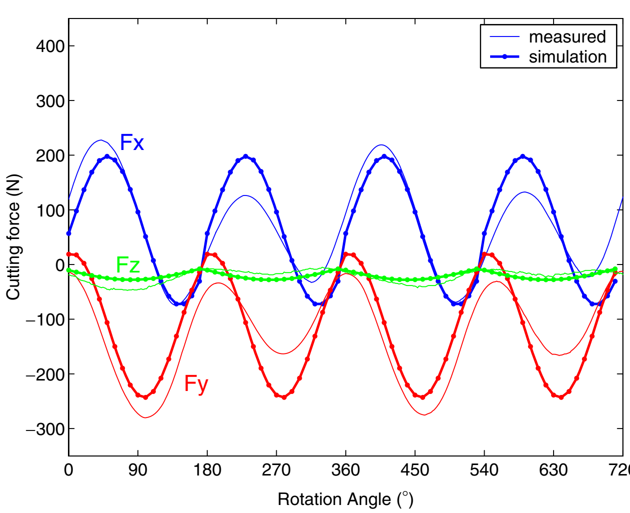

Fig. 8 Comparison of the simulated and measured signal without taking runout into account

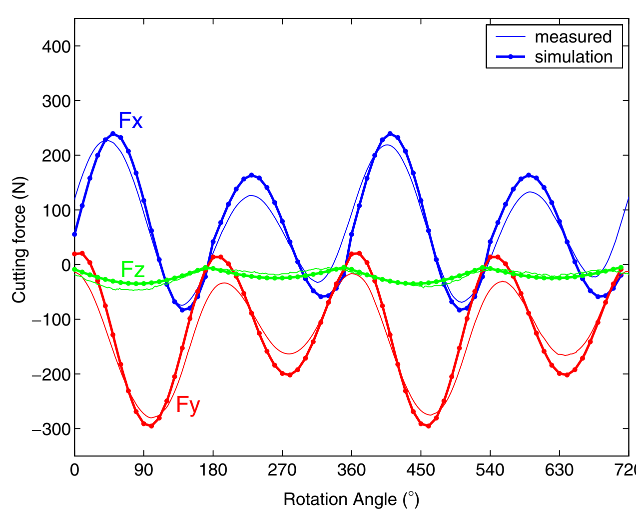

Fig. 10 Comparison of the simulated and measured signal with simplified modeling of the runout

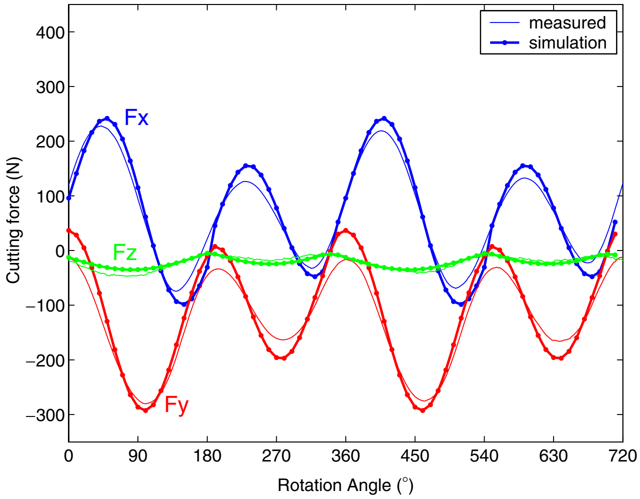

Fig. 11 Comparison of the simulated and measured signal with exact modeling of the runout

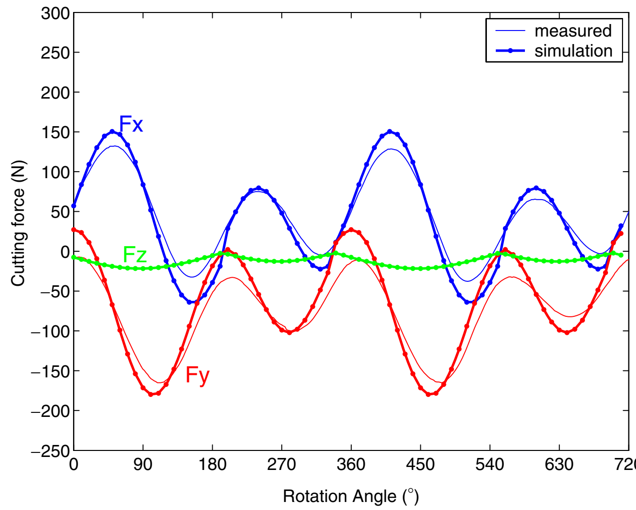

Fig. 12 Comparison of the simulated and measured signal for other cutting parameters

simulated effort gives a mean value between the efforts of both teeth.

3.3 Experimental validation taking runout into account

The identification method is now used on the same measurement taking the runout of the cutter into account. Several values of runout were simulated to find out a minimum value of RMS error. Both simple (see Section 2.1.1) and improved models (see Section 2.1.2) were tested. The minimum error is reached for a radial runout value of −8 μm for the second tooth (see Fig. 9). This value will be taken as the actual runout of the cutter for the next simulations. The comparison between measured and simulated signal using both models of runout are shown in Figs. 10 and 11.

Both methods give a smaller RMS error than the method without runout (about 30% lower). Table 1 summarizes the different cutting coefficients for the three simulations and the RMS error between simulation and measurement.

Taking runout into account gives a more reliable estimation of cutting coefficients. Although the computing time is five times longer while using the exact model of the runout, the difference is small in terms of precision. The simplified method can thus be used for faster computation

4 Exploitation of the method

Extraction of cutting coefficient from measured data is only useful if the model can be used for prediction. In order to estimate the quality of the cutting forces model, cutting forces were simulated for different cutting conditions (depth of cut, feed, cutting speed) and the results were compared to experimental data. Figure 12, for example, shows the comparison between experiment and simulation of a slot milling test with the same tool and the same steel but with a different set of parameters (ADOC 1 mm, 1,050 RPM, 0.044 mm/tooth).

The cutting force parameters obtained by the identification method described in Section 3.3 were used (see Table 1). As the measurements were made without any tool change, the runout of the second tooth is again of −8 μm. The adjustment between simulation and experiment is good if the cutting parameters have small

Table 1 Cutting coefficients and RMS error for the different models

Type of runout	No runout	Simple	Exact
K_{tc} $[MPa]$	2,510	2,700	2,620
K_{rc} $[MPa]$	1,520	1,610	1,560
K_{ac} $[MPa]$	260	320	331
K_{te} $[N/mm]$	10	6	7
K_{re} $[N/mm]$	4	2	3
K_{ae} $[N/mm]$	3	2	1
RMS $[N]$	89	61	54

variations around the value used for the identification test (±20% for cutting speed and feed per tooth, for example).

5 Conclusion

The simulation of the cutting process needs reliable input parameters for computation of the cutting forces. The complex phenomena occurring during machining impose the use of identification methods from cutting tests. The radial runout of the cutter can disrupt the measured signal, so it must be modeled for a more reliable identification.

This paper uses two models of the radial runout of a milling tool and its influence on the undeformed chip thickness. These models are linked to an identification procedure to extract cutting coefficient from experimental tests. Both simple and complex models of the runout are able to predict cutting forces. The simple method is less time-consuming and gives good approximate results if only a fast simulation is needed.

Finally, the reliability of the model is tested on different measurements made with the same couple tool/material. The adjustment remains correct while the cutting parameters vary around their nominal value. These parameters can be reliable input parameters for the simulation of the complete milling process.

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