FINITE ELEMENTS MODEL OF THE MACHINING OPERATION

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Abstract: The achievement of improved manufacturing productivity, product quality and cost reduction require predictive performance models for use in process planning systems for machining. This paper presents a brand-new approach of FE modeling of the machining operation. According to it, the operation must be described in the structure Workpiece – Tool – Machine – Part (WTMP). More specific, at basic level the modeling concerns the interaction between a workpiece FE and a tool FE, during a process sequence (also seen as FE). The proposed FE modeling of the machining operation supposes more modeling levels and, as output, delivers predictions for ten features of the machining operation, namely the volume of detached chips, the cutting force, torque and energy, the tool wear, the part geometry and roughness of the machined surface, the process stability, operation timespan and cost. A very important issue of the new modeling approach is that it allows using the same type of model no matter of the addressed operation type.

Key words: machining operation model, finite elements, operation discrete defining, modeling levels, active points identification.

1. INTRODUCTION

Machining is any of various processes in which a piece of raw material is cut into a desired final shape and size by a controlled material-removal process [1]. Conventional machining continues to occupy a dominant position inside the manufacturing domain. New advances in machine tool and cutting tool technologies, along with advanced materials development, all aimed at improved manufacturing productivity, product quality and cost reduction, require predictive performance models for use in process planning systems for machining. During recent years, significant progresses have been achieved in developing industry-driven models of the machining operations. Industry is interested in process performance measures such as productivity, tool-life, surface finish, part accuracy, etc. Quantitative input is used to predict output parameters in two distinct stages. Physics-based models are developed, at first, to predict fundamental process variables, which are used, then, to predict industry-relevant outcomes (Arrazola et al., 2103).

In what concerns the modeling approaches, the most popular techniques that are applied are: *i)* analytical, *ii)* numerical, *iii)* AI-based, *iv)* empirical, and *v)* hybrid. Among these, the numerical modeling works on the base of continuum mechanics, using finite elements (FE), finite differences (FD), or meshless FE.

The finite element method (FEM) is the most widely used method for solving problems of engineering and mathematical models. The FEM is a particular numerical method for solving partial differential equations in two or three space variables (i.e., some boundary value problems). To solve such a problem, the FEM subdivides a large system into smaller, simpler parts that are called finite elements. A finite element method is characterized by a variational formulation, a discretization strategy, one or more solution algorithms and post-processing procedures [3]. There are several types of FEM – Applied Element Method, Generalized FEM, Mixed FEM, hp-FEM, hpk-FEM, Extended FEM, Scaled boundary FEM (Logan, 2011, Olek et al., 2013, Babuška et al., 2004, Solin et al., 2003, Song and Wolf, 1997).

In machining, FEM has found application in modeling of the chip formation process (Arrazola and Ozel, 2010, Movahhedy et al., 2000, Ozel et al., 2011), cutting forces prediction (Jin and Altintas, 2012, Wang et al., 2006), local temperatures prediction (Grzesik, 2007), stress and strain prediction (Negoescu and Santos Martin, 2019, Pavel and Cărăuşu, 2017), tool-wear analysis (Attanasio et al., 2008), evaluation of part distortion (Marusich et al., 2008).

Despite many of the developed models are leading to satisfactory or even good results when applied in practice, some shortcomings of the actual approaches in FE modeling are obvious, as mentioned below.

- The models are built only at the level of the physical phenomena, the delivered results needing further processing for predicting the industry-relevant outcomes.

- The models have particular character, addressing only a given process, taking place in given conditions.
- The models do not individually cover the entire range of outcomes presenting interest (i.e. different models are needed for predicting the temperature, the force, the distorsion, the tool-wear etc.).

This paper presents a brand-new approach of FE modeling of the machining operation, trying to overcome these shortcomings. The approach starts by making a clear distinction between the *machining process*, seen as mechanical interaction between tool and workpiece, during their relative motion, and the *machining operation*, comprised as accomplishment of a nominal manufacturing task (involving one or more manufacturing processes), following a given procedure and using a given machine tool. According to this approach, the operation must be described in the structure **W**orkpiece – **T**ool – **M**achine – **P**art (WTMP). More specific, at basic level the modeling concerns the interaction between a workpiece FE and a tool FE, during a process sequence (also seen as FE). The proposed FE modeling of the machining operation supposes more modeling levels and, as output, delivers predictions for ten features of the machining operation, namely the volume of detached chips, the cutting force, torque and energy, the tool wear, the part geometry and roughness of the machined surface, the process stability, operation timespan and cost. A very important issue of the new modeling approach is that it allows using the same type of model no matter of the addressed operation type (milling, turning, drilling, shaping etc.).

In what concerns paper structure, next section presents the building of the milling operation FE model. The third section is dedicated to a case-study of using the milling operation FE model for analysis. The fourth section concerns the extending of the model to other machining operations, while the last section is for conclusion.

2. BUILDING OF THE MILLING OPERATION FE MODEL

The core idea in FE modeling of the machining operation is that, instead of looking directly for a global model of the concerned operation, which may not result effective and accurate, it could be more suitable to find this model in three successive steps, explained below.

- At first, the addressed operation is decomposed in elementary sequences, such as each of them means a particular, actual form of the operation and is seen as a finite element of the operation. This step will be further referred as *machining operation discrete defining*.
- Then, each finite element resulted from operation discretization is modeled. Obviously, modeling a sequence is much easier than modeling the entire operation, because we may accept that during such a sequence the process parameters do not change their values. This step will be further referred as *FE modeling*.
- At last, the FE models are assembled in what will be the operation model. This step will be further referred as *machining operation modeling*.

The proposed method for FE modeling of the machining operation regards any type of operation. However, for easier understand how the method works, the milling operation will be addressed at first, in detail. Many of the models for other types of operations can be obtained then, by extending the milling FE model.

2.1 Milling operation discrete defining

Any machining operation is accomplished due to the relative motion between tool and workpiece, which results by composing two motions: cutting motion and feed motion. Two reference systems are necessary in order to describe these motions, the first one being attached to the cutting tool and the second - to the workpiece. By cutting motion we mean the tool and/or workpiece motion relative to its reference system. By feed motion we mean the relative motion between the two reference systems. In the here addressed milling case, the cutting motion means mill rotation around one of tool system axis, while the feed motion is a plane motion.

Starting from these, according to proposed method, the operation discrete defining is accomplished in a spatio-temporal frame structured onto four levels: workpiece (W), tool (T), machine tool (M), and processed part (P).

<u>At W-level</u>, the operation discrete defining supposes to specify the position vectors $\vec{w}_{nk}$ for a number N_n of points W_n (n = 1, 2 … N_n) belonging to workpiece surface, each point being considered in N_k successive positions (so k = 1, 2 … N_k) needed for defining the workpiece cutting motion. In milling case the workpiece does not execute a cutting motion, hence, at this level, k-index may be ignored.

<u>At T-level</u>, the operation discrete defining consists in generating a set of points for defining / replacing the tool peripheral surface (the surface generated by tool teeth into their rotation). In the case of a generic mill having N_i teeth, these points result as further explained.

- Let us consider an arbitrary position of the i-th tooth, A_iB_i, on tool peripheral surface Σ, which has O_Tz as rotation axis, see Figure 1. This position can be defined by η_i angle, measured relative to O_Tx axis, into xy plane.

- The Σ surface is divided in N_j strips (having not necessarily equal heights, this depending on teeth shape) by planes normal to O_Tz. Let us consider the j-th strip (further referred as *j-zone*) of Δz_j height. The intersection between *j-zone* and A_iB_i is $C_{ij}D_{ij}$ arc, whose middle point is denoted by T_{ij}. The position of T_{ij} can be defined by the angle δ_j, measured between T_{ij} projection into *xy* plane and A_i. The horizontal plane (parallel to *xy*) passing by T_{ij} intersects O_Tz axis in the point O_i.

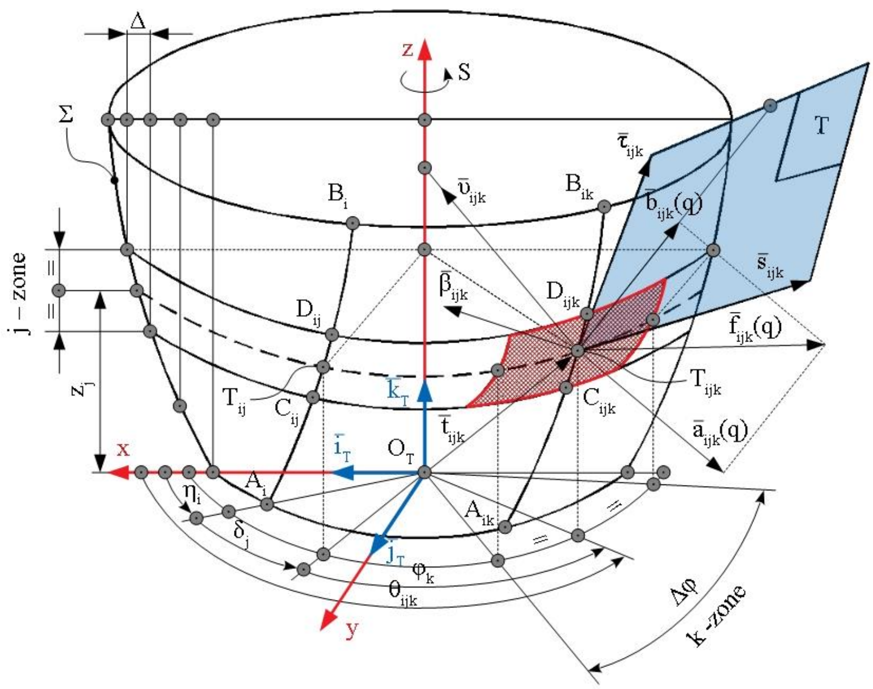

Fig. 1. Tool discrete definition

At M-level, the operation discrete defining concerns the discretization of the both cutting and feed motions.

- The tool cutting motion (here rotation around O_Tz axis) is discretized by considering N_k equidistant positions of the i-th tooth at a complete rotation. Its k-th position is denoted by $A_{ik}B_{ik}$. The intersection between *j-zone* and $A_{ik}B_{ik}$ is the arc $C_{ijk}D_{ijk}$, whose middle point is denoted by T_{ijk}. The position of $A_{ik}B_{ik}$ is given by the angle φ_k, measured between the projections of T_{ij} and T_{ijk} into *xy* plane. The *k-zone* on Σ surface is defined between the curves obtained by rotating $A_{ik}B_{ik}$, in both senses, around O_Tz axis, with $\Delta\varphi/2$ angle.

- A curvilinear quadrilateral from tool peripheral surface, resulting from intersecting *j-zone* with *k-zone* is associated to each T_{ijk} point, following to be used in FE modeling step.

- The feed motion is discretized by considering N_q successive positions of the tool reference system along feed path, the distance between two consecutive positions corresponding to the completion of a tool cutting cycle (here, rotation), hence to the feed.

- For each position q of the tool reference system ($q = 1 \ldots N_q$), its peripheral surface intersects the workpiece after a different surface. Thus, in Figure 2 there are represented two consecutive intersection surfaces, S_{q-1} ($A_{q-1}B_{q-1}C_{q-1}D_{q-1}$) and S_q ($A_qB_qC_qD_q$), in the particular case of a mono-tooth tool. The intersection between S_{q-1} and S_q is the curve *EF*. If the tool is considered in its discrete representation defined at T-level, then a number of points from the tool peripheral surface will retrieve on S_{q-1} and S_q. Among these points, some are real intersection points (further referred as *active points*), while the rest are virtual intersection points. The last ones are called "virtual" because despite belonging to the geometrical intersection between tool and workpiece, the material from their position was already removed by the tool, at the previous cutting cycle. More specific, in the case of S_q, only the points inside A_qB_qFE contour are active.

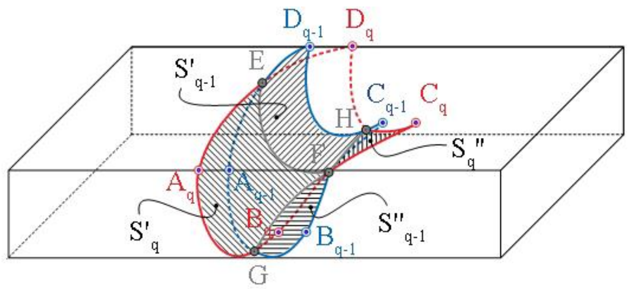

Fig. 2. Tool successive cuts

At P-level, seven features of the machining operation FE are considered, following to be modelled for each FE of the addressed operation: the detached chips volume (V), the cutting force ($\vec{R}$) and torque ($\vec{M}$), the consumed energy (E), the tool wear (U), the geometry (G) and the roughness (H).

2.2 Milling operation FE modeling

Let us consider the problem of building the model for the generic finite element of the milling operation, corresponding to T_{ijk} point. This means the evaluation of the seven features from above, using appropriate analytical models for each of them and firstly requires to express some auxiliary variables, namely:

- The angles η_i, δ_j, φ_k, θ_{ijk} and the distance z_j giving the position of T_{ijk} point onto Σ surface,

- The unit vector of the cutting speed in T_{ijk} point, calculated as:

$$\vec{s}_{ijk} = \begin{pmatrix} \cos\theta_{ijk} \\ \sin\theta_{ijk} \\ 0 \end{pmatrix}, \quad (1)$$

- The unit vector of the tangent to the cutting edge, drawn in T_{ijk}:

$$\vec{\tau}_{ijk} = \frac{\overrightarrow{C_{ijk}D_{ijk}}}{\left|\overrightarrow{C_{ijk}D_{ijk}}\right|}, \quad (2)$$

- The unit vector of the normal to Σ surface, drawn in T_{ijk} point:

$$\vec{v}_{ijk} = \vec{s}_{ijk} \times \vec{\tau}_{ijk}, \quad (3)$$

- The unit vector of the binormal to Σ surface drawn in T_{ijk} point:

$$\vec{\beta}_{ijk} = \vec{\tau}_{ijk} \times \vec{v}_{ijk}, \quad (4)$$

- The length of the elementary chip corresponding to curvilinear quadrilateral associated to T_{ijk} point (see Figure 3):

$$L_{ijk} = \sqrt{\left({t_{ijk}}^2 - {z_j}^2\right)} \cdot \Delta\varphi, \quad (5)$$

- The width of the elementary chip corresponding to curvilinear quadrilateral associated to T_{ijk} point:

$$l_{ijk} = \left|\overrightarrow{C_{ijk}D_{ijk}}\right|, \quad (6)$$

- The angle Φ of cutting force direction, relative to the normal to the cutting edge in T_{ijk} point (Figure 3), depending on tool tooth geometry,

- The unit vector of the feed speed:

$$\vec{f}_{ijk}(q) = \vec{a}_{ijk}(q) + \vec{b}_{ijk}(q). \quad (7)$$

The first term from right side of relation (7) means the unit vector component in the normal ν direction, while the second - the unit vector projection onto the plane tangent to Σ surface, drawn in T_{ijk} point. Hereby,

$$\vec{a}_{ijk}(q) = \left(\vec{f}_{ijk}(q) \cdot \vec{v}_{ijk}\right) \cdot \vec{v}_{ijk}, \quad (8)$$

and

$$\vec{b}_{ijk}(q) = \vec{f}_{ijk}(q) - \vec{a}_{ijk}(q). \quad (9)$$

Then, the values of other parameters, which do not depend on the discrete definition of the machining operation, are also needed:

- The process parameters: tool rotation speed, S, feed, F, and cutting resistance of the machined material, σ_a.

- The durability exponent, m, and the specific speed of tool wearing, K, their values depending on the properties of both tool and workpiece materials, on tool geometry and on cutting regime.

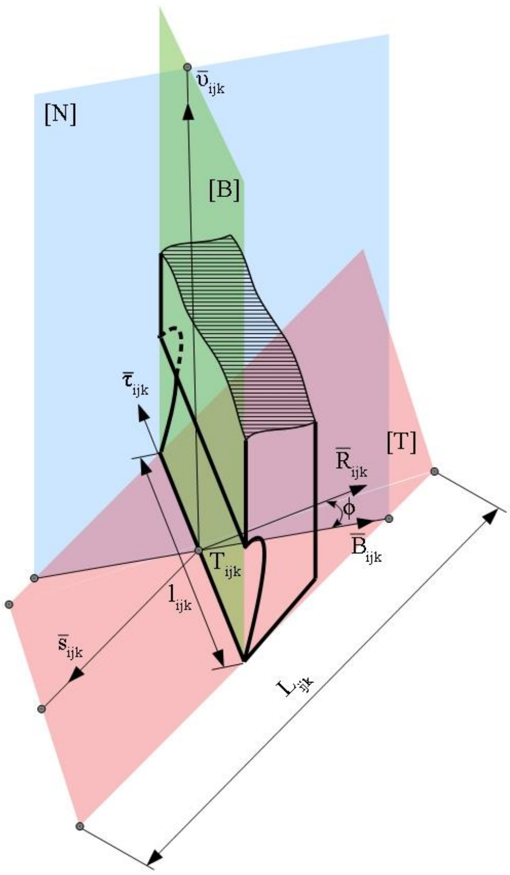

Fig. 3. The elementary fragment of tool tooth

Finally, the expressions of the seven features can be written, as follows:

- The elementary volume of detached chips:

$$V_{ijk}(q) = L_{ijk} \cdot l_{ijk} \cdot \left(\vec{s}_{ijk} \cdot \vec{\beta}_{ijk}\right) \cdot F \cdot a_{ijk}(q) = \\ = {V_{ijk}}^{*} \cdot F \cdot a_{ijk}(q). \quad (10)$$

- The elementary cutting force:

$$\vec{R}_{ijk}(q) = l_{ijk} \cdot \left(\vec{v}_{ijk} \cdot \cos\phi + \vec{\beta}_{ijk} \cdot \sin\phi\right) \cdot \sigma_a \cdot \\ \cdot F \cdot a_{ijk}(q) = {\vec{R}_{ijk}}^{*} \cdot \sigma_a \cdot F \cdot a_{ijk}(q). \quad (11)$$

- The elementary cutting torque, calculated relative to O_T point:

$$\vec{M}_{ijk}(q) = \left(\vec{t}_{ijk} \times \vec{R}_{ijk}{}^{*}\right) \cdot \sigma_a \cdot F \cdot a_{ijk}(q) =$$
$$= \vec{M}_{ijk}{}^{*} \cdot \sigma_a \cdot F \cdot a_{ijk}(q). \qquad (12)$$

- The energy needed for detaching the elementary volume of chips:

$$E_{ijk}(q) = \left(\vec{R}_{ijk}{}^{*} \cdot \vec{s}_{ijk}\right) \cdot L_{ijk} \cdot \sigma_a \cdot F \cdot a_{ijk}(q) =$$
$$= E_{ijk}{}^{*} \cdot \sigma_a \cdot F \cdot a_{ijk}(q). \qquad (13)$$

- The tool wear for detaching the elementary volume of chips:

$$U_{ijk}(q) = K \cdot L_{ijk} \cdot \left(\sqrt{\left(p_{ijk}{}^2 - z_j{}^2\right)}\right)^{\frac{1-m}{m}} \cdot \sigma_a \cdot$$
$$\cdot S^{\frac{1-m}{m}} \cdot F \cdot a_{ijk}(q) = U_{ijk}{}^{*} \cdot \sigma_a \cdot S^{\frac{1-m}{m}} \cdot F \cdot a_{ijk}(q). \qquad (14)$$

- The geometrical dimension of the machined surface is calculated by interpreting the coordinates of the tool active points which leave their print onto the machined surface (further called remaining points).

- The elementary geometrical roughness:

$$H_{ijk}(q) = 8 \cdot C_{ijk}{}^{(b)}(q) \cdot \left(F \cdot b_{ijk}(q)\right)^2, \quad (15)$$

where $C_{ijk}^{(b)}$ means the curvature of Σ surface on direction normal to feed direction (hence on binormal direction).
In relations (10) … (14), the variables marked with asterisk mean invariant features of the given tool – in other words, their values do not depend on the machined workpiece or on the process parameters.

2.3 Milling operation modeling

The third step of finding the milling operation model involves three actions:

- The active points $T_{ijk}(q)$ from tool surface must be identified in each of the N_q relative positions between tool and workpiece reference systems, for each of the N_k positions of the tool around its axis.
- The remaining points are identified among the active points.
- The values in the active points of the seven operation features being modeled at FE level are processed (cumulated, analyzed or compared) in order to deliver the required information about the addressed operation.

<u>The active points identification</u> can be performed by successively running three tests:

- The belonging test, for finding if the considered point is inside the workpiece body,
- The self-interference test, for revealing if the considered point passes beyond the trace leaved in workpiece material by the tool at the previous, (q-1) cutting cycle, and
- The cross-interference test, for seeing if the considered point is not overcut due to interference with other teeth of the tool.

The belonging test is run by checking if $T_{ijk}(q)$ coordinates satisfy the geometrical condition defining the workpiece material domain, having the generic form $\overrightarrow{T_{ijk}(q)W_{nk}} \cdot \vec{v}_{nk} > 0$, for any value of n between 1 and N_n.
The self-interference test is performed by calculating the product $\vec{f}_{ijk}(q) \cdot \vec{v}_{ijk}$. If the product sign is "+", then the answer to the test is positive.
The cross-interference test is applied by calculating the products $\overrightarrow{T_{ijk}(q)T_{i^*jk}(q)} \cdot \vec{v}_{ijk}$, where T_{i^*jk} is a point having $i^* \neq i$, which was brought into the reference position by rotating it with $(\eta_i - \eta_{i^*})$ angle around O_Tz axis. The addressed point passes this test only if all these products are positive.
The $T_{ijk}(q)$ point is active only if concomitantly passes all three tests. The information about the active points is stored with the help of the tridimensional massive $A(q)$ whose element $a_{ijk}(q)$ is 1 if $T_{ijk}(q)$ is active and 0 if not.
<u>The remaining points selection</u> is accomplished by testing the condition $\varepsilon - \left|\vec{f}_{ijk}(q) \cdot \vec{v}_{ijk}\right| > 0$, where ε is a positive parameter near to zero, whose value is established depending on the targeted modeling accuracy. The $T_{ijk}(q)$ point is considered as remaining point if satisfies the mentioned condition. The information about the remaining points is stored with the help of the tridimensional massive $G(q)$ whose element $g_{ijk}(q)$ is 1 if $T_{ijk}(q)$ is a remaining point and 0 if not.
<u>The processing of features values modeled at FE level</u> is done depending on the specific of the addressed feature. For example, in the cutting force case:

- For analyzing the time dependence of the total cutting force R, in a given position q of the tool reference system relative to workpiece reference system, the values of the elementary cutting force for all active points are successively cumulated for the values k = 1, 2, … N_k, thus resulting the series of momentary forces R_1, R_2, … R_{N_k}.
- For finding the distribution map of the cutting force, at a given moment (corresponding to a certain value of k), the values of the elementary force in the active points are represented after the values of i and j.

3. CASE-STUDY OF USING THE MILLING OPERATION FE MODEL FOR ANALYSIS

A case-study addressing the analysis of cutting forces torsor at milling versus the tool used in this purpose is further presented in order to suggest the potential applications of the machining operation FE model in the analysis of the various issues concerning the process. The torsor features that will be evaluated depending on tool features are: force modulus and direction, force space mapping, force dynamics, force static and dynamic action on the machining system.

The tools features considered for the mentioned analysis are: teeth profile, teeth positioning, tool speed and feed. A peripheral milling operation, using a face mill (R_{min} = 35.7 mm, R_{max} = 49.75 mm, h = 30 mm) with axial profile in arc of circle (R_g = 50 mm) and helical teeth (z = 15 teeth, see Figure 4) was addressed.

Tool discrete definition (according to section 2.1) comprises N_i = 15 teeth and N_j = 15 strips, hence 225 T_{ij} points. The tool cutting motion (rotation) was discretized in N_k = 100 teeth positions / tool rotation, while the rotation speed was of 600 rot/min and the feed – 1 mm/rot.

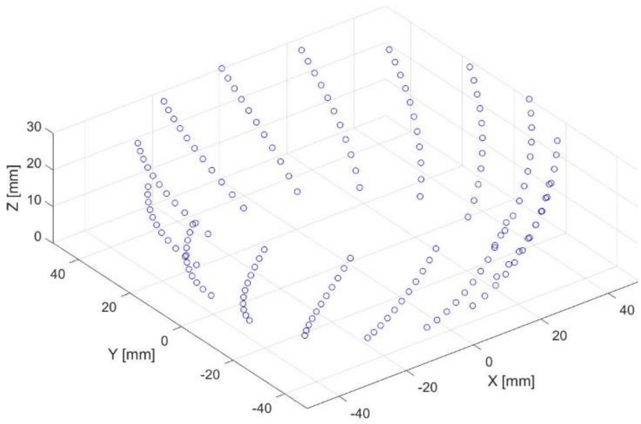

Fig. 4. Face mill teeth profile

The workpiece was supposed to have parallelepipedal shape (with length, width and height equal to 150, 50 and 40 mm, respectively). Tool axis was vertically positioned, at the middle of workpiece width, while mill end – at 20 mm above workpiece base surface.

A MatLab application has been developed in order to:

- Generate the coordinates of T_{ijk} points (see section II.1), on the base of input parameters defining tool geometry,
- Calculate the values of the auxiliary variables and of the seven operation features at FE level (see section II.2), in all T_{ijk} points, and
- Identify the active points at each position q of the tool along the feed-motion path (see section 2.3).

Another complementary MatLab application has been created for processing the values of the features modeled at FE level, aiming to enable the analysis of cutting forces torsor during the milling operation performed in the specified conditions.

The cutting force $\vec{R}_{ijk}(q)$ space mapping can be drawn, using the values calculated by FE modeling, depending on the followed purpose, after any combination of indexes selected from i, j, k and q. Regarding cutting force dynamics, in Figure 5, the variation of the cutting force, cumulated at tool level, is depicted, while in Figure 6, the cumulated cutting force hodograph is represented. In both cases, the tool teeth were considered as equidistant (meaning an angle of 16 degrees between any two consecutive teeth).

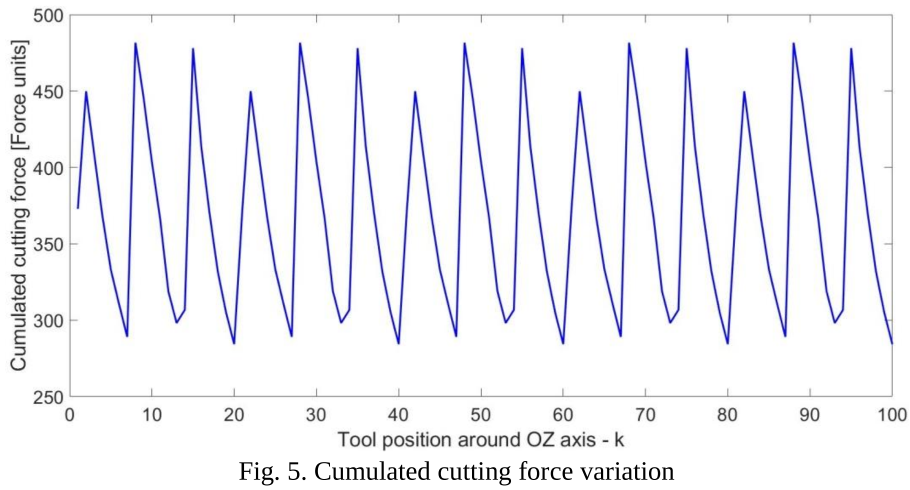

Fig. 5. Cumulated cutting force variation

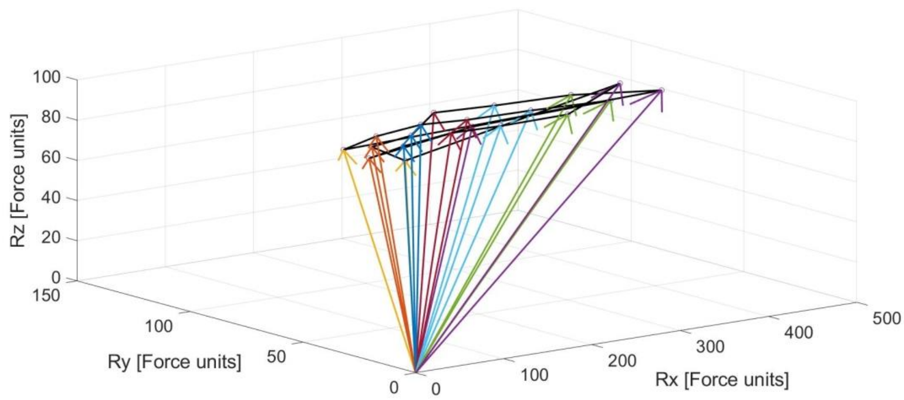

Fig. 6. Cumulated cutting force hodograph

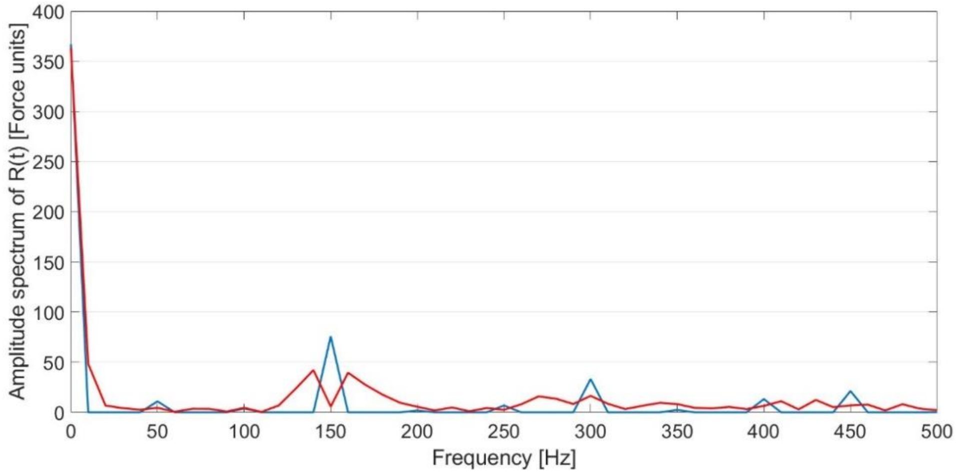

Fig. 7. Amplitude spectrum of cutting force R: tool with equidistant teeth (blue) vs. tool with successive teeth placed at different angular intervals (red)

For studying the force dynamic action on the machining system, the FFT has been applied to force variation function $R(t)$, which can be easily obtained by converting $R(k)$, resulted after the FE modeling of the addressed milling operation. In Figure 7 one can see the amplitude spectrum depicted in blue. It is easy to notice a significant value of the amplitude at 150 Hz, corresponding to the frequency of teeth incoming / outcoming into the cutting process. If the angular interval between the successive teeth is variable (monotone increase for the first eight teeth and decrease for the rest), then the maximum values of the amplitude obviously smoothens (the red spectrum).

4. EXTENDING THE MODEL TO OTHER MACHINING OPERATIONS

The FE model extending to other machining operations can be reached by customizing its general form, presented in Figure 8, to the characteristic issues of each addressed operation.

The meanings of the notations from Figure 8 are:

- i – current number of tool cutting edge / tooth;
- j – current number of the point belonging to a given cutting edge / tooth;
- p – current number of the considered fraction of a certain cutting cycle;
- q – current number of the considered cutting cycle;
- m – current number of a line used for defining the workpiece surface;
- n – current number of the point belonging to such a line;
- $\vec{s}(p,q)$ – the relative speed ($T – W$), and
- $\vec{f}(p,q)$ – the relative displacement ($T – W$).

The notations of the modeled features at FE, respective operation level are summarized in Table 1.

In order to define a general shape of workpiece surface, the set of points W_{mn} might comprise several sub-sets, each of them describing a different surface delimiting the workpiece. At the same time, in order to define a general type of tool, the set of points T_{ij} might also comprise several sub-sets, each of them describing a group of cutting edges.

The set of sequences $M(p, q)$ of T-W relative motion can involve more components, e.g. $\vec{s}_T(p,q)$ and $\vec{s}_W(p,q)$ for $\vec{s}(p,q)$, or $\vec{f}_T(p,q)$ and $\vec{f}_W(p,q)$ for $\vec{f}(p,q)$. The relative motion actually results by composing these components, after referring them to same system (either of the tool or of the workpiece).

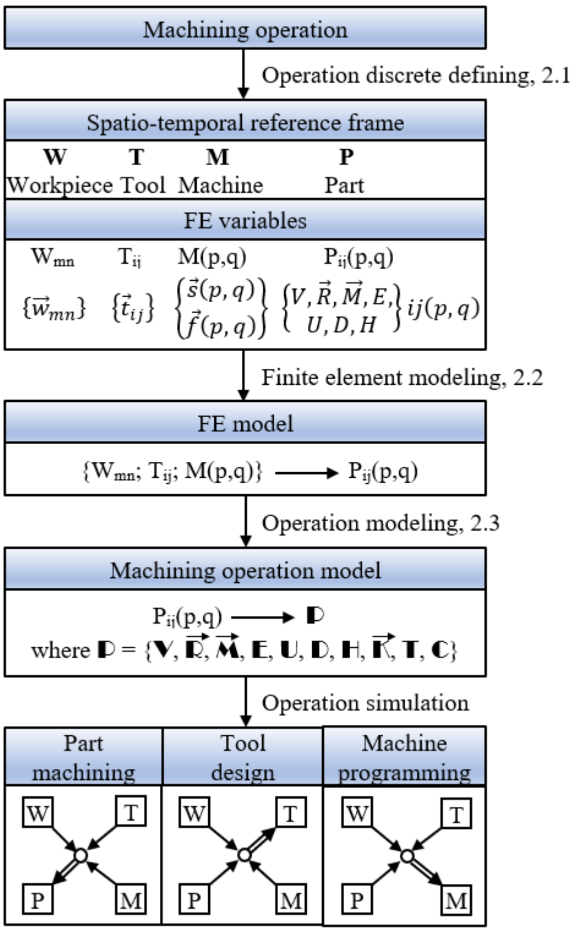

Fig. 8. Extending the model to other machining operations

Table 1. Modeled features notations

Crt. no.	Modeled feature	FE level $P_{ij}(p,q)$	Operation level **P**
1	Volume	V	**V**
2	Force	$\vec{R}$	$\vec{\mathbf{R}}$
3	Torque	$\vec{M}$	$\vec{\mathbf{M}}$
4	Energy	E	**E**
5	Wear	U	**U**
6	Geometry	G	**G**
7	Roughness	H	**H**
8	Stability	-	$\vec{\mathbf{K}}$
9	Timespan	-	**T**
10	Cost	-	**C**

5. CONCLUSIONS

This paper presents a brand-new approach of FE modeling of the machining operation, trying to overcome the shortcomings of current approaches. According to this approach, the operation must be described in the structure Workpiece – Tool – Machine – Part (WTMP). The proposed FE modeling of the machining operation supposes more modeling levels and, as output, delivers predictions for ten features of the machining operation. The model has been introduced in the case of the milling operation. The results of a numerical simulation for analysis of the cutting forces torsor versus the tool features proves FE model efficiency and utility.

The new modeling approach allows using the same type of model, no matter of the addressed operation type, by particularizing a general form, also developed.

6. ACKNOWLEDGEMENT

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