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Cutting Forces Simulation for End Milling

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Abstract. The cutting force in end milling is the essential perturbation of the machining system that limits the productivity of the process. Therefore, forecasting the cutting force when assigning the processing mode and the geometry of the allowance layer to be cut is an urgent task that requires an operational tool for its solution. The method of calculating the cutting force is presented, based on a mechanistic approach, when the geometric ratios of the cutter blades’ positions on the sweep determine the thickness of the undeformed chip. The developed algorithm calculates the cutting force by double integration, first by the length of the cutting edge and then by the number of such edges. The algorithm also allows the simulating of the outrun of the mill on the cutting force and its components. The created application program visualizes the simulating process by oscillograms of the cutting force components for both up and down milling. Experimental studies, in general, proved the adequacy of the developed modeling method. The created program is a tool for operational forecasting of the cutting force during the technological preparation of the end milling process in production.

Keywords: cutting force, end milling, process innovation, numerical simulation.

1 Introduction

Due to its versatility and flexibility, end-milling operations have found wide use in machining machine parts, especially the contour machining of parts of aviation and automotive equipment, stamps, and molds. Efforts to increase productivity due to the intensification of the cutting process encounter obstacles in the form of vibrations, which lead to a deterioration in the quality of machining, rapid tool wear, and even its breakage.

The cutting process occurs in a closed machining system, which is influenced by a power disturbance in the form of a cutting force. The process’s closedness consists of the fact that the cutting force, which, among other factors, depends on the mode, provokes changes in the cutting conditions, which, in turn, causes a change in the cutting force. Therefore, the quality of the machined surface depends entirely on the cutting force, which must be determined from the operating conditions of the machining system, which naturally has feedback.

The technological preparation of the end milling process on CNC machines and the design of control programs occurs with the wide application of CAD/CAM systems. However, the designation of the cutting mode, which will determine the cutting force in the system and the machining quality, is performed by a technologist-programmer who uses his own experience or the tool manufacturer’s recommendations. This approach does not guarantee the optimization of the process based on the parameters of the specific machining system where the machining takes place. The task becomes more complicated with contour end milling, where the cutting conditions change a priori according to the shape formation trajectory.

So, the optimization problem has an essential constituent task: forecasting and determining the cutting force acting in the machining system.

Prediction of the cutting force is significant in the final milling of thin-walled parts in the machining system of low rigidity, which is widely used in the aerospace and automotive industries [1]. It is clear that without an adequate model of the cutting force when milling such parts, it is impossible to solve the optimization problem.

Many models have been developed to study the end-milling process, but with the development of measuring techniques and numerical computational approaches, new opportunities appear to improve models and create an effective tool for the technologist in parts production. In addition to solving the optimization problem, the model of the cutting force as the main disturbing factor is necessary for controlling vibrations in the machining system.

Therefore, the development of mathematical models of the dependence of the cutting force on the cutting mode, geometric parameters of cutting allowance, and the creation of reliable modeling methods is an urgent task for the general problem of optimizing end milling. This article presents a new end-milling model built into an application program with the possibility of predicting the cutting force when the tool is beaten, as well as the results of experimental studies.

2 Literature Review

Three approaches are mainly used to build cutting force models during milling: analytical, numerical, and mechanistic [2].

Analytical models are built on the connection of the cutting force with the parameters of the cutting process, which are determined from the conditions of engagement of a separate segment of the cutter edge with the workpiece. Such a relationship is determined by empirical coefficients obtained during experimental research. The dependence of the cutting force coefficients on the cutting mode – feed per tooth, cutting speed, and cutting depth is evaluated [3].

Two methods for determining such coefficients are described: the average force method in linear regression and the instantaneous force method in nonlinear optimization. The conducted studies allow obtaining adequate analytical dependences of the coefficients of the cutting force formula on the parameters of the cutting mode, including in the area of stability of the cutting process. However, they do not consider the periodic nature of the cutting force during end milling depending on the axial coordinate of the milling cutter along the milling width.

The cutting force is the most important parameter of the end-milling operation, so research on the definition of models does not stop. The most developed is the mechanistic method of determining the dependence of the cutting force during milling. The models are built based on the assumption that the instantaneous cutting force is proportional to the cross-sectional area of the undeformed chip through empirical coefficients [4]. The complexity of modeling such processes lies in the complex geometry of the engagement between the cutting tooth of the cutter and the workpiece (CWE – Cutting Workpiece Engagement), especially when considering the helical surface of the edge of the cutter along the axial coordinate. It is claimed that a similar modeling technique can be used for more complex milling processes, such as milling with a spherical end of a cutter and five-coordinate milling.

The importance of modeling the cutting force for predicting milling stability, especially at high cutting speeds, is emphasized in [5]. It is proved that the determination of the stability diagram is impossible without an accurate model of the cutting force in the dynamic system of the machine tool.

The mechanistic approach to modeling the cutting force during milling is proposed to identify the milling process with the complex shape of the cutting edge of the milling cutter, composed of carbide plates [6]. However, statistical research methods are required in numerous experiments to determine the coefficients as a function of the cutting mode and workpiece material.

Recently, a digital modeling method has been developed when a scan of the microgeometry of the cutting edge of the milling cutter is used to create a model of the cutting process [7]. An approach to digital modeling is proposed, including a global scan to determine the microgeometry of the cutting edge of the end mill, to measure the slope profiles, and a finite element analysis of orthogonal cutting to determine the coefficients of the force model. The result is the ability to predict the cutting force using a fully digital integral approach, including the simulation of the milling cutter. The proposed digital method has great promise, although its application in production is associated with certain difficulties.

Modeling the cutting force during end milling forms the basis for predicting the stability of the process, detecting errors, and analyzing the formation of the part's surface [8]. An attempt to take into account the spiral of the cutter tooth by presenting it as a combination of cylindrical cutters shifted at an angle to each other along the slope of the spiral is described. A modeling algorithm for determining the cutting force during end milling with the possibility of considering tool runout is presented.

A mechanistic force model was used, which was built based on the parameters of the undeformed chip, which is calculated from the trajectories of the trochoidal flutes, and the force coefficients were determined by statistical methods based on the linear regression model.

Predicting the cutting force is essential for choosing a cutting mode that ensures minimal damage when machining composite materials [9]. To solve such problems, the mechanistic modeling method is also used to simulate cutting with a helical flute edge. A spiral end mill consists of finite-thickness discs with beveled cutting edges. The cutting force for each disc is calculated using mechanistic and transformed methods, and the total cutting force is determined as the sum of the contributions of all discs.

In [10], it is noted that changes in the cutting conditions along the forming trajectory are significant during end contour milling. A chip thickness model built on geometric dependencies for milling round contours is proposed. Simultaneously, the model is not universal because it does not consider chip changes when machining arbitrary parts contours.

It has been proven [11] that it is necessary to use numerical modeling methods to determine the primary influence: the cutting parameters of the workpiece allowance. This approach makes it possible to determine such a key indicator of the cutting process as the allowance's material removal rate (MRR) during the end milling of arbitrary contours. To determine the cutting force, when identifying the MRR, the presence of specific force coefficients is necessarily assumed [12].

For the linear end milling process, commercial software ABAQUS/Explicit v6.4 and ALE modeling approach are often used to perform FEM simulation of orthogonal cutting [13]. However, this approach does not represent the shape of the changes in cutting force components but shows the integrated cutting force acting on the cutter flute.

It is essential to determine and predict the cutting force during micro-milling. Catastrophic tool failure can occur if cutting forces are not controlled below critical limits. In addition, the cutting force is essential in determining the surface roughness. Therefore, accurate prediction of cutting forces and selection of appropriate cutting parameters, mainly feed, are also important in micro-end milling [14]. This study uses appropriate software to create a cutting force model using the finite element method (FEM). However, the integral cutting force results are provided, which does not allow for evaluating the dynamics of the process in the elastic machining system.

Determining the dependence of cutting force on chip geometry is very important for assessing dynamic processes during milling, which makes it possible to identify combinations of parameters that cause vibration. The prediction of dynamic force and stability in milling is proposed to be performed using the Production Module feed rate planning software provided by Third Wave Systems [15]. The algorithm for determining the parameters of undeformed chips is focused on the use of the finite element method, which slows down the modeling process, and the presented model in the form of second-order differential equations does not take into account the closedness of the cutting process in an elastic processing system, which, of course, reduces the adequacy of the modeling.

The purpose of this study is to develop a model for determining the cutting force and its components when applying a mechanistic approach in a geometric model based on the analysis of the sweep of the cutting teeth of an end mill and creating a software tool for calculating the components of the cutting force depending on all parameters of the cutting process, including axial coordinate, with the possibility of taking into account the milling cutter. This will make it possible to increase the adequacy of the operative determination of the cutting force and ensure adequate assignment of the cutting mode.

3 Research Methodology

The mathematical model of the end milling process must be built considering the mechanistic approach to calculating the cutting force by determining the geometric parameters of the undeformed chip by each tooth along its length. It is proposed to compose such a model according to the geometric ratios of the scheme in Figure 1, which shows the sweep of the cutter edges along the axial coordinate.

The diagram shows the positions of the cutting edges of the milling cutter, which has four teeth along the cutting width B – lines 1, 2, 3, and 4. The blades interact with the workpiece in the range of the cutting arc:

$$\varphi_{\max} = \arccos\frac{R_m}{R_m - H}, \tag{1}$$

where R_m – mill radius; H – cutting depth.

On the sweep, a zone is limited by line 5 at a distance from the beginning of the cutting $h_c = R_m cos(\varphi_{max})$.

The position of the edges on the sweep will change when an angle φ rotates the milling cutter, and the distance from the A-A line of the beginning of the workpiece along the width B determines the cutting edges:

$$b_j = (\varphi + \varphi_z j - \varphi_{\max}) R_m / \tan(\beta), \tag{2}$$

where φ_z – the angle between the teeth of the milling cutter; β – the helical angle of the flutes; j – the number of teeth.

In Figure 1, such distances for a cutter with four teeth are marked b_1, b_2, b_3, and b_4.

According to the location of the projections of the cutting flutes on the diagram, only edge 2 engages with the workpiece at a distance from the intersection with line 5 to width B. Simultaneously, the cutting angle φ on this edge changes from φ_{max} to zero. It is clear that when the width, depth of cutting, or the number of cutter teeth are changed, this picture will change – more cutting spirals flutes will take part in cutting. This process is taken into account using developed mathematical models and computational procedures.

Using formulas involving numerical integration to determine the cutting force and its components is advisable. Thus, the circumferential cutting force can be defined as the sum of the forces acting on the cutting edges and behind each edge at elementary distances δB and its components along the coordinate axes:

$$F_y = \sum_{j}^{z} \sum_{i=1}^{n} C_P (a_i)^k \, \delta B_i Cos(\varphi + \varphi_z j - \gamma - \beta), \tag{3}$$

$$F_x = \sum_{j}^{z} \sum_{i=1}^{n} C_P (a_i)^k \, \delta B_i Sin(\varphi + \varphi_z j - \gamma - \beta), \tag{4}$$

where C_P, k – empirical coefficients and exponents; a_i – the cutting thickness on the section of the cutter tooth; δB_i – the width of the elementary section; γ – the rake angle of the cutter edge; z – the number of cutter edges; n – the number of sections by the milling width.

The following formula determines the cutting thickness at each section:

$$\mathrm{a_i = f_t \cdot \sin(\varphi_i)}, \tag{5}$$

where f_t – the feed per tooth of the milling cutter; φ_i – the angle of the cutting arc in the corresponding section.

Here, conditionally, with sufficient accuracy, the cutting arc is replaced by the arc of a circle of radius R_m of the cutter. Therefore, the value of the angle of the cutting arc in each section depends on the angle of rotation of the milling cutter.

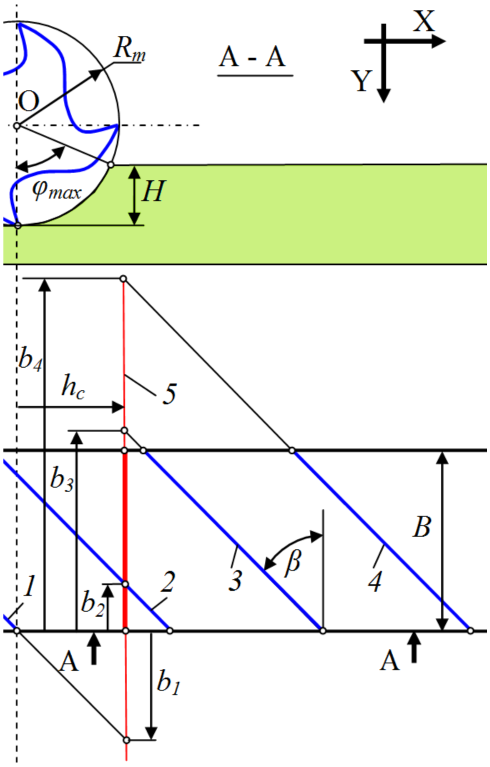


Figure 1 – Scheme for determining the geometric engagement of the cutter and the workpiece (CWE)

The cutting mode during modeling is considered depending on

$$f_t = \frac{f}{z n_s}, \tag{6}$$

where f – the feed; n_s – the spindle speed of the mill.

The empirical coefficient and exponent in (3) and (4) depend on the material of the workpiece. To increase the adequacy, such data can be adjusted considering the geometry of the cutter edge.

Since the proposed approach involves numerical methods, an algorithm was developed to perform the calculations (Figure 2), which is the basis of the applied simulating program. The algorithm directs calculations based on the analysis of the sign of the distance b in two directions, where the exact formulas are used to determine the components of the cutting force but with different parameter values.

The algorithm provides modeling of both up and down milling with procedures identical in structure.

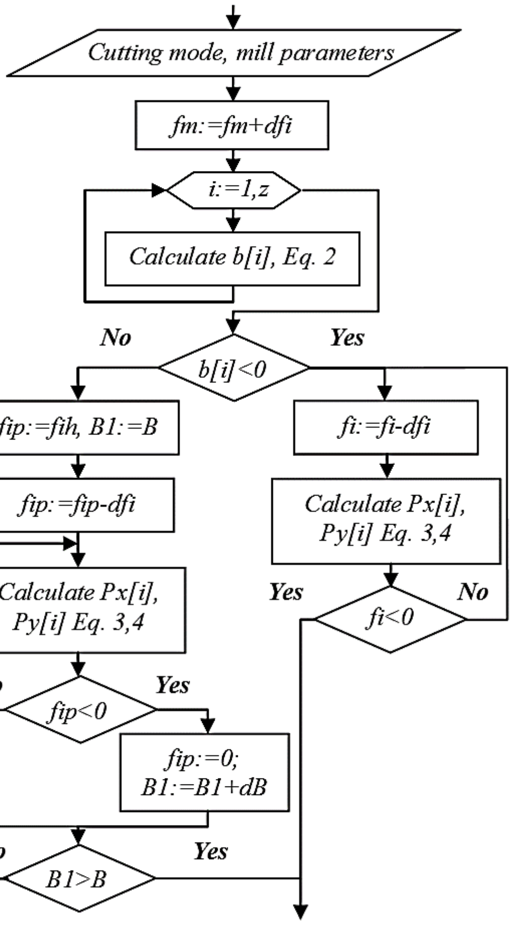


Figure 2 – Cutting force modeling algorithm

This modeling approach allows for considering the impact of the milling cutter on the milling process as a change in the cutting depth according to the harmonic law:

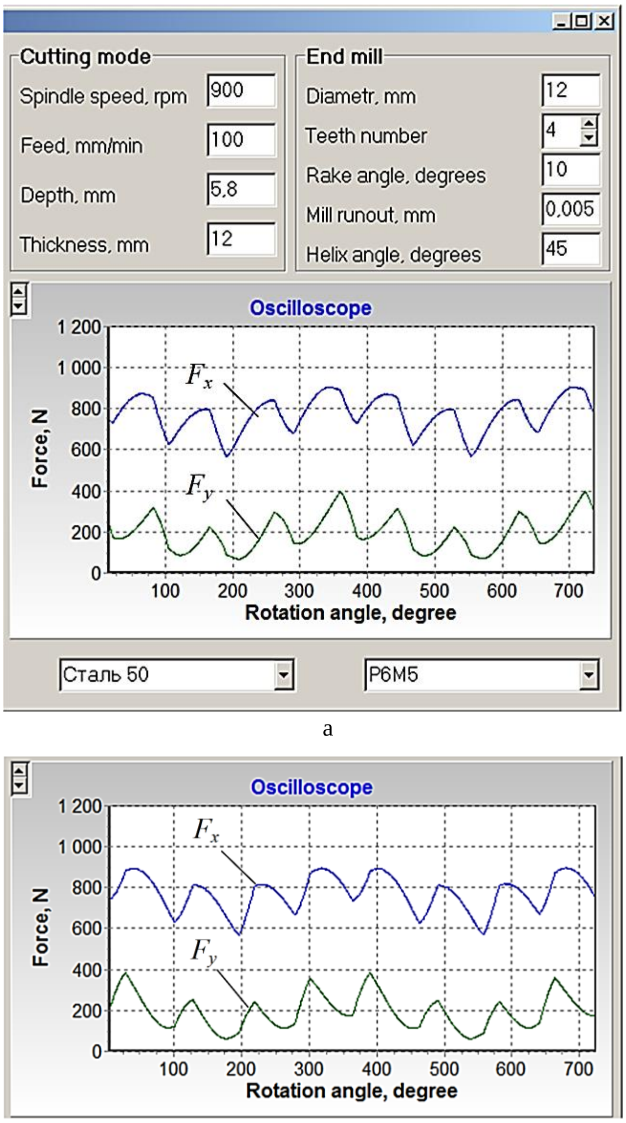
$$H = H - \delta h Sin(\varphi), \tag{7}$$

where δh – the runout value.

In the algorithm, the Latin designations of variable identifiers are adopted instead of the Greek ones that were used in the formulas: *fm* – the angle of rotation of the milling cutter; *dfi* – the step of changing the angle; *fi* – the angle that determines the limits of calculations when *b[i]* < 0; *fip* – the angle that determines limits of calculations when *b[i]* > 0; *fih* – the angle corresponding to the depth of cutting on the sweep; *dB* – the calculation step for the length of the edge on the sweep.

The algorithm represents the calculations that are performed when simulating up milling. Similar actions are provided for modeling the cutting force components during down milling.

To automate the modeling process, an application program was created, the interface of which is presented in Figure 3.



Cutting mode

Spindle speed, rpm: 900

Feed, mm/min: 100

Depth, mm: 5.8

Thickness, mm: 12

End mill

Diametr, mm: 12

Teeth number: 4

Rake angle, degrees: 10

Mill runout, mm: 0.005

Helix angle, degrees: 45

Сталь 50

P6M5

a

b

Figure 3 – Modeling program interface:
a – up milling; b – down milling

The output data defining the cutting mode and parameters of the end mill are entered in the corresponding windows of the interface. The material of the workpiece and the tool is selected according to the drop-down list in the windows at the bottom of the built-in virtual oscilloscope.

As a result of the simulation, graphs of the components of the cutting force as a function of the angle of rotation appear gradually in the window of the virtual oscilloscope, with the execution of calculations based on the change in the angle of rotation of the mill. It is possible to observe the runout of the mill on the nature of the changes in the graphs and the difference in the shape of the cutting force components during up and down milling.

It should be noted that the empirical coefficient and exponent in the formulas of the components of the cutting force (3)–(4) were determined according to reference data and were adapted similarly [11].

4 Results

The final confirmation of the obtained results was obtained during a full-scale experiment. The corresponding experiments were performed when milling a workpiece made of Steel 50 with an end mill Ø12 mm, material P6M5 with TiAlCrN coating, hardness HRC 65.

The mill has four spiral flutes with an inclination of 45°. The workpiece was fixed on the table of a three-of-the-component dynamometer MCS 10-005-3C of HBM Germany (Figure 4).

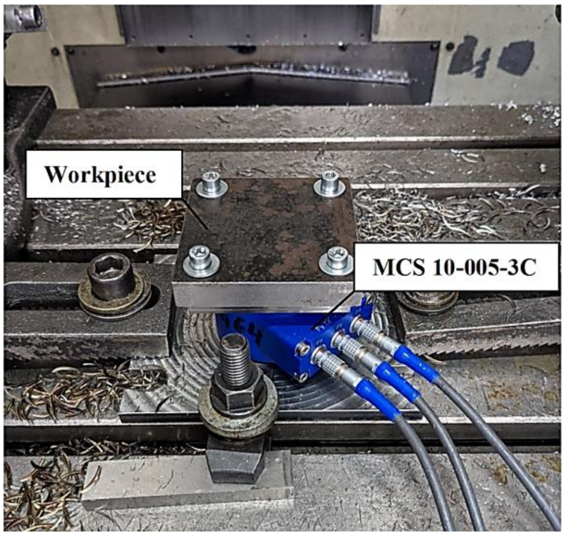


Figure 4 – Working area of the experiment

The three-component dynamometer sensors are connected to HBM ClipX BM40 amplifiers connected to a PC with the appropriate software for recording signals. The experiments were conducted on an XYZ VMC 1010 machine with a Siemens 810D CNC system (Figure 5).

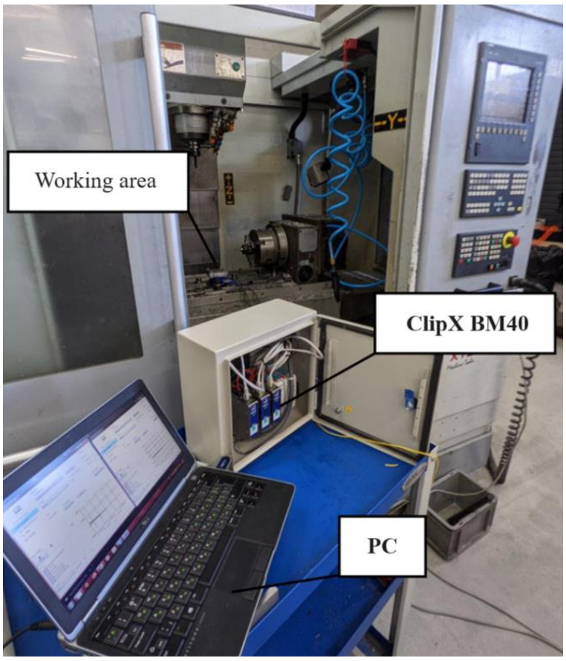


Figure 5 – Experimental setup

The experiments were carried out during the down milling of the workpiece at cutting modes in the medium and high speeds zone. Moreover, the width and depth of milling guaranteed simultaneous cutting with several cutter edges to check the adequacy of the functioning of the created milling algorithm in the same modes.

To compare the obtained experimental and simulation results, both digital files were loaded into a particular program, whereby by changing the experimental oscillograms by angle, the maximum coincidence of the graphs by phase was ensured (Figure 6).

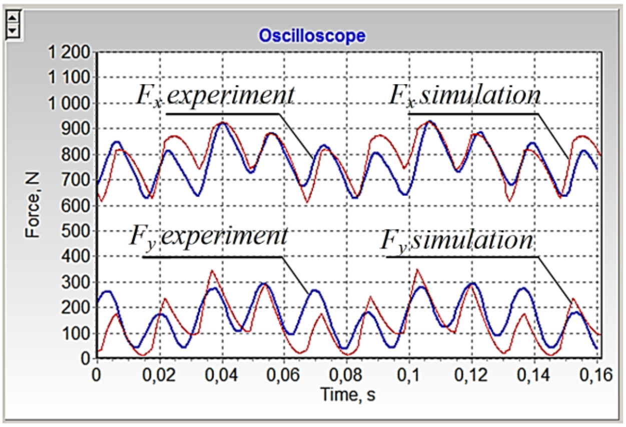


Figure 6 – Simulated and experimental components of cutting forces at a feed of 100 mm/min and a cutter rotation frequency of 900 rpm

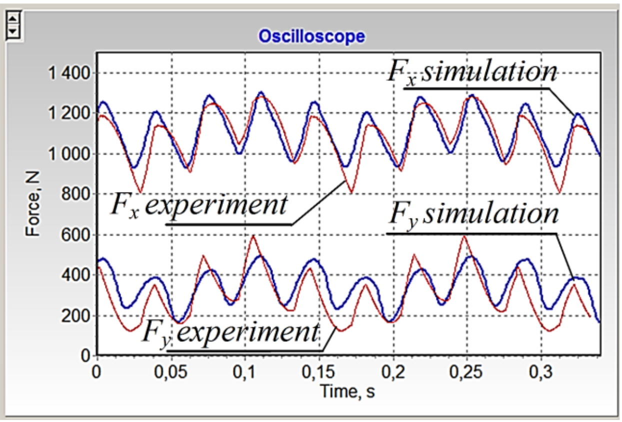


Figure 7 – Simulated and experimental components of cutting forces at a feed of 75 mm/min and a cutter speed of 420 rpm

With such manipulations, the absolute value and shape of the oscillograms remain unchanged to preserve the authenticity of the experimental data. In addition, according to the cutting mode, the horizontal scale is converted to time. Figures 6 and 7 show the graphs of the cutting force components for two mill revolutions.

The analysis of the obtained results shows a reasonably good match between the experimental and theoretically predicted cutting force components at different modes, which generally confirms the adequacy of the developed model. The average values of the cutting force components according to the data of experiments and modeling completely coincide, which confirms the correct choice of the empirical coefficient and exponent in formulas (3) and (4).

5 Discussion

When modeling end milling processes, a critical stage is determining the cutting force and its components. The developed model is based on a mechanistic approach, where the main option is determining the thickness of the layer of undeformed chips cut by each tooth of the mill. The geometric representation of the trace of the cutting edges on the sweep (Figure 1) made it possible to determine the integral cross-sectional area of the layer of undeformed chips, which is cut simultaneously by several cutter edges, depending on the geometric parameters of the cutter and the allowance layer.

The proposed criterion for determining the cutting edge is the distance *b* from the starting line of the time of the workpiece along the width *B* on the sweep – equation (2). This technique determined the structure of the algorithm (Figure 2), where the cutting edges for a given angle of rotation of the mill are first determined, and then the elementary values of the thickness of the chip layer and, accordingly, the cutting force is calculated. Such dependencies (3) and (4) are already presented in the form where the double integral is calculated by a numerical method in the created application program.

The application program allows for simulating the process in a wide range of parameter changes and cutting modes for up and down milling. For this, interface windows (Figure 3) are provided for entering data in interactive mode. The built-in virtual oscilloscope provides operational visualization of the simulating process.

Comparison of the results with known studies proves their ability to simulate cutting with several cutter teeth simultaneously. The works [3, 6, 7, 9] present graphs of force components with zero values at some stages, indicating insufficient geometric parameters (width and depth) of the allowance being cut. It is possible to observe the sections of the process when the cutting edge completely leaves the workpiece. Such milling conditions are a separate case, which is determined by the geometric parameters of the cutter and the allowance layer being cut.

It should be noted that the milling conditions when processing parts of the aviation and automotive industry are quasi-stationary as a result of contour processing. Therefore, using the models proposed in [4, 7, 8, 10] does not guarantee an adequate result. The created algorithm and software can simulate such processes thanks to a new approach that considers the possibility of simultaneous cutting with several blades. Such a feature determines the practical usefulness of the study and guarantees the adequacy of forecasting the cutting force during contour end milling, which is essential for the optimal assignment of the cutting mode in such operations.

The analysis of the obtained results shows that the developed model corresponds to the most frequently used actual milling modes. The results of experimental studies confirm the adequacy of the developed model. Some discrepancies in graphs and oscillograms can be explained by different radii of the cutter teeth, which is present in practice but not taken into analysis and processing of experimental data, the account in the model. Representation runout of the milling cutter in the model as a change in the depth of cut generally gave an adequate result.

6 Conclusions

The developed mathematical model of the cutting force during end milling is based on a mechanistic approach and a geometric representation of the movement of the milling cutter edges on the sweep, which allows for simulating the process under different cutting modes and geometric parameters of the cut allowance layer when several milling cutter edges are in interaction with the workpiece at the same time.

An application program has been created that is a technologist’s tool when assigning a cutting mode and allows for predicting the end milling process based on its main characteristic – the cutting force, which will avoid emergencies in practice.

The proposed algorithm for simulating the cutting force and its components can be used to design a generalized dynamic model of the end milling process, increasing its adequacy.

The adequacy of the obtained results is confirmed both by computer simulating and by a full-scale experiment of milling with cutting modes and geometric parameters of the process, which determine simultaneous cutting with several cutter edges, as well as taking into account the runout of the tool.

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