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SIMULATION MODELING OF 2.5D MILLING DYNAMICS BY END MILLS

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ABSTRACT *A mathematical model for simulation modeling of 2.5D end milling is presented. The model takes into account the loop closed of the cutting process in the elastic machining system through the feedback in the form of elastic shifts along the coordinate axes. The dynamics of the system are represented by a single-mass model with two degrees of freedom. A block diagram of the milling process using transfer functions, which reflects the cross-links of the real machining system. It is shown that the main cause of regenerative oscillations is cutting along the trail from the previous pass. The mathematical model is compiled in state variables, which allows the use of numerical methods for simulation modeling. The linearization coefficients relate the cutting force to the feed per tooth of the mill and the cutting depth. An application program has been created that uses a time-frequency approach to modeling the 2.5D milling process. Therefore, it is possible to observe dynamic processes both in the form of transient characteristics in time and in the form of amplitude-frequency characteristics in the form of a Nyquist diagram. An application program has been created, which makes it possible to observe processes in time in an interactive mode, thanks to the built-in virtual oscilloscope. It provides the possibility of a simulation experiment to determine the influence of all the initial data of the system on the dynamics of its behavior. The results of the influence of the cutting mode for determining the boundary of stability in the coordinates of the cutting speed – feedrate are presented. It is shown that a modified stability criterion according to the parameters of the Nyquist diagram on the complex plane can be used to estimate the stability of the machining system. The created application program allows to determine the chatter-free cutting mode and in practice is an important tool for the programmer-technologist when assigning the cutting mode to the control program 2.5D milling on CNC machine.*
Keywords: *simulation modeling; milling dynamics; stability diagram; chatter-free cutting mode*

ІМІТАЦІЙНЕ МОДЕЛЮВАННЯ ДИНАМІКИ 2.5D ФРЕЗЕРУВАННЯ КІНЦЕВИМИ ФРЕЗАМИ

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АНОТАЦІЯ *Представлено математичну модель для імітаційного моделювання 2.5D фрезерування кінцевими фрезами. Модель враховує замкненість процесу різання в пружній обробній системі через зворотні зв'язки у вигляді пружних зсувів за осями координат. Динаміка системи представлена одномасовою моделлю з двома ступенями свободи. Складено структурну схему процесу фрезерування з використанням передатних функцій, що відображає перехресні зв'язки реальної обробної системи. Показано, що основною причиною виникнення регенеративних коливань є оброблення за слідом. Математична модель складена у змінних станах, що дозволяє застосовувати чисельні методи для імітаційного моделювання. Коефіцієнти лінеаризації пов'язують силу різання з подачею на зуб фрези та з глибиною різання. Створено прикладну програму, яка використовує часово-частотний підхід до моделювання процесу 2.5D фрезерування. Тому є можливість спостерігати динаміку обробної системи при різанні як у перехідних процесах у часі, так і у вигляді амплітудно-частотних характеристик діаграми Найквіста. Створено прикладну програму, яка дає можливість спостерігати в інтерактивному режимі процеси в часі, завдяки вбудованому віртуальному осцилографу. Вона забезпечує можливість імітаційного експерименту визначення впливу всіх вихідних даних системи на динаміку її поведінки. Наведено результати впливу режиму різання для визначення межі стійкості в координатах швидкість різання – подача. Показано, що з оцінки стійкості обробної системи можна використовувати модифікований критерій стійкості за параметрами діаграми Найквіста на комплексній площині. Створена прикладна програма дозволяє визначати безвібраційний режим різання і на практиці є важливим інструментом програміста-технолога при призначенні режиму різання в управляючу програму 2.5D фрезерування на верстаті з ЧПК.*
Ключові слова: *імітаційне моделювання; динаміка фрезерування; діаграма сталості; безвібраційний режим різання*

Introduction

The manufacture of parts in modern mechanical engineering is mainly carried out by subtractive methods by removing the allowance during the cutting process on CNC machines. A large number of operations are carried out by milling, and control programs for CNC machines are designed in CAM systems. Achievement of the main goal – maximum productivity under the conditions of processing in terms of accuracy and quality – is implemented by such systems by the method of control by a priori information. With the complication of the geometry of machined surfaces, the increase in requirements for the quality of processing, and the

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increase in cutting speeds, the problem of assigning a vibration-free machining process is becoming increasingly important [1]. It is clear that with such a control method for solving such problems, in particular, the choice of cutting mode and some other process parameters, there is no alternative to a preliminary computer simulation of the process. This approach allows reproduce the behavior of real systems in virtual reality systems and predicts processing without significant material costs [2]. Therefore, the creation of an adequate digital model of the milling process and the development of methods for its computer simulation is an urgent scientific and technical problem.

Problem status analysis

An adequate model of the milling process can quickly and accurately predict the vibration limits, which are set by analytical dependencies that relate the vibration limit to the cutting mode. These dependencies form a Stability Lobes Diagram (SLD) in the feed–cutting speed coordinates [3]. However, the proposed analytical method does not allow the use of more complex models that predetermine the use of numerical modeling methods. To ensure the adequacy of the model, it is necessary to take into account four main characteristics of the milling process: the coefficients of the linearized dependence of the cutting force, the dynamic parameters of the system, the cutting mode, and the tool geometry [4].

It is proposed to use the time-frequency method to obtain the SLD for the milling process, and then optimize the cutting process. Among the reasons causing chatter during cutting, the main one is trace machining, which should be represented in the model by a function of a delay argument. In this case, the only possible method of modeling in the time domain should be the numerical method, which leads to adequate solutions [5]. The proposed approaches to modeling the milling process make it possible to outline ways and means of eliminating chatter by both passive and active methods.

To simulate the milling process, taking into account the machining along the trace, it is necessary to determine the geometry of the machined surface, both taking into account the formation of micro rough nesses during the interaction of the cutter edge with the workpiece, and the vibrations of the technological machining system. It is clear that these two processes occur simultaneously and form a layer of allowance for the next cutter tooth. In works [6,7], devoted to chatter during milling, one can find an image of such a surface, presented graphically without taking into account the interaction of these two processes. In addition, it should be noted that the formation of the surface in each section of the cutter is performed by one tooth, i.e. its peak, which is also insufficiently represented in the modeling of the process [8]. It should be noted that the relief of the machined surface is schematically depicted in various machining schemes in the form of a wavy line, but is not presented as a result of a computer simulation of the milling process. Therefore, the adequacy of such a representation is also questionable.

Chatter is a type of self-excited vibration, and the two most widely used theories to explain vibration in milling are the regenerative effect and the mode coupling effect. Ignoring this relationship leads to a large difference between the results of stability prediction using the classical model and the experimental results [9]. These two mechanisms are shown to coexist during the actual milling process, and the generally ignored effect of structural mode coupling has a large impact on the stability lobe diagram in many practical milling applications. Therefore, the development of a model that takes into account cross-related terms will significantly increase its adequacy.

If the tool can vibrate in two directions, then this leads to self-excited vibrations [10]. It is proposed, at a given spindle speed, to predict the depth of cut at which self-excited vibrations become unstable. This is called the vibration stability boundary, and the relationship between RPM and the depth of cut is called the stability lobe diagram. Therefore, it is important to have a tool for predicting the stability margin.

The aim and objectives of the study

To develop a mathematical model for simulating the 2.5D milling process, taking into account the cross-links of the structure of a closed machining system, using numerical methods in the time and frequency domain to determine the chatter-free cutting mode with the Stability Lobes Diagram.

To achieve this objective, it is necessary to solve the following tasks:

1. Compile a mathematical model of 2.5D milling, taking into account a single-mass model with two degrees of freedom.
2. In the model, provide a representation of the cutting process in a closed elastic machining system and cutting along the trace.
3. Develop an application program for modeling dynamic processes in the time and frequency domains using the modified Nyquist stability criterion.

Statement of the main material

The main disturbing influence is the cutting force, which, when milling with end mills, can be determined by the empirical dependence:

$$F = C_p a^k b\,, \qquad (1)$$

where a is the thickness, b is the cutting width, C_p, k are the empirical coefficient and exponent.

The cutting force acts in an elastic machining system and can be decomposed into normal F_n and tangential F_t components (Fig. 1).

In [11], it is proposed to determine the components of the cutting force by empirical dependencies:

$$F_t = k_{tc} b f_t Sin\varphi + k_{te} b\,,\quad F_n = k_{nc} b f_t Sin\varphi + k_{ne} b\,,\quad (2)$$

where k_{tc}, k_{te}, k_{nc}, k_{ne} are empirical coefficients, f_t is the feed per tooth, φ is the cutting angle.

The experimental data obtained in [12] for the machining of an aluminum alloy show that the coefficients for the milling width are several orders of magnitude smaller than the coefficients for the first term. Similar data are for the machining of other alloys. Therefore, with a high degree of adequacy, only the first of the terms in formulas (2) can be taken into account.

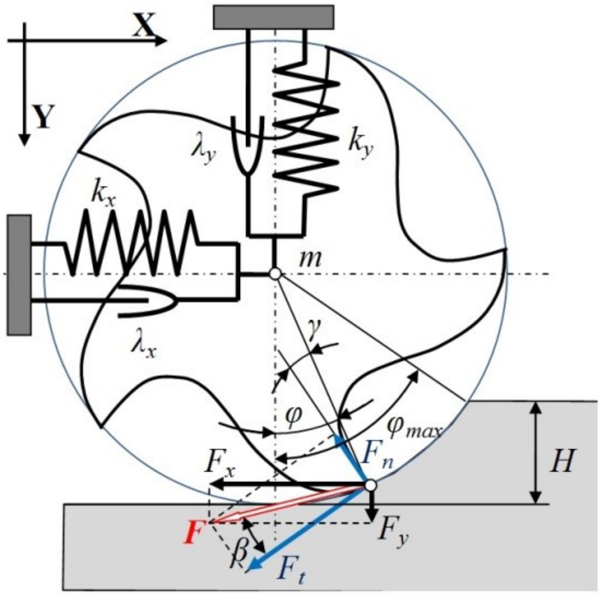

Fig. 1 – Scheme of end milling

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Thus, from the geometric relationships of the diagram in Fig. 1, the cutting force is:

$$F = b f_t Sin\varphi \sqrt{k_{tc}^2 + k_{nc}^2}\,. \quad (3)$$

Taking into account that the tangential component acts along the normal to the front surface of the cutting wedge of the cutter tooth, it is possible to determine the components of the cutting force along the coordinate axes:

$$F_x = FCos(\varphi - \gamma - \beta),\ F_y = FSin(\varphi - \gamma - \beta) \quad (4)$$

where γ – rake angle ~ 10 degrees, and angle *$\beta = arctan(F_n/F_t) = arctan(k_{nc}/k_{tc}) = arctan(0.5) = 26.5$ degrees.*

The maximum value of the cutting angle φ is determined from the geometric relations of the scheme in Fig. 1:

$$\varphi_{\max} = \arccos \frac{R_m - H}{R_m}\,, \quad (5)$$

where R_m – radius of mill, H – cutting depth.

From formula (1), taking into account (5), it follows that the cutting force is determined by two components of the cutting mode: the feed f_t per cutter tooth and the cutting depth H. Such a dependence is non-linear and can be linearized with a sufficient degree of accuracy as a function of the cutting mode:

$$F = k_f f_t + k_H H\,, \quad (6)$$

where k_f, k_H – linearization coefficients.

The linearization coefficients are determined according to general rules as partial derivatives of the cutting force (1) undercutting conditions at the linearization point. To determine them, it is necessary to obtain the dependence of the cutting force on the components of the mode – the feed f_t per tooth and the depth H of cutting. The cutting thickness for cylindrical milling is $a = f_t Sin\varphi$ and to express the cutting angle through the depth H, it can use the formula (5) and the trigonometric relationship:

$$Sin\varphi = Sin\left(\arccos \frac{R_m - H}{R_m}\right) = \frac{\sqrt{2R_m H - H^2}}{R_m}\,. \quad (7)$$

Substituting (7) into (3), it obtains a cutting force formula convenient for differentiation:

$$F = C_p \left(\frac{f_t}{R_m}\right)^k \left(2R_m - H^2\right)^{\frac{k}{2}}. \quad (8)$$

Now there is a possibility to find the required linearization coefficients. Dependence of cutting force on feed:

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$$k_f = C_p k (f_t)_0^{k-1} \left(\frac{2R_m H_0 - H_0^2}{R^m} \right)^k . \qquad (9)$$

The dependence of the cutting force on the depth of cut is determined by the coefficient:

$$k_H = C_p (f_t)_0^k k \left(2R_m H_0 - H_0^2\right)^{k-1} (2R_m - 2H_0) . \qquad (10)$$

The dynamic system is represented as a single-mass system with two degrees of freedom with elastic constraints with stiffnesses k_x and k_y and damping λ_x and λ_y in the direction of the XY axes of the coordinate system. The equations of motion are:

$$\begin{cases} \dfrac{s^2 x}{\omega_x^2} + \dfrac{sx}{\omega_x} + x = \dfrac{1}{k_x} F_x \\ \dfrac{s^2 y}{\omega_y^2} + \dfrac{sy}{\omega_y} + y = \dfrac{1}{k_y} F_y \end{cases} , \qquad (11)$$

where ω_x, ω_y are the frequencies of natural vibrations, x, y are elastic displacements along the corresponding coordinate axes, s is the Laplace operator.

The frequencies of natural vibrations of the system along the coordinate axes are determined experimentally according to the method presented in [13]. From the analysis of the amplitude-frequency characteristic, the main harmonic of the experimental spectrum is taken as the frequency of natural oscillations.

To simulate the milling process, it is convenient to present it in the form of a block diagram shown in Fig.2. In accordance with (11), the elastic technological system is presented as a single-mass system with two degrees of freedom with rigidities k_x i k_y, periods of natural vibrations $T_x = 2\pi/\omega_x$ and $T_y = 2\pi/\omega_y$, and oscillation damping coefficient ξ. This is how the representation of the cross-links present in the actual machining system is provided. The closure of the elastic technological system is ensured by the introduction of feedback for each coordinate by their elastic displacements:

$$f_{ta} = f_{t1} - \delta f , \quad H_a = H_1 - \delta h . \qquad (12)$$

Machining along the traces is represented by two links of the delay argument $e^{-\tau s}$, where τ is the time of cutting the allowance between the passes of two adjacent cutter teeth. The components F_x and F_y of the cutting force, in accordance with the diagram in Fig. 1, depending on the cutting angle:

$$k_{Fx} = Cos(\varphi_m - \gamma - \beta) , \quad k_{Fy} = Sin(\varphi_m - \gamma - \beta), \qquad (13)$$

where φ_m – middle cutting angle $(\varphi_{max}/2)$.

According to this scheme, it is possible to obtain a mathematical model of the process, which determines both time and frequency characteristics. It can be seen that the process can be characterized by four transfer functions:

$$W_1(s) = \frac{\delta f(s)}{f_r(s)} , \; W_2(s) = \frac{\delta f(s)}{H(s)} ,$$
$$W_3(s) = \frac{\delta h(s)}{f_r(s)} , \; W_4(s) = \frac{\delta h(s)}{H(s)} . \qquad (14)$$

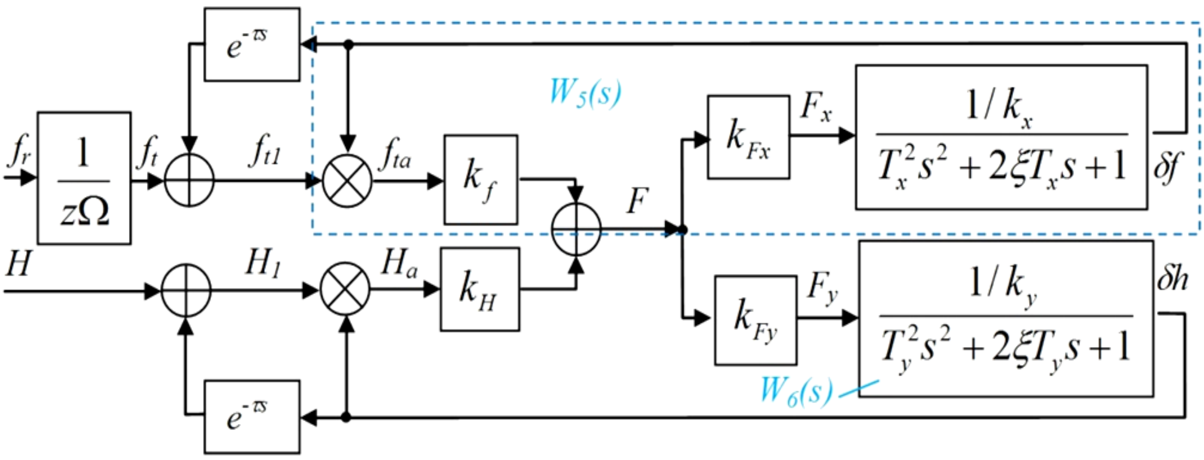

Fig. 2 – Block diagram

The transfer functions $W_2(s)$ and $W_4(s)$ have the greatest influence on the formation of the relief of the machined surface. The expression of such transfer functions can be obtained from the functional diagram using the transformation rules. To obtain the transfer function $W_4(s)$, it is necessary to take $f_r=0$. Then the block diagram takes the form shown in Fig. 3.

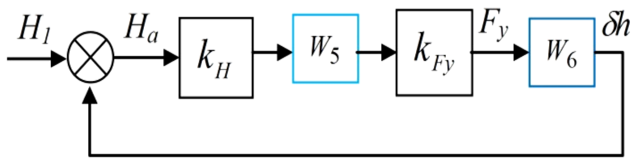

Fig. 3 – Transformed block diagram at f_r=0

The contour constituting the blocks of the transfer function $W_5(s)$ is closed (see Fig. 2), therefore, its transfer function, according to the rules for transforming block diagrams, has the form:

$$W_5(s)=\frac{1}{1+\frac{k_{Fx}}{k_x\left(T_x^2s^2+2\xi T_xs+1\right)}k_f}. \quad (15)$$

Then, the transfer function of the entire system on the input H:

$$W_H(s)=\frac{k_HW_5(s)k_{Fy}\frac{1}{k_y\left(T_y^2s^2+2\xi T_ys+1\right)}}{1+k_HW_5(s)k_{Fy}\frac{1}{k_y\left(T_y^2s^2+2\xi T_ys+1\right)}}. \quad (16)$$

Substituting into (16) the expression of the transfer function from (15) and performing simple transformations, these finally obtain:

$$W_H(s)=\frac{T_{02}^2s^2+T_{12}s+k_1}{T_{03}^4s^4+T_{13}^3s^3+T_{23}^2s^2+T_{33}s+1}, \quad (17)$$

where $T_{02}^2=T_x^2k_xk_Hk_{Fy}/k_2$,

$T_{12}=2\xi T_xk_xk_Hk_{Fy}/k_2$, $k_1=k_x/k_2$,

$k_2=k_yk_x+k_yk_{Fx}k_f+k_Hk_{Fy}k_x$, $T_{03}^4=T_x^2T_y^2k_xk_y/k_2$,

$T_{13}^3=k_xk_y2\xi\left(T_xT_y^2+T_yT_x^2\right)/k_2$,

$T_{23}^2=\left(k_xk_y\left(T_x^2+4\xi^2T_xT_y+T_y^2\right)+k_yk_{Fx}k_fT_y^2+k_xk_{Fy}k_HT_x^2\right)/k_2$,

$T_{33}=\left(k_xk_y2\xi\left(T_x+T_y\right)+k_yk_{Fx}k_f2\xi T_y+k_xk_{Fy}k_H2\xi T_x\right)/k_2$.

The equation of motion of the system with concerning the input H can be represented in state variables in the form of a matrix, which is convenient for the numerical integration procedure:

$$\begin{cases} sU[1]=-A_1U[1]+U[2] \\ sU[2]=-A_2U[1]+A_5H+U[3] \\ sU[3]=-A_3U[1]+A_6H+U[4] \\ sU[4]=-A_4U[1]+A_7H \end{cases}, \quad (18)$$

where $A_1=T_{13}^3/T_{03}^4$, $A_2=T_{23}^2/T_{03}^4$, $A_3=T_{33}/T_{03}^4$, $A_4=1/T_{03}^4$, $A_5=T_{02}^2/T_{03}^4$, $A_6=T_{12}/T_{03}^4$, $A_7=k_1/T_{03}^4$.

Since the resulting model has a fourth order, the integration in the simulation program is performed by the fourth-order Runge-Kutta numerical method. The implementation of the lagging argument function is performed according to the recurrence relation:

$$H_j=H_0+(\delta h)_{j-1}, \quad (19)$$

where $(\delta h)_{j-1}$ – elastic displacement of the system in the direction of the cutting depth on the previous pass of the cutter edge.

Similarly, one can obtain the transfer function of the entire system from the input f_t:

$$W_f(s)=\frac{T_{04}^2s^2+T_{14}s+k_3}{T_{05}^4s^4+T_{15}^3s^3+T_{25}^2s^2+T_{35}s+1}, \quad (20)$$

where $T_{04}^2=T_y^2k_yk_fk_{Fx}/k_4$,

$T_{14}=2\xi T_yk_yk_fk_{Fx}/k_4$, $k_3=k_y/k_4$,

$k_4=k_yk_x+k_xk_{Fy}k_H+k_fk_{Fx}k_y$, $T_{05}^4=T_x^2T_y^2k_xk_y/k_4$,

$T_{15}^3=k_xk_y2\xi\left(T_xT_y^2+T_yT_x^2\right)/k_4$,

$T_{25}^2=\left(k_xk_y\left(T_y^2+4\xi^2T_xT_y+T_x^2\right)+k_xk_{Fy}k_HT_x^2+k_yk_{Fx}k_fT_y^2\right)/k_4$,

$T_{35}=\left(k_xk_y2\xi\left(T_x+T_y\right)+k_xk_{Fy}k_H2\xi T_x+k_yk_{Fx}k_f2\xi T_y\right)/k_4$.

Simulation

An application program was created to simulate the 2.5D milling process to evaluate its dynamic quality. The application program allows you to simulate the behavior of the processing system in the form of displacements along the coordinate axes in time and frequency characteristics in the form of a Nyquist diagram. The simulation is performed by numerical methods using models (17) and (20) with a step of 0.000005 s, which makes it possible to observe the fast dynamic processes of a real system. The frequency characteristics of the system, taking into account the function of the delay argument, are also modeled by a numerical method in a given frequency range.

The initial data for modeling correspond to the real parameters of the 2.5D milling process: stiffness along the X axis 8000 H/mm, natural frequency 2400 Hz, stiffness along the Y axis 7000 H/mm, natural frequency 2100 Hz. The frequencies of natural oscillations and the damping coefficient of oscillations were determined from experimental data under the procedure presented in [13]. The tool chosen was a Ø20 mm end mill with 5 tooth.

The created application program allows executing virtual experiments to assess the stability limit of the milling process, which is usually represented as an SLD in the coordinates of the cutting speed – feed rate [3, 4]. The influence of the cutting mode on stability can be assessed both by transient processes in the form of elastic displacements δh (in the direction of the Y axis) and δf (in

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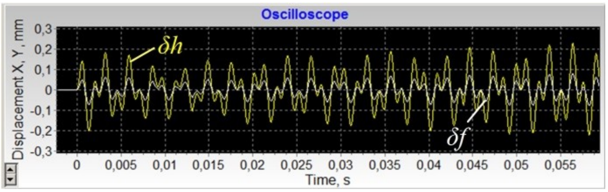
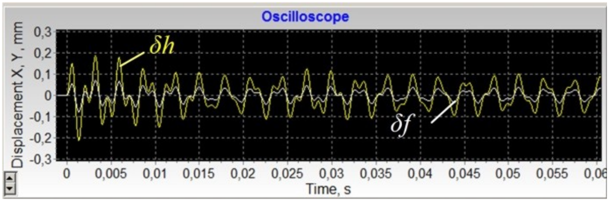
the direction of the Y axis) in time and by frequency characteristics in the form of Nyquist diagrams on the complex plane. For example, from the oscillograms of the virtual oscilloscope built into the application program, one can see that the system at a cutting speed of 60 m/min and a feed of 5000 mm/min has a divergent transient, which indicates its instability (Fig. 4, a). Changing the cutting speed to 57 m/min leads the system to stable processes – the oscillograms of elastic displacements decay over time (Fig. 4, b).



a



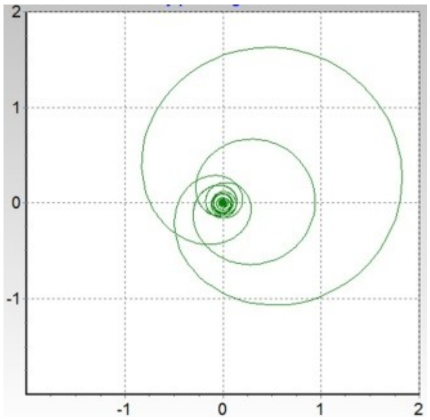
b

Fig. 4 – Transition process: a – cutting speed is 60m/min, feedrate is 5000 mm/min; b – cutting speed is 57 m/min, feedrate is 5000 mm/min

It is known that, according to the Nyquist stability criterion, the system is stable if the graph of its amplitude-frequency characteristic in the open state does not cover points with coordinates [-1,0] on the complex plane. Since in this case the delay link is connected with the output of a closed processing elastic system and creates a second feedback loop, the stability criterion changes somewhat. Comparing the graphs of transients and amplitude-frequency characteristics, it can be seen that when the graph covers a point with coordinates [-1,0], the system has a stable process, and when it covers a point with coordinates [1,0], it is unstable. This correspondence is not random but is repeated each time the simulation is performed for different cutting conditions.

When designing a control program for the end milling process on CNC machines, along with other technological tasks, it is important to assign a cutting mode that ensures chatter-free machining. Therefore, the prediction of this mode will allow you to choose the most productive machining without chatter. Usually, such a task is solved by the SLD representation.

Which are obtained based on algebraic transformations of the frequency response function (FRF) of the dynamic model in the form of a single-mass system with two degrees of freedom. Simulation modeling makes it possible to study the influence of the cutting mode on the stability of the cutting process in a more complex system and obtain the boundary of the region of stable values of the cutting mode (Fig. 6).



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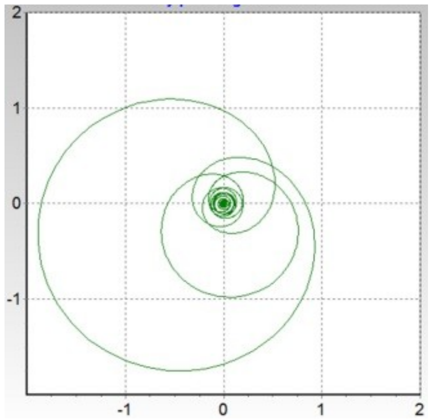

b

Fig. 5 – Nyquist diagrams: a – cutting speed is 60 m/min, feedrate is 5000 mm/min; b – cutting speed is 57 m/min, feedrate is 5000 mm/min

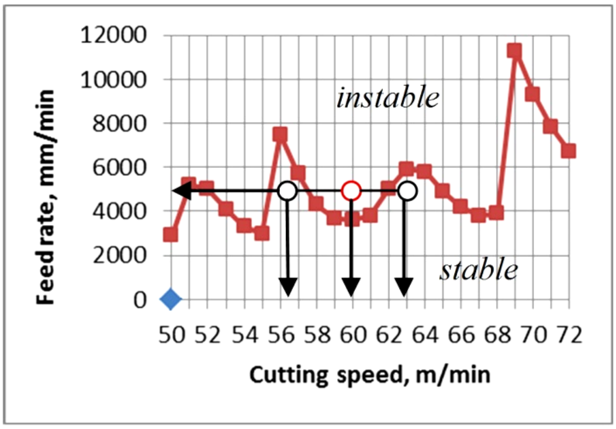

Fig. 6 – Stability diagram

Such virtual experiments can be used to select chatter-free cutting conditions. For example, it follows from the diagram that it is enough to change the cutting speed from 60 m/min at a feed of 5000 mm/min to the larger (63 m/min) or smaller (57 m/min) side and the cutting process is performed without chatter.

Discussion of 2.5D milling dynamic

A mathematical model of the 2.5D milling machining by end mills has been developed using a systematic approach, which makes it possible to represent the system in the form of separate blocks indicating the relationships between them (Fig. 2). The model represents the dynamics of the system as one-mass with two degrees of freedom, which implements the cross-links existing in the real system. The possibility of using a linear model of the dependence of the cutting force on the geometric engagement between the mill and the workpiece is shown.

The chosen representation form makes it possible to build a mathematical model using the concepts of transfer functions and the equation of motion in the form of variable states (18). This makes it possible to successfully use numerical methods to determine the behavior of the system in terms of elastic displacements in the direction of two axes at once.

The created application soft makes it possible to observe processes in an interactive mode in time, thanks to the built-in virtual oscilloscope. It provides the possibility of a simulation experiment to determine the influence of all the initial data of the system on the dynamics of its behavior. The results of the influence of the cutting mode for determining the stability limit in the coordinates of the cutting speed – feedrate are presented (Fig. 4).

The possibility of showing the dynamic characteristics of the system, with a time-frequency approach is presented. On the soft interface a graph of the amplitude-frequency characteristic to assess the stability of the system using the Nyquist stability criterion. Comparing the results of the process in time with the frequency response function leads to the modifications of this criterion (Fig. 5). Such features can be associated with taking into account in the model a closed-loop structure with feedback and a function of a delay argument that determines machining along the trail.

The adequacy of all new results obtained will be significantly improved by confirmation by numerous experiments. The created program with the inclusion of such experimental results can serve as a decision-making tool when assigning a cutting mode to 2.5D end milling on CNC machine.

Conclusions

The developed mathematical model takes into account the loop closed of the cutting process in the representation of a single-mass structure with feedback on elastic displacements and two degrees of freedom in the direction of the coordinate axes.

The main reason for the occurrence of regenerative vibrations should be considered processing along the trace in combination with cross kinematic links, which are closed through the cutting process. Such a structure is taken into account in the mathematical model by two links with a delay argument.

The created application simulation program allows building an area of stable solutions in the "cutting speed – feed rate" diagram, which can serve as a decision-making tool for the technologist-programmer when assigning a cutting mode to the CNC machine.

The possibility of assessing the stability of the machining system simultaneously by the transient and frequency response leads to the need to formulate a modified criterion for the stability of closed systems with a second loop through a link with a delay argument.

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