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Investigation of the plain milling process dynamic stability taking into account the contact interaction on the flank face of the cutting wedge

Nikita Zhukov[1,*], *Vladimir* Kuts[1], and *Bogdan* Suldin[1]

[1]Bauman Moscow State Technical University, Applied Mechanics Department, 105005 Moscow, Russian Federation

Abstract. The single degree of freedom numerical model of plain milling in time domain is represented in this article. This model allows to take into account the process damping phenomena, which is caused by contact interaction along the cutting edge flank face, on the dynamic behavior of the compliant technological system. The particular feature of this research is the usage of the iterative procedure to make more accurate the solutions on each time step of the modeling, which ensures the fulfillment of stiffness equations in the formula for the contact interaction forces calculation along the cutting edge flank face. The analysis of results, which were obtained using the represented milling dynamics model, shows that the process damping may have a significant influence on the technological system dynamics when machining on the modes with low value of the cutting tooth pass frequency ratio to the natural frequency of the system. The proposed methodology of the contact interaction forces calculation along the flank face of the cutting edge may be developed later on for the 3D multiaxial machining of figurine-shaped workpiece.

1 Introduction

Not only do the forced vibrations appear due to the cutting forces in the compliant system "tool-workpiece" during cutting, but also the self-excited vibrations - the regenerative "chatter" [1]. The vibrations amplitudes may significantly increase because of the certain values of the technological parameters, which leads to the deterioration of the machined workpiece surface quality. The process damping phenomena has a considerable influence on the cutting dynamics, which is caused by the contact interaction between the worn-out flank face of the cutting edge and the machining workpiece material. The consequences, which are caused by this effect, are the extension of the technological modes domains which are free from high-amplitudes vibrations, rapid wear of the tool, the cutting forces increase [2]. Lee [3] noticed that this effect particularly takes place when the speed of spindle rotation is low. It is needed to take into account this effect during the research into the machining dynamics of compliant parts made from hard-to-machine alloys and the vibratory drilling process [4,5].

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[*] Corresponding author: jukov.n.a@bmstu.ru

It is needed to carry out research into the technological operation dynamics to define the favorable machining modes, which are free from high-amplitudes vibrations in the system “tool-workpiece” [6, 7]. There are plenty of approaches how to take into account the process damping in the literary sources. They can be divided into two main groups: the first group approaches propose to introduce the extra forces which are proportional to the deformed by the flank face volume [3,8-10], while the second group approaches introduce the auxiliary cutting edge [2]. The approximate analytical equations [8,9], as well as the numerical procedures with the usage of geometry algorithms [3,10], are used to calculate the deformed material volume in the cutting dynamics models.

The approaches, which are described in [2,3], are taken as a base in this piece of research. The particular feature of this research is the usage of the stiffness relation between the contact force on the tool flank face and the worn-out cutting edge part penetration into the workpiece as the process damping process model. To fulfill this relation at each discrete moment of time, the iterative refining of the solution at each time step is used. The flat milling dynamics modelling results and the analysis of the influence of the contact interaction along the worn-out part of the cutting edge flank face on the technological system dynamic behavior are given in this article.

2 Plain milling dynamics model

The plain milling dynamics model, which is used in this paper, includes the following components: the geometry modeling algorithm, the machining workpiece dynamics model, the cutting forces phenomenological model. The input data needed is the machining workpiece geometry and modal characteristics, the geometric parameters of the tool, the cutting forces model parameters [11], the technological parameters of the machining mode. The cutting process dynamics modeling is carried out in time, the technological operation time interval discretization is executed with the fixed step. The in-depth description of this methodology of numerical cutting process dynamics modeling in the time domain is given in the piece of research by Kiselev [11].

The tool body is broken down to flat disks with specified thickness which are perpendicular to its axis [12]. In this paper it is done to look into the plain milling dynamics with the usage of cylindrical helical mills. The geometric model of the machining surface is built upon the technology of Z-buffer with the regular discretization grid [13]; the independent Z-buffer is created for each flat disc of the cutter model.

It is suggested in this paper that the force, which affect the elementary cutting edge during machining, consists of two components with different origins: the forces on the rake face of the cutting edge (position 1 in the figure 1a), which are caused by the material being cut off and the chips being produced, and the forces, which appear from contact interaction between the material being squeezed out from the cutting edge and the cutting edge flank face (position 2 in the figure 1a).

$$F = F^{c}(h) + F^{fl}(h_{fl}) \tag{1}$$

where F – the resultant force, which affect the elementary cutting edge; F^{c} – the cutting force component which depends on the uncut chip thickness h; F^{fl} – the cutting force component which is caused by the interaction along the cutting wedge flank face and depends on the penetration of the cutting edge flank face into the workpiece h_{fl}.

The values of h and h_{fl} are to be defined for each elementary cutting edge of the tool in the geometry modeling block. In this paper the linear stepped model for the component $F^{c}(h)$ is used [1]:

$$F_{tc,rc}(h) = K_{tc,rc} * h * da + K_{tb,rb} * da \tag{2}$$

where F_{rc} – the radial component of the cutting forces; F_{tc} – the tangent component of the cutting forces; da – the length of the line along which the elementary cutting edge and the machining surface interact; $K_{rc}, K_{rb}, K_{tc}, K_{tb}$ – the cutting forces model parameters.

The interaction along the flank face of the cutting wedge is considered as contact and for the second component of the resultant force $F^{fl}(h_{fl})$ the following stiffness relation between the maximum penetration value and the appearing force is proposed:

$$F_n^{fl} = K_{fl} * da * fl_w * h_{max}^{fl} \tag{3}$$

$$F_t^{fl} = \mu * F_n^{fl} \tag{4}$$

where F_n^{fl} - the normal force component from the interaction along the flank face for the elementary cutting edge; F_t^{fl} – the tangent force component from the interaction along the flank face; h_{max}^{fl} - the value of maximum penetration of the flank face of the cutting wedge; fl_w –the width of the worn-out part of the cutting wedge flank face ; K_{fl}, μ – the model parameters.

The single degree of freedom model of the technological system dynamics is used in this paper. The machining workpiece is compliable only in the direction of the tool feed (fig. 1b). The dynamic behavior of this system on the current time step is described by this differential equation:

$$\ddot{x} + 2n * \dot{x} + p^2 * x = F(t) \tag{5}$$

where $x(t)$ – the workpiece vibrations movements in the feed direction; n – the damping coefficient; p – the natural frequency of the system; $F(t)$ –the linear function of the resultant force from the cutting edges projection on the feed direction (on the time step); The consecutive refining of the solution of the differential equation (5) is to be done by the iteration procedure because the values of the uncut chip thickness h, the maximum penetration of the flank face h_{max}^{fl} and the resultant cutting force are interdependent and unknown at the end of the current time step. The usage of such approach ensures the fulfillment of the stiffness relations (3-4) at each discrete time moment.

Fig. 1. (a) - the forces affecting the cutting edge; (b) - the model of the compliable technological system.

To research into the influence of the process damping phenomena on the technological system dynamics, the process of the plain milling of the plate which is firmly fixed on the springing table was scrutinized. The rigidity of the springing table in the feed direction is significantly less than in any other direction. Consequently, this elastic system is to be considered as the single degree of freedom one, which allows not to take into account the axial component of the appearing cutting forces (2). The milling process was carried out by the cylindrical end mill with two teeth. This cutter has the following parameters: the diameter equals to 12mm, the helix angle is 30 degrees. The basic technological parameters of the machining are the following: the axial cutting depth $h_a = 4\,mm$, the radial cutting depth $h_r = 1\,mm$, the feed value equals to 40 μm/tooth, the workpiece material is aluminum. The technological system possesses the following dynamic characteristics: the natural frequency $p = 73\,Hz$, the unitless damping coefficient $\xi = \frac{n}{p} = 0.0057$. The values of the cutting forces model coefficients for the component $F^c(h)$ (2) are the same as in the piece of research [11]. $K_{fl} = 4e4\frac{N}{mm^3}, \mu = 0.3$ for the component $F^{fl}(h_{fl})$ (3-4). The value of the fixed time step dt to solve the system of equations (5) was chosen in such a way so that 400 time steps were equal to one mill revolution. The mill model were broken down to 50 flat discs along its axis, the width of each flat disc $da = 80$ μm.

3 The results

The series of numerical calculations of the plain milling dynamics for the system described above have been carried out with the different machining conditions. The variable parameters are the value of the relative rotating frequency of the spindle ω_{rel} and the width of the worn-out part of the cutting wedge flank face fl_w (3). The value of ω_{rel} is to be calculated as the ratio of the system natural frequency to the cutting tooth pass frequency $(\omega * m)$, where ω – the spindle rotating frequency, m – the number of the tool cutting edges. Therefore, the increase in the value of ω_{rel} leads to the decrease in the tool actual rotating frequency. The variation of the width of the flank face worn-out part fl_w allows to assess the influence of the process damping on the technological system dynamics during cutting when the tool wear increases. The calculation results are represented as a 3D diagram, which is the figure 2. The maximum and minimum values of the workpiece vibrations amplitudes are calculated and pointed along the vertical axis of the 3D diagram for each pair of the variable parameters ω_{rel}, fl_w in the steady domain of the time realization of the compliant workpiece vibrations.

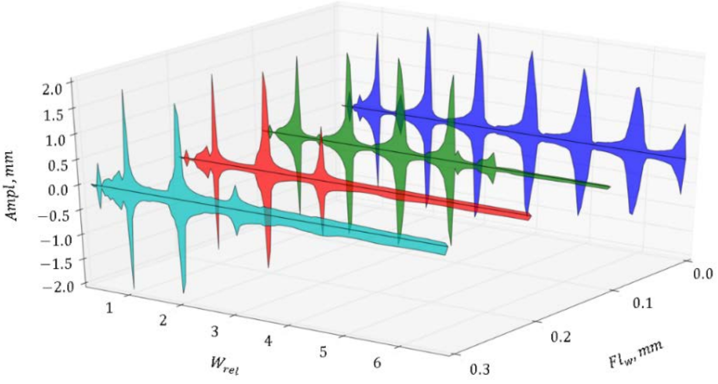

Fig. 2. The 3D diagram of the workpiece vibrations amplitudes for various values of the spindle rotational speed and the dimensions of the cutting edge worn-out part.

This diagram allows to assess the influence of the process damping effect on the technological system dynamics for the wide range of the rotational speed and the tool wear. The figure 2 shows that the increase of the value fl_w significantly decreases the vibrations amplitudes when the relative rotational frequencies $\omega_{rel} > 3$. The results of the numerical modeling of the plain milling dynamics ($\omega_{rel} = 3.8$, the actual spindle rotational frequency $\omega = 576.3\,rpm$) are shown in the figure 3. The vibrations amplitudes in the steady domain when $fl_w = 0.3\ mm$ (fig. 3b) are significantly lower than in case of the tool wear absence ($fl_w = 0\ mm$, fig. 3a). This effect is put down to the fact that the interaction intensity along the cutting edge worn-out flank face in the domain of the low values of the spindle rotational frequencies increases.

The detection of the "chatter" was carried out for the time realizations of the workpiece vibrations. The methodology of this detection is described in [14] and the results of this detection is shown on the figure 4. It is clear that the machining mode domains free from "chatter" expand while the tool wear increases and these domains correspond to the modes domains free from high-amplitudes vibrations (fig.2). The particular trait of the vibrations when $\omega_{rel} = 3.8$ can be seen on the spectrum of the time realizations of the workpiece vibrations (fig.3 c,d). If the tool is not worn-out, there is a harmonic at the frequency which is near the natural frequency of the system (fig. 3c). This indicates that there is "chatter" in the system. (it is shown by the red point in the figure 4). There are only frequencies which are divisible by the cutting tooth pass frequency $\omega * m = 19.2\ Hz$ (fig. 3d) on the time realization spectrum in case $fl_w = 0.3\ mm$. There is a blue point which corresponds to this mode in the figure 4.

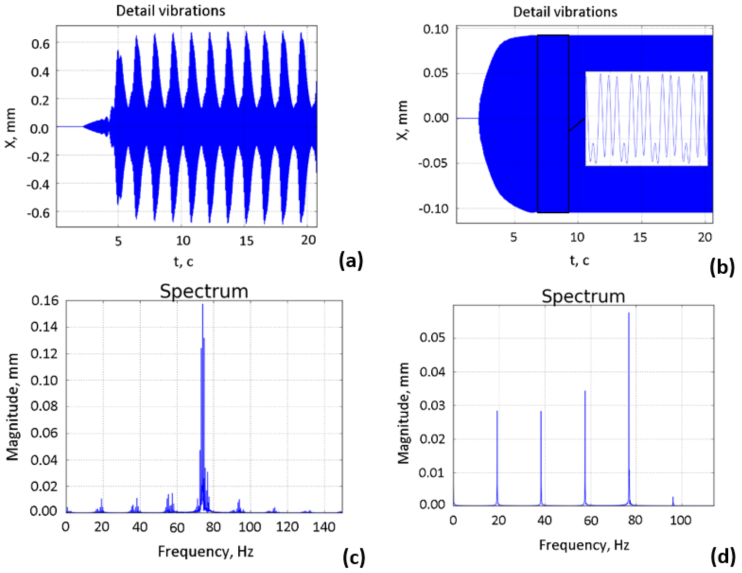

Fig. 3. The milling dynamics modeling results in case $\omega_{rel} = 3.8$: (a),(c) – the time realization of the workpiece vibrations and its spectrum in case $fl_w = 0\ mm$; (b),(d) – the time realization of the workpiece vibrations and its spectrum in case $fl_w = 0.3\ mm$.

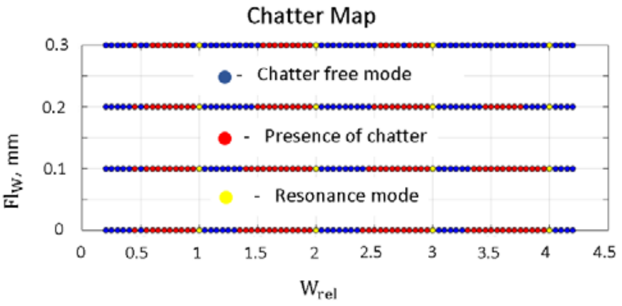

Fig. 4. The detection of the "chatter" results in the time realizations of the workpiece vibrations (in accordance with the methodology described in [14])

4 Conclusion

The single degree of freedom model of the plain milling dynamics is presented in this article. This model allows to take into account the influence of the contact interaction along the cutting edge flank face on the dynamic behavior of the compliant technological system. The analysis of the obtained results of the multivariant numerical modeling of the plain milling dynamics for a range of the machining technological conditions showed that the process damping may significantly influence the technological system dynamics in the machining modes domains in which the cutting tooth pass frequency is much lower than the system natural frequency and there is the tool wear presented.

The represented model can be used for the efficient machining modes choice, which are free from the unwanted high-amplitudes vibrations of the technological system components. The used in this paper method of taking into account the contact interaction forces along the cutting edge flank face can be later on used for the 3D multiaxial machining of the figurine-shaped workpieces.

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