NUMERIC SIMULATION OF THE AUTOOSCILATIONS AT THE PROCESSING OF METALS AND ROCK MATERIALS BY MILLING

Mikov I. N.[1], Shemetov M. G.[2], Rybin A. G.[2], Mezentzeva I. L.[1], Stefanova N. N.[3]

[1] *Moscow State Mining University, Russia*
[2] *Scientific and Research Institute for Aircraft Technologies, Moscow, Russia*
[3] *University of Mining and Geology „St. Ivan Rilski", Sofia, Bulgaria*

ABSTRACT. Because of the intermittence of the cutting at milling, the tool and the material are subjected to periodic oscillations, caused by the interaction of the tool and the material processed.
Often, at processing by cutting autooscillations begin and this as a rule, brings to unsatisfactory quality of the processed surface and sometimes, to the tool breaking and the blank damage.
The beginning of autooscilations brings to disturbance of the steady periodic motion of the tool centre, i. e. there is a presence of instability.
In the paper is researched the tool oscillation at milling by numerical simulation on the basis of simulative model of the milling process, including the tool dynamics (the calculation scheme of the model is composed with rendering an account of the experimental dependences of the alteration of cutting force at metal processing and the dynamic characteristics of the elastic system, determined experimentally by modal analysis) and the parameters of unevenness of the obtained surface. The Poincare section is used in the analysis of simulation.
Dependences of cutting forces at the processing of rock materials are suggested.
The model adequacy regarding the regeneration of the surface at the rock materials processing is researched, which allows the field of the model application to be assessed and enlarged.
The approach suggested, allows the zone of autooscillations of the system technological parameters to be determined and the quality of the processed surface to be assessed.

ЦИФРОВО МОДЕЛИРАНЕ НА СОБСТВЕНИТЕ КОЛЕБАНИЯ ПРИ ОБРАБОТКАТА НА МЕТАЛИ И СКАЛНИ МАТЕРИАЛИ ЧРЕЗ ФРЕЗОВАНЕ

Миков И. Н.[1] , Шеметов М. Г.[2], Рыбин А. Г.[2], Мезенцева И. Л.[2], Стефанова Н. Н.[3]
[1] *Московски държавен минен университет, Русия*
[2] *Научноизследователски институт по авиационни технологии, Москва, Русия*
[3] *Минно-геоложки университет "Св. Иван Рилски", София, България*

РЕЗЮМЕ. Поради прекъснатостта на рязането при фрезоване, инструментът и материалът са подложени на периодични колебания, предизвикани от взаимодействието им.
Често, при обработка чрез рязане, възникват собствени колебания, което, като правило води до неудовлетворително качество на обработената повърхност, а понякога - до счупване на инструмента и повреждане на заготовката.
Възникването на собствени колебания в системата предизвиква нарушаване на равномерното периодично движение на центъра на инструмента, т. е получава се загуба на устойчивост.
В работата се изследва колебателното движение на инструмента при фрезоване с използване на цифрово моделиране на базата на симулационен модел на процеса фрезоване, включително динамиката на инструмента (изчислителната схема на модела е съставена с отчитане на експерименталните зависимости на изменението на усилието при рязане при металообработка и динамичните характеристики на еластичната система на машината, определене експериментално, с помощта на модален анализ). И параметрите на неравностите на получената повърхност. За анализ на резултатите от моделирането е използвано изображенита на Поанкаре.
В работата са предложени зависимости за силите на рязане при обработката на скални материали. Изследвана е адекватността на модела по отношение регенерацията на повърхността при обработката на скални материали, което позволява да се оцени и разшири областта на приложение на модела.
Предложеният подход позволява да се определи зоната на собствените колебания в технологичните параметри на системата и да се оцени качеството на обработената повърхност.

Quality of the surface obtained at milling is influenced by the tool chatters and the forces arising between the tool and the blank. Depending on the values of the technological parameters it is possible the values of these factors to become unacceptable in some areas. In such cases, it is said that a loss of system stability appears, and more precisely, it has to be said that a loss of stability of its periodic motion appears. It is important the areas of processing parameters, where a stable cutting and obtaining of the required surface quality are provided to be separate.

Different methods for assessment of the periodic oscillations of the tool at milling have obtained wide use in the field of metal working (Altintas Y., 2000; Inspeger, T., Stepan, G., 2000; Гуськов А.М., Рыбин А.Г., 2002). The adaptation of computation models allows the use of these approaches also at stone processing.

The oscillating motion of the tool at milling will be computed by use of numerical modeling on the basis of simulation model of the milling process with analysis of the tool dynamics and the roughness parameters of the surface obtained, suggested for working of metals (Миков И.Н., Рыбин А.Г., Мезенцева И.Л., 2008).

The computation diagram for the model in question is presented in fig. 1.

The main parameters are: cutter radius R, teeth number Z, feed of the tooth S_z, axial cutting depth b. Elastic characteristics of the tool fastening: rigidity k, damping value d, natural frequency of the system p_0.

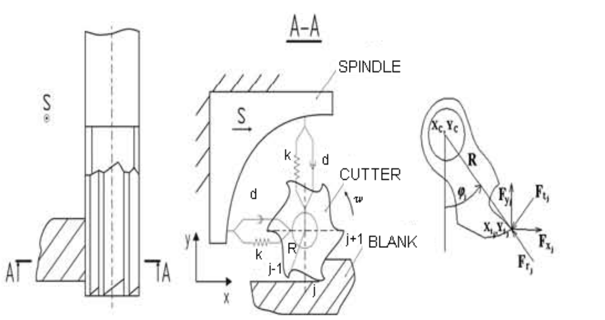

Fig. 1. Computation diagram

The projection of the cutting force on the axes Ox and Oy can be recorded as follows:

$$F_{xj} = -F_{rj}\sin(\varphi_j) - F_{tj}\cos(\varphi_j) \quad (1)$$

$$F_{yj} = F_{rj}\cos(\varphi_j) - F_{tj}\sin(\varphi_j) \quad (2)$$

The forces in radial and circumference directions could be approximated by the dependencies (Гуськов А.М., Рыбин А.Г., 2002):

$$F_{rj} = g_r \sigma_b b^2 \left(\frac{S_z}{b}\right)^q \left(\frac{h_j}{S_z}\right)^q \quad (3)$$

$$F_{tj} = g_t \sigma_b b^2 \left(\frac{S_z}{b}\right)^q \left(\frac{h_j}{S_z}\right)^q \quad (4)$$

Where g_r, g_t - dimensionless factors, characterizing the condition of the tool cutting edges; b - axial depth of cutting $[m]$; $\sigma_в$ - strength limit of the processed material $[N/m^2]$; S_z - feed of the tooth $[m]$; h_j - second chip thickness $[m]$; q - non-linearity factor of the dependency of the cutting force on the chip thickness. It has to be mentioned that such a form of the record is preferable from the point of view of the dimensions theory and is invariant with respect to the system of the used quantities.

The full system of equations, describing the kinematics and dynamics of the system is as follows:

$$\begin{cases} x_c = x_0 + S_z Zt + u(t) \\ y_c = y_0 + v(t) \\ x_{tj} = x_c + R\sin(\varphi_j) \\ x_{tj} = y_c - R\cos(\varphi_j) \\ \ddot{u} = -p_0^2 u - 2dp_0\dot{u} + \frac{1}{m}\sum_{j=0}^{z-1} -F_{rj}\sin(\varphi_j) - F_{tj}\cos(\varphi_j) \ldots (5) \\ \ddot{v} = -p_0^2 v - 2dp_0\dot{v} + \frac{1}{m}\sum_{j-0}^{z-1} F_{rj}\cos(\varphi_j) - F_{tj}\sin(\varphi_j) \\ h_j \leftarrow A(x_{tj}, y_{tj}, S) \end{cases}$$

In the model presented, the second chip thickness is determined with rendering an account of the shape forming of the surface S. The processed surface S is determined as an array of points $S = \{P \mid P(x_k, y_k), k = 1,2\ldots\}$.

The trajectory of the cutting edge is approximated to another circle determined by three points (three consecutive positions of the cutting edge). Points located on the cutting edge trajectory are added to the surface array in case of crossing of the approximating curve and the polygon restricting the surface. The points, which "have to be cut", are extracted from the array.

The chip thickness is determined as a distance from the cutting edge to the point of intersection of the line connecting the center of the cutter and the cutting edge with the line of the surface.

The research in stability is made by the Poincare section. At the section plotting, the points of intersection of the phase trajectory of the system with some non-tangential straight line have to be fixed, in this case, with the axis of ordinates of the phase plain. This way, *n* points of the Poincare section correspond to the steady periodic motion. In case of stability loss, the number of points in the section alters. The plotting of the section depending on any parameter (in this case, on the spindle turning velocity) gives the bifurcation diagram.

The modeling has been made for milling at the following parameters: cutting with two-tooth cutter with diameter 14 mm, feed of a tooth 0, 1 mm, radial cutting depth 1, 5 mm. Parameters of fastening: $k = 3 \cdot 10^6 H/м, \xi = 0{,}06, v = 300Hz$

Factors for force dependences: $g_r = 2,\ g_t = 1,\ q = 1, \sigma_в = 750MPa$.

The computations have been made for velocities of tool turning 9000 *min-1* and 10000 *min-1*. In the first case, the frequency of the system excitation (frequency of the teeth cutting-in) is equal the natural frequency of the non-damped system. The cutting axis depth has varied from 4, 0 to 9, 6 mm.

The Poincare section and character of oscillations of the centre of cutter mass obtained according to the computation results are presented in figures 2 and 3.

The graphics show that in the resonance area the oscillations of the mass center in the total range, the alterations of the axial cutting depths corresponds to the periodical motion with growing amplitude. In case of processing at velocity 10000 *min*$^{-1}$, the loss of stability begins at cutting axis depth 5, 2 mm. With the increase of the cutting axis depth, the oscillations amplitude becomes bigger than the oscillations amplitude at resonance frequencies. From the bifurcation diagram a conclusion can be made that in the concrete case at loss of stability begins Poincare- Andronov- Hopf bifurcation.

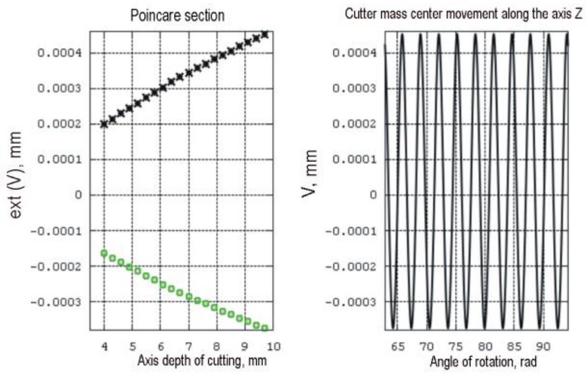

Fig. 2. Bifurcation diagram and oscillations of the centre of cutter mass(axial cutting depth 9.6 mm) at processing at velocity of the spindle turning 9000 min^{-1}

The approach suggested also allows the quality of the processed surface to be assessed.

Figure 4 shows the profile of the processed surface, obtained as a result of modeling.

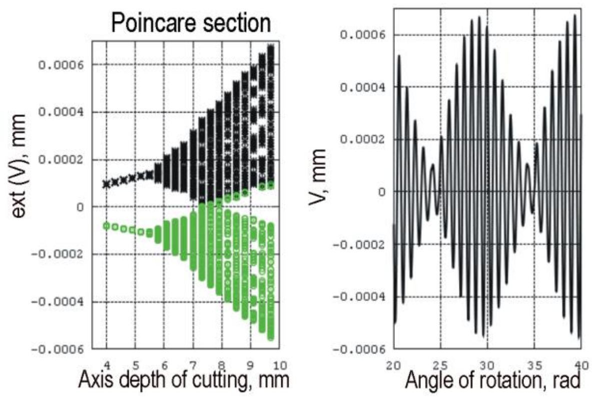

Fig. 3. Bifurcation diagram and oscillations of the centre of cutter mass(axial cutting depth 5.2mm) at processing at velocity of the spindle turning 10000 min^{-1}

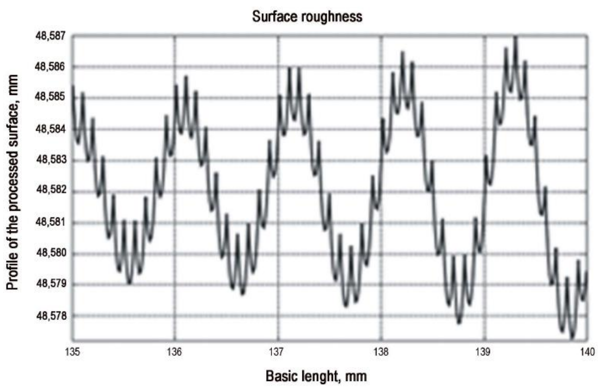

Fig. 4. Unevenness of the surface after processing at velocity 10000 min^{-1} and axial cutting depth 5.2 mm

For the unevenness of the processed surface has been plotted a section, similar to that made for the oscillations. The area of stability loss has also been well shown by the sections obtained.

Traditionally, abrasive mills are used at processing of rock materials, and the process of milling of stones is brought to grinding. In order to be used, the suggested model of natural oscillations analysis has to be adapted.

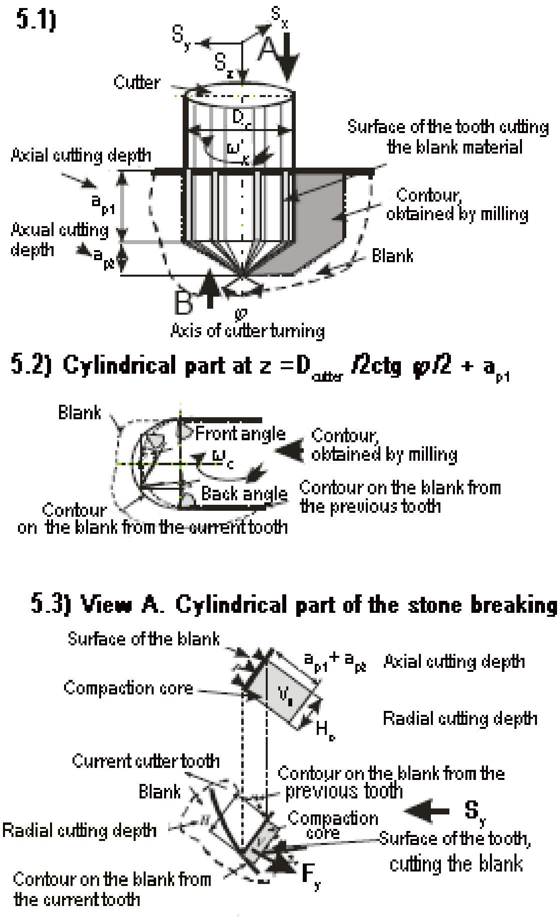

Fig. 5. Shank cutter at contour milling

Stone processing by milling according two or three co-ordinates is similar (analogous) to breaking out of the edge at presence of one or two free surfaces (Протасов Ю.И., 1995).

Under the influence of forces F_x, F_y and F_z, the tool breaks out layers- chips. The stone breaking consists in the following: for example, at the motion of the cutting edge along the axis Oy, the force F_y deforms a volume V_0 of the stone creating a compaction core (fig. 5.3). The forces F_x and F_z act respectively at motion along the axes Ox and Oz. The compaction core compresses in direction of the force action and expands in direction perpendicular to it, i.e. to the free surface, working against the reaction force P of the stone. At that a volume V of the stone is broken out. In connection with the shape forming three phases has to be considered:

1. Micromotion of the cutter along the axis $z = H_{\min}$. In this case, there is no milling, but the cutter operates as a gouge (fig.6)

In this case the cutter will drive in to depth $H_{\min}$ (Протасов Ю.И. 1995) if

$$F_{z\min} = \frac{1{,}1\sigma BkH_{\min}}{\mu b\eta} \quad (6)$$

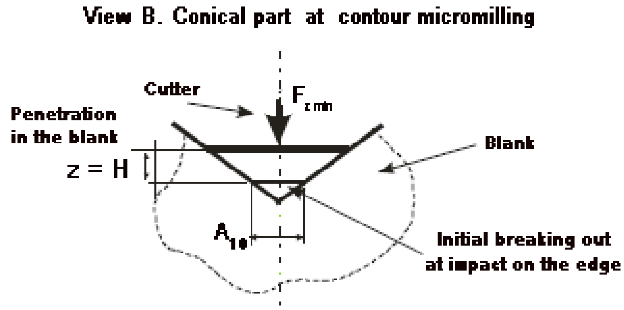

Fig. 6. Shank cutter at contour microcut-in

2. Millimotion of the cutter along the axis $z = H$ within the limits of the cutter conic end (fig.7). In this case the total force is a vector sum of $F_{z.\min}$ and $F_{y.\min}$. Then

$$F_{y.\min} = \frac{\sigma BkH}{2\mu b} \quad (7)$$

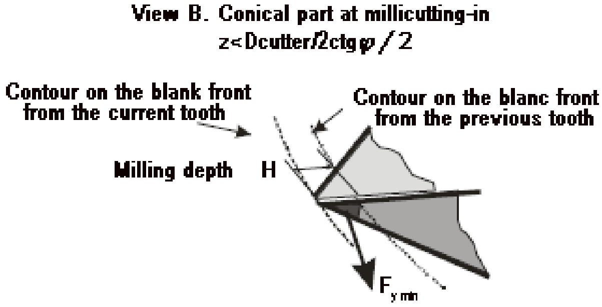

Fig. 7. Shank cutter at contour millicut-in

3. Operating motions of the cutter along the axis Oz within the limits of the cutter cylindrical end. (fig. 5.2, 5.3 and 8). In this case the total force is the vector sum $F_{z.\min}$, $F_{y.\min}$ and F_y.

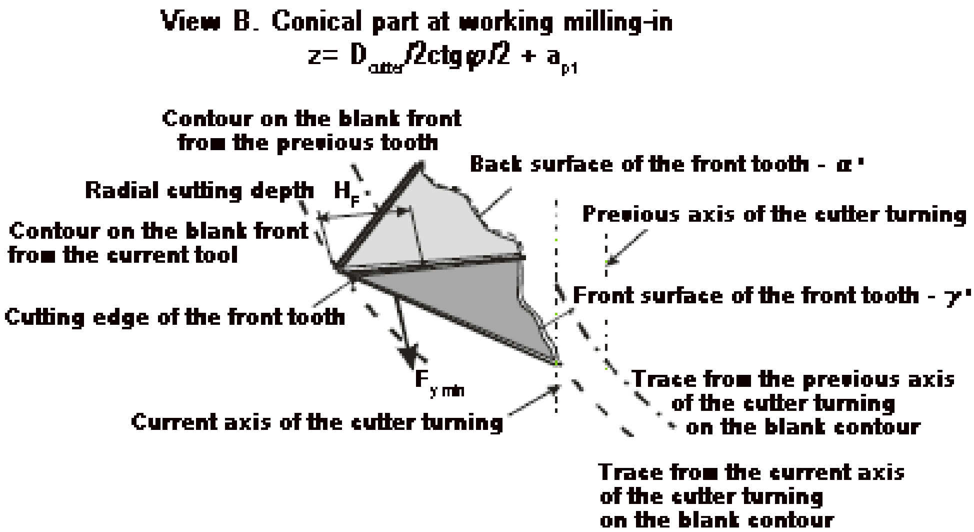

Fig. 8. Conical part of a shank cutter at a contour millicut-in

In (Протасов Ю.И., 1995) could be find the dependency of the cutting force along the axis *y*.

$$F_y = \frac{\sigma BkH}{\mu b}, \quad (8)$$

Where: σ – tensile strength limit of the rock $\left[N/m^2\right]$; *B* – length of the operational part of the tool cutting edge, axial cutting depth $[m]$; k – factor rendering an account of the boundary conditions of stone breaking and ductility; H – radial cutting depth $[m]$; μ – Poisson's ratio; b – factor of the shape of the breaking out stone volume. Taking as a basis the general expression for the force $F_i = \frac{\sigma k A}{\mu b}$ in local co-ordinates of the grain, a similar approach for description of the forces can be used for each grain separately. Here A – working area of the grain, similar to the product $B \cdot H$. Then the cutting forces influencing the instrument could be presented as:

$$F_x = \sum_N F_i \cos\varphi_i \quad (9)$$

$$F_y = \sum_N F_i \sin\varphi_i \quad (10)$$

where φ_i – angle of the inclination of the normal of the grain cutting platform to the immovable co-ordinate system; N – number of the examined grains. At summation by grains more appropriate is the probabilistic approach to be used, for example as it is suggested in (Rogelio L. Hecker, Igor M. Ramoneda and Steven Y. Liang, 2003).

At the adaptation of the model for computation of natural oscillations at every step of integration it is necessary the tool contact line (described as a circle) with the blank to be examined.

The suggested approach allows the area of beginning of the natural oscillations of the system technological parameters to be determined and the quality of the processed surface to be assessed. The method allows the character of the stability loss (the bifurcation type) to be disclosed. The frequencies of the beginning oscillations are determined by the results of computation, which is expedient to be used for identification of the areas of natural oscillations at experimental researches. The advantage of the numerical modeling is the fast adaptation to the required conditions. For example, it is possible the influence of hard inclusions in the rock material to be researched by determination of their distribution in the processed surface on accidental principle.

Recommended for publication of Editorial board

REFERENCES

Altintas Y. Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design, *Cambridge University Press*, 2000, p. 286.

Inspeger, T., Stepan, G. (2000). Stability of the milling process, Periodica Polytechinca, *Mechanical Engineering*, 44 (1), pp. 47-57.B. Balachandran, M.X. Zhao. A Mechanics Based Model for Study of Dynamics of illing Operations, *Meccanica* 35, 2000, pp.89-109.

Гуськов А.М., Рыбин А.Г. Численный анализ динамики цилиндрического фрезерования. Проблемы динамики и прочности исполнительных механизмов и машин. *Материалы научной конференции. Астрахань, 2002г*, с. 119-122

Миков И.Н., Рыбин А.Г., Мезенцева И.Л.Численное моделирование автоколебаний при обработке фрезерованием. *Горный Информационно-Аналитический Бюллетень*, М.: МГГУ, № 6 , 2008.

Протасов Ю.И. Разрушение горных пород. М.: *Издательство МГГУ*, 1995.- 452 с.

Rogelio L. Hecker, Igor M. Ramoneda and Steven Y. Liang. Analysis of Wheel Topography and Grit Force for Grinding Process Model. *Transactions of NAMRI/SME,* Vol. 31, 2003.