

# Simulating turning cycles on CNC lathe machines

Y.V. Petrakov<sup>1</sup> • J.M. Ezenduka<sup>1</sup>

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**Abstract.** It is shown that the turning of the contour shaped surfaces of parts is mainly carried out according to the cycles of rough turning G71, G72, G73 with a finishing pass according to the cycle G70. In any case, the cutting process is quasi-stationary, which determines the need to control the cutting mode to stabilize and optimize the process. It is proposed to use a special program for designing the control program of a CNC machine tool, which, based on a priori information about the technological machining system, performs the simulation of the process. During simulation, in the process of solving the optimization problem according to the criterion of maximum Material Removal Rate, all components of the cutting mode are automatically determined: depth, feed and spindle speed. The results are presented in the form of control files, according to which a control program in G-codes can be compiled to optimize the process. In addition, it is additionally possible to obtain a prediction about the actually machined contour, taking into account the elastic deformation during the cutting process, and data on the correction of the trajectory of the shaping movement in the last pass.

**Keywords:** contour turning, cutting control, modeling, cutting process optimization.

## Introduction

To process machined parts of round cross section on CNC lathes, control programs are used in which special cycles for removing the rough allowance are used [1, 2]. Despite the convenience of programming such machining, the problems caused by the quasi-stationary conditions of contour cutting remain unresolved, which leads to a loss in productivity and quality of machining. When machining parts, it is necessary to strive to perform three sequential actions: stabilization of cutting conditions, optimization of the process, and, if necessary, correction of the shaping trajectory on the last pass [3].

However, even when CAM systems are used to prepare CNC control programs, the issues of assigning a cutting mode and its optimization remain unresolved. Recently, leading companies in the high-tech market have begun to offer software products that, as stated, are able to automatically calculate the optimal cutting mode. Such

technologies, developed by various companies, offer a solution based on the analysis of the shaping motion path for milling operations, which is not adequate to the interaction of the tool with the workpiece [4], and for turning, there is still no automated assignment of the optimal cutting mode in known CAM systems. Therefore, it remains relevant to create technologies for optimal control of the cutting mode during turning contouring of shaped parts on CNC Lathe Machine.

## Problem status analysis

When programming turning contouring operations on CNC lathes, it is recommended to use the G71, G72, and G73 rough contouring canned cycles followed by the G70 finishing cycle.

Fig. 1 shows an example of a control program for the FANUC G71 cycle for roughing the contour of a part. Programming the machining of the contour in a cycle eliminates the need to set the movement separately for each pass, automatically provides for a stop at a given depth of the finishing allowance and provides the same trajectories of reverse idle moves. The main parameters of the cycle are the geometric data of the machined contour, which are

✉ Y. V. Petrakov  
ypetrakov.86@gmail.com

<sup>1</sup> Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine

linked to the assigned depth of cut. The machining efficiency is determined by the cutting mode, which contains three components: depth of cut, feed and spindle speed. All these parameters are not automatically offered in the CAM system, but are assigned by the technologist, which often leads to errors and losses.

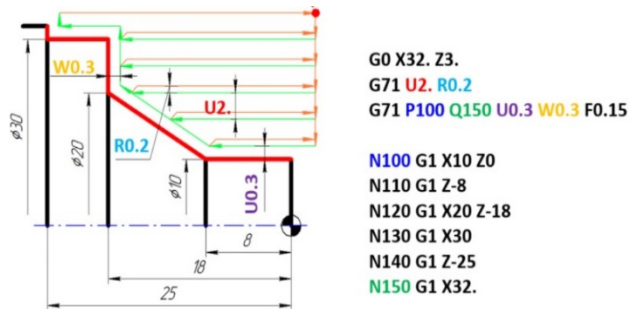


Fig. 1. Cycle Fanuc G71

The cutting process during contouring is characterized by a change in cutting conditions on the passes, and on the finishing pass, the resulting allowance causes significant changes in the depth of cut [5]. All this makes it necessary to permanently control the process in order to stabilize it and further optimize it. Thus, the control program using cycles must be supplemented with cutting data that achieves these goals. Such parameters for contouring processes are still determined based on experience or trial and error modeling scenarios in order to obtain the most convenient result for real implementation [6].

It is known that the efficiency of roughing is determined by the parameter Material Removal Rate (MRR), which can be taken as a criterion for the optimality of the process. However, it is proposed to search for the necessary mathematical model of the process by statistical methods [7]. Once experiments are planned, performance indicators such as surface roughness of test specimens and MRR are calculated using existing formulas.

The effect of parameters on MRR and surface roughness is determined using analysis of variance (ANOVA) and process parameter interactions are also taken into account for significance. An attempt to optimize machining parameters with several goals, namely, maximizing MRR and minimizing surface roughness, is difficult to consider effective for machining parts on CNC machine tools, since the surface roughness parameter is always set by the designer and it makes no sense to exceed it. Therefore, ensuring the required roughness should be considered a limitation.

The main perturbation in the contouring of shaped surfaces is a significant change in the cutting conditions along the shaping trajectory. Therefore, the stabilization of the process according to the MRR criterion is of paramount importance. It is known that in order to stabilize the cutting process when machining such surfaces, it is recommended to use processing methods that are characterized by the information used for designing control: a priori, streaming or a posteriori [3]. Control by streaming or a posteriori infor-

mation requires the creation of special control systems, which makes it difficult to use them in practice. When controlling by a priori information, programming with MRR stabilization is possible, however, the design of such control is possible only with preliminary modeling of the machining process. It is proposed to determine the machining parameters, such as the depth of cut, feed rate and spindle speed, through the use of a genetic algorithm [8]. However, such an approach, still aimed at searching for analytical dependencies, cannot be considered rational. Using an algorithm to compare the results of experimental and theoretical measurement of cutting force in a turning operation can still improve the accuracy of determining the regression model of cutting force.

Determination of the main characteristics of the process of turning shaped surfaces for the design of control actions, which are the components of the cutting mode, is possible when modeling the process. It is proposed to use approaches based on the representation of the interaction of a tool and a workpiece using geometric primitives that describe any surface with two parameters: diameter and angle of inclination of the tangent to the longitudinal axis [9]. Analytical dependencies are proposed that determine the position of the current point corresponding to the position of the cutter nose when machining the most common elementary surfaces. However, this approach cannot take into account the interaction parameters of the cutting edge along its entire length, which significantly reduces its adequacy.

Thus, the problem of assigning a cutting mode when programming cycles for turning shaped surfaces remains relevant.

## Objective

To develop a programming technique for standard cycles of turning shaped surfaces with the determination of the optimal cutting mode and possible correction of the shaping trajectory at the finishing pass.

## Statement of the main material

The problem of optimizing the turning process was formulated as a single-criterion task with an objective function  $f = FS \rightarrow \max$ , where  $F$  is the feed,  $S$  is the spindle speed. The solution is performed by searching for the maximum on the phase plane "longitudinal feed - spindle speed", which is determined by the coordinates of the vertex of the area of admissible values formed by the intersection of restrictions on roughness, tool life, allowable cutting power or feed force [10].

When programming turning cycles, the first thing to do is assign a depth of cut, which will determine the distance between passes. As the analysis showed, such an important process parameter is assigned by the technologist-programmer intuitively or by trial and error, which leads to

loss of productivity or unacceptable equipment overloads. To solve this important problem, a special algorithm was developed, which provides for the search for the optimal depth of cut according to the criterion of the maximum Material Removal Rate of the allowance  $MRR = F_{opt}H \rightarrow \max$ , where  $F_{opt}$  is the optimal feed, determined by the method described in [10]. The algorithm is based on calculating the MRR under the conditions of solving the optimization problem when changing the cutting depth from 0.1 mm to 10 mm with a step of 0.1 mm. The depth of cut that delivers the maximum MRR is automatically adopted.

Determination of the main characteristics of the process of turning shaped surfaces is carried out with digital modeling of the process, where all the characteristics necessary to solve the problem are determined by numerical methods.

Simulation involves the preparation of digital arrays of workpiece contours  $F_w(x_b z_i)$ , motion paths in the cutting process  $F_c(x_b z_i)$  in accordance with the selected turning cycle (G71, G72 or G73), digital array  $F_p(x_i z_i)$  of the part contour. To perform the simulation of the finishing pass using the G70 cycle, a digital array of  $F_b(x_b z_i)$  equidistant to the part contour is prepared. The simulation process is based on the solution of the geometric problem of the intersection of the tool surface with the surface of the workpiece 1, which is given by the generatrix in the form of a digital array (Fig. 2, a). As a result of the interaction of two digital arrays, a new array of the workpiece contour with a given step is created using a special algorithm, which is represented by digital array 2. In this case, the cutting tool blade moves along path 3.

Simulation of geometric interaction is performed with automatic search for the coordinates of the point A of the intersection of the cutting edge of the tool with the contour of the workpiece (Fig. 2, a). Here, the workpiece contour  $(z_w)_j, (x_w)_j$  and the tool edge  $(z_t)_i, (x_t)_i$  are represented by digital arrays conventionally shown as circles in the diagram. The algorithm, the block diagram of which

is shown in Fig. 2, b, allows determining the coordinates  $x_p, z_p$  of a new workpiece contour at each simulation step.

Thus, the simulation is performed by a numerical method with a predetermined step (0.1 mm), provides for the calculation of the actual cutting depth  $H$  and the appeal to the procedures for solving the optimization problem: determining the values of the feed and the spindle speed at each step. The calculation of the actual depth of cut is performed by a special procedure for comparing the digital arrays of the current trajectory of the tool edge and the contour of the workpiece formed in the previous pass, taking into account the side cutting-edge angle. The determination of the feed rate is carried out according to the procedure described in [10] and allows calculating the feed allowable by the roughness parameter  $Rz$  at each simulation step. The cutter moves along the trajectories formed at the previous stages of the optimization module.

As a result, at each simulation step, it becomes possible to calculate the cutting depth  $H$  and the height of the surface ridge, which represents the deterministic component  $Rz$  of the surface roughness. This approach allows to calculate the MRR at each simulation step:

$$MRR = (H - Rz / 2) Feed_{pr} \tag{1}$$

where  $H$  is the depth of cut,  $Rz$  is the roughness parameter,  $Feed_{pr}$  is the feed per revolution of the spindle.

In addition, the simulation process provides for the calculation of the cutting force using a linearized dependence of the horizontal component  $F_{xz}$  of the cutting force, the position of which in the  $XOZ$  coordinate system is determined by the chip flow angle  $\eta$ . The module of this component:

$$F_{xz} = MMRk_F \tag{2}$$

where  $k_F$  is the coefficient of the linearized dependence of the cutting force on the depth [10], since when machining with feed control, which is used when performing cycles, its value is kept constant.

The components of the cutting force, which exert a

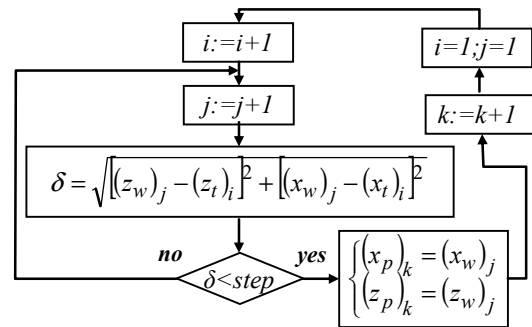
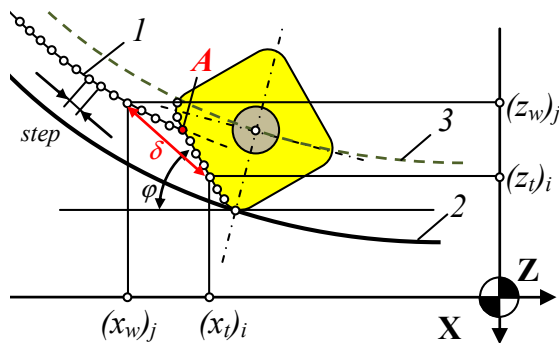


Fig. 2. Scheme (a) and algorithm (b) of geometric simulation

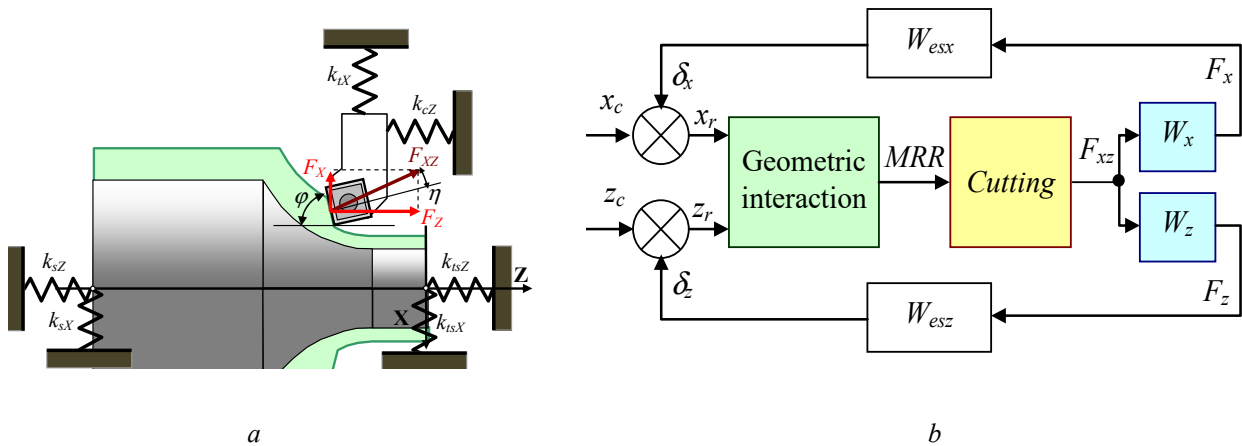


Fig. 3. Cutting process: *a* – elastic machining system, *b* – functional diagram

force perturbation on the elastic machining system in the direction of the *X* and *Z* axes, are determined by the formulas, obtained from the geometric relationships of Fig. 3, *a*:

$$F_x = F_{xz} \sin(\phi - \eta), \quad F_z = F_{xz} \cos(\phi - \eta) \quad (3)$$

where  $\phi$  is the side cutting-edge angle.

The components of the cutting force act in a closed elastic machining system (Fig. 3, *b*) and cause a shaping error caused by elastic deformations along the normal to the contour:

$$\Delta = \delta_x \sin \alpha_k + \delta_z \cos \alpha_k, \quad (4)$$

where  $\delta_x, \delta_z$  are deformations of the elastic system in the direction of the corresponding axes,  $\alpha_k$  is the angle of inclination of the contour.

In the first approximation, without taking into account the dynamic properties of the processing system and the rigidity of the workpiece, the elastic system of the machine in the direction of the *X* axis can be calculated by the formulas:

when installing the workpiece in the chuck

$$W_{esX} = \frac{k_{tX} k_{sX}}{k_{tX} + k_{sX}},$$

when installing the workpiece in the chuck and center of

$$\text{tailstock} \quad W_{esX} = \frac{k_{sX} + k_{tX} k_{tsX}}{k_{tX} + k_{sX} + k_{tsX}}. \quad (5)$$

When calculating in the direction of the *Z* axis in formulas (5), the corresponding indices change. In this way:

$$\delta_x = F_x / W_{esX}, \quad \delta_z = F_z / W_{esZ}. \quad (6)$$

All designations in formulas (5) and (6) coincide with the designations in Fig. 3.

It should be noted that the cutting process seems to be carried out in a closed elastic machining system, which must be taken into account when modelling it.

### Simulation

An application program was created to simulate turning cycles and prepare a control CNC program with automatic assignment of the cutting mode. It implemented the basic concept of control of the process of turning, outlined above. The processed contour of the part and workpiece is specified by the coordinates of the points of the vertices of the sections in the tables “Part contour” and “Workpiece contour” (Fig. 4). The “Form” column specifies the section type (1 – straight line, 2 – circular arc). If an arc of a circle is specified, then the radius is specified in the “R” column. All these data are initially contained in the drawing, or in the listing of the control program designed in any CAM system.

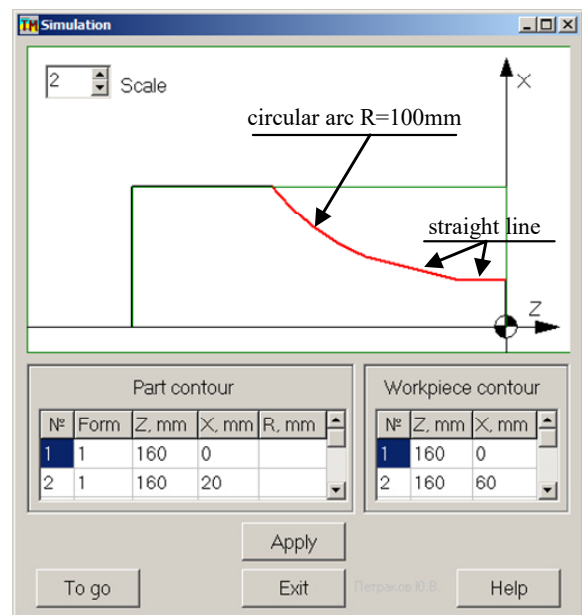


Fig. 4. Main interface

Next, the type of roughing cycle is selected and the technological parameters of the process are entered. To simulate the machining of such a part, the G71 cycle and the following parameters are selected: allowance for finishing 0.5 mm,  $R_z$  roughing 20  $\mu\text{m}$ ,  $R_z$  finishing 1  $\mu\text{m}$ , tool nose radius 0.5 mm, side cutting-edge angle 85 degree, end cutting-edge angle 15 degree, tool life 20 min. It is also necessary to enter into the program the data of the machine on which the part will be processed: CNC machine lathe ST 20 HAAS (Power 14.9 kW, Max spindle speed 4000 rpm, Z-axis Max feed m/min). To predict the processing accuracy, it is necessary to set the stiffness data of the spindle and caliper along the X and Z axes: spindle 20000 N/mm, tool turret 18000 N/mm.

By default, the maximum allowable deformation of the technological system is taken, according to which the program calculates the maximum allowable feed force. Next, you need to select the method of installing the workpiece (Chuck or Chuck and Center), the material of the part (Steel 30 GOST) and the tool (T5K10 GOST).

As can be seen, the components of the cutting mode are not assigned in the initial data, the depth, cutting speed and feed allowable for a given roughness in roughing are calculated automatically at the beginning of the simulation according to special procedures [10]. The number of roughing passes is calculated by the formula:

$$n = \text{trunc} \left[ (x_{w_{\max}} - x_{p_{\min}} - H_f) / H_r \right] \quad (7)$$

where  $x_{w_{\max}}$  is the maximum coordinate of the workpiece,  $x_{p_{\min}}$  is the minimum coordinate of the contour of the part,  $H_f$  is the allowance for finishing,  $H_r$  is the depth of cut in roughing. Since the number of rough passes must be an integer, the value found in the algorithms is refined for the G71 rough cycle:

$$\text{if } (x_{w_{\max}} - x_{p_{\min}} - H_f) > 0.25H_r, n, \text{ then } n := n + 1 \quad (8)$$

Therefore, on the first pass (Fig. 5, a) the cutting depth may differ from the optimal one.

After the end of the roughing cycle G71, the workpiece has the shape shown in Fig. 5, b. It is clear that such a shape provokes significant changes in the depth of cut on the G70 finishing cycle (Fig. 6, a) with the corresponding reaction of the elastic machining system. Since the optimization procedure is invoked at each step in the simulation, such variations cause the corresponding response of the optimization module in the form of a change in the spindle speed. The feed with this regulation remains constant, the value of which is determined by a numerical procedure to ensure a given roughness of the finished part contour along the entire contour.

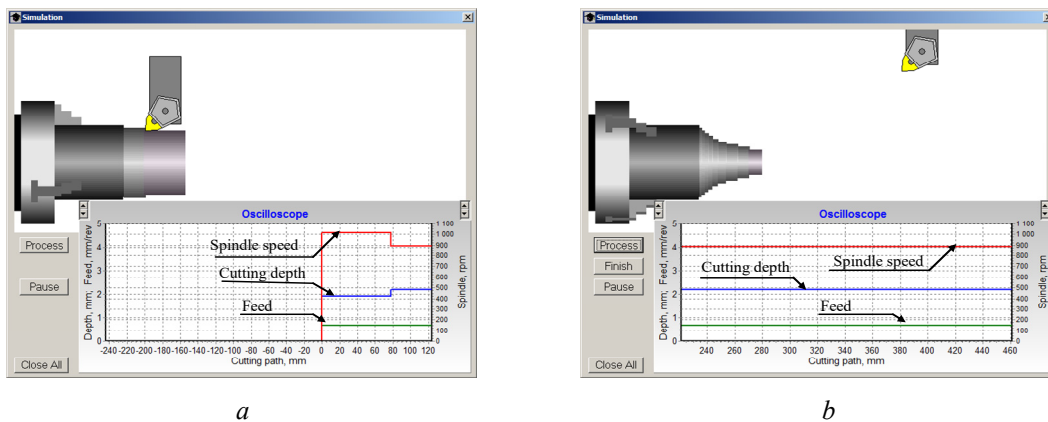


Fig. 5. Simulation steps: a – first pass of cycle G71, b – end of roughing

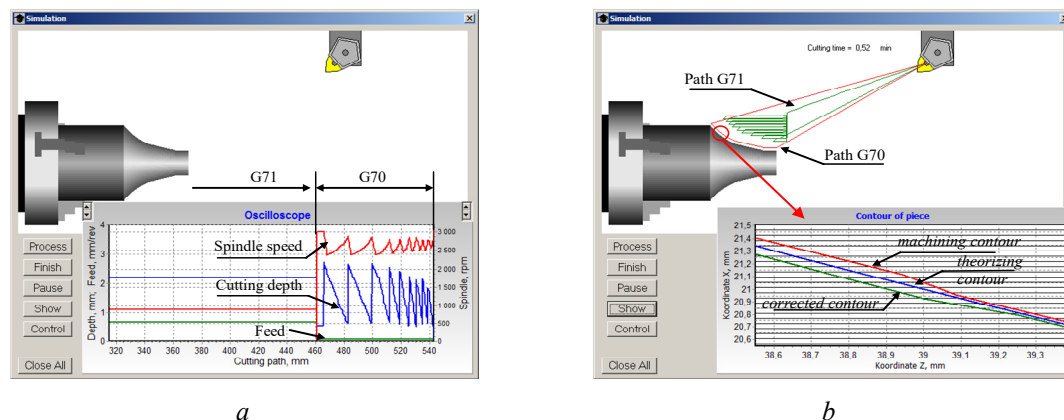


Fig. 6. Simulation steps: a – after execution of cycle G70, b – tool paths and workpiece contour

The program provides for the calculation at each step of the simulation of elastic deformation and correction of the shaping trajectory to compensate for the contour shape error using a priori information about the technological machining system. Given that the real cutting process is carried out in a closed technological system (see Fig. 3, *b*), a special procedure for calculating the cutting force, components and elastic deformations is performed 5 times with the solution refined at each modelling step. The correction of the shaping trajectory is calculated according to the algorithm described in [10].

During the simulation, an intermediate control file is generated containing geometric information about the shaping trajectories, as well as the calculated values of feed and spindle speed obtained from the solution of the optimization problem at each step.

## Conclusions

1. When programming cycles for contour turning of shaped parts on CNC machines, it must be taken into account that in any cycle the cutting process is quasi-stationary, which requires permanent control of the cutting mode in order to stabilize, optimize and, if necessary, correct it.

2. The most important parameter of the machining cycle is the depth of cut, which should be determined as a result of solving the optimization problem in the phase space “spindle speed - feed”, with the setting of restrictions, according to the criterion of the maximum Material Removal Rate.

3. To determine the optimal components - feed and spindle speed - during turning, a simulation program is proposed, where the optimization problem by the criterion of maximum productivity is solved by numerical methods at each simulation step and is presented in the form of control files, according to which a control program can be compiled in G-codes.

4. In the process of simulation in the created program, force perturbations in the machining system are automatically determined, and both the actual contour of the part and the correction of the shaping trajectory are predicted.

5. The implementation of the controls obtained in the process of simulation on a CNC machine depends on the capabilities of a particular control system, the availability of the Look Ahead option, but automatic selection of the cutting depth on a rough cycle will in any case solve the problem of technological preparation of production and increase productivity.

## References

- [1] *CNC Programming Tutorials Examples G & M Codes* (2022). CNC Programming Example with Fanuc G71 Rough Turning Cycle and G70.[Online]. Available: <http://www.helmancnc.com/cnc-programming-example-with-fanuc-g71-rough-turning-cycle-and-g70/>
- [2] FANUC CNC TURNING ALL PROGRAMMING MANUAL.[Online]. Available: [http://tctechology.com/cgi-bin/content/view.php?data=fanuc\\_cnc\\_turning\\_all\\_programming\\_manual&filetype=pdf&id=cec185b14ecaf5d106bb335e27ca239b](http://tctechology.com/cgi-bin/content/view.php?data=fanuc_cnc_turning_all_programming_manual&filetype=pdf&id=cec185b14ecaf5d106bb335e27ca239b)
- [3] Y.V. Petrakov, “Metodi upravlinnya protsesami rizannya”, *Visnik ZhDTU*, No. 2(80), pp. 124–134, 2017. [https://doi.org/10.26642/tn-2017-2\(80\)-124-134](https://doi.org/10.26642/tn-2017-2(80)-124-134)
- [4] Y.V. Petrakov and A.V. Myhovich, “IMachining technology analysis for contour milling”, *Mech. Adv. Technol.*, No. 2(89), pp. 114–120, 2020. <https://doi.org/10.20535/2521-1943.2020.89.202065>
- [5] Yu.V. Petrakov and J. Yezenduka, “Controlling turning contouring of shaped parts”, in *Proc XXII PROGRESSIVE TECHNICS, TECHNOLOGY AND ENGINEERING EDUCATION*, 2021, pp. 111–114. <https://doi.org/10.20535/2409-7160.2021.XXII.239130>
- [6] N.A. Fountas *et al.*, “Intelligent optimization for sculptured surface CNC tool-paths, 5th CIRP Global Web Conference Research and Innovation for Future Production”, *Procedia CIRP* 55, pp. 140–145, 2016. <https://doi.org/10.1016/j.procir.2016.08.033>
- [7] M.V. Satish Kumar *et al.*, “Optimization of CNC Turning Parameters in Machining EN19 using Face Centered Central Composite Design Based RSM”, *International Journal of Recent Technology and Engineering (IJRTE)*, ISSN: 2277–3878, Vol. 9 Issue-2, pp 889–896, 2020. <https://doi.org/10.35940/ijrte.B3923.079220>
- [8] A. Gjelaj, B. Berisha and F. Smaili, “Optimization of Turning Process and Cutting Force Using Multiobjective Genetic Algorithm”, *Universal Journal of Mechanical Engineering*, No. 7(2), pp. 64–70, 2019. <https://doi.org/10.13189/ujme.2019.070204>
- [9] L.V Borshova, V.F. Pegashkin and M.V. Mironova, “Optimizatsiya protsesa mekhanicheskoi obrabotki detalei slozhnogo profilya monografiya”, *Nizhnii Tagil*, NTI (filial) UrFU, 2019.
- [10] Yu.V. Petrakov, O.I. Drachev, *Modelirovanie protsessov rezaniya*, Staryi Oskol: TNT, 2019.

## Моделювання токарних циклів на токарних верстатах з ЧПК

Ю.В. Петраков, Дж.М. Езендука

***Анотація.** Показано, що токарна обробка контурних фасонних поверхонь деталей переважно виконується за циклами чорнового точіння G71, G72, G73 з чистовим проходом по циклу G70. У будь-якому випадку процес різання є квазістаціонарним, що визначає необхідність управління режимом різання для стабілізації та оптимізації процесу. Пропонується для проектування керуючої програми верстата з ЧПУ використовувати спеціальну програму, яка на базі апріорної інформації про технологічну обробку систему виконує моделювання процесу. Під час моделювання в процесі розв'язання задачі оптимізації за критерієм максимуму продуктивності, автоматично визначаються всі складові режиму різання: глибина, подача та швидкість різання. Результати представляють у вигляді файлів управліннь, за якими може бути складена керуюча програма в G-кодах, що забезпечує оптимізацію процесу. Крім того, додатково можливо отримати прогноз про реально оброблений контур з урахуванням пружної деформації в процесі різання і дані щодо корекції траєкторії формотворчого руху на останньому проході.*

**Ключові слова:** токарна контурна обробка, керування різанням, моделювання, оптимізація процесу різання.