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Roman STRYCZEK[1*]
Wojciech SZCZEPKA[2]

SIMULATION TESTS OF ADAPTIVE CONTROL STRATEGIES FOR CNC MACHINE TOOLS

The issue addressed in the article concerns the current needs and possibilities of computer-aided design of adaptive control strategies in machining processes. A simulative method of selecting the adaptive feed control strategy while rough turning materials difficult to machine, effective and inexpensive in its implementation, based on controlling the load placed on the machine's drives, has been presented. The results of a number of virtual tests of the proposed feed control strategy have been included, while paying particular attention to the stability of the machining process during moments of sudden change in the machining allowance. The obtained results meet the accepted quality indicators of the control algorithm. At the same time, the experiences collected by the author while conducting the tests confirmed the complexity of the issue and the resulting necessity to implement a comprehensive simulation testing program.

1. INTRODUCTION

Adaptive control (AC) of machines is a natural extension of the functions of the numerical control system with elements of machine intelligence. It provides versatile benefits, such as: extending the periods of maintenance-free work of a machine tool, reducing unproductive breaks in its operation, better use of the machining capabilities of the cutting tool, reducing the catastrophic wear of the cutting tool, increasing rough turning performance, protecting the machine's drives against overloads, reducing costs associated with the process and more. Therefore, new possibilities of increasing the role of AC in machining operations are constantly being sought. For applying AC systems to complex machining processes, further efforts are needed to build a self-learning module that can deal with the high dynamics and variations of these processes [1].

The fourth industrial revolution assumes the promotion of IT solutions that are able to take advantage of the potential possibilities of the available means of production to a bigger extent. A virtual programming environment that is currently available to an engineer

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[1] University of Bielsko-Biala , Faculty of Mechanical Engineering and Computer Science, Bielsko-Biala, Poland
[2] Siemens sp. z o. o., Industry Automation and Drive Technologies, Katowice, Poland
[*] E-mail: rstryczek@ath.bielsko.pl

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of machining processes emerges in order to meet these expectations. It constantly expands its possibilities, reflecting the conditions prevailing at a production plant with ever-increasing accuracy. The incorporation of aspects related to the active functions of AC was impossible in the off-line mode until recently. After manufacturers of CNC control systems released software for personal computers that was functionally compatible with numerical control systems, as well as provided the possibility of creating a machine tool's virtual image, completely new possibilities opened up in this regard.

Attempts to build a virtual model which would accurately reflect the complex processes of removal machining, including the process of chip formation, tool wear, distribution of forces, stresses, distortions and temperatures in the machining zone, have inspired researchers for many years [2, 3]. However, accurately reflecting the effects resulting from unfavourable phenomena such as tool deflection, vibrations associated with machining, cutting edge wear, uneven machining allowance and machinability, is very difficult to achieve using virtual simulation. The machine allowance means: the material provided beyond the finished contours on a casting, forging or roughly prepared component, which is subsequently removed in machining. This is mainly due to the random nature of the course of these disturbances and the high labour consumption of preparing the right set of data for carrying out virtual tests. Increasingly advanced analytical modelling of the machining process [4], modelling of the machine tool – machine process interaction [5], advanced techniques of monitoring the course of the machining process [6, 7] and simulation tests with reference to the above-mentioned processes, due to the broad area of research and complexity of issues, have not yet led to the creation of a practically useful suite of software supporting the work of machining engineers in practice.

A different approach to constructing a model of the machining process consists in conducting a number of experiments and, based on their results, developing mathematical models using non-linear regression procedures [8] or neural networks [9]. At the stage of searching for the optimal solution, computational intelligence (CI) is taken advantage of most frequently [10]. This type of approach is possible to be implemented in a production plant environment, as long as data is acquired through a passive experiment, i.e. without interfering with the normal operation of the machine tool. In addition, there exists support in the form of specialist software to facilitate the construction of this type of models. The knowledge acquired over the course of the above-mentioned tests can be applied during a real-time simulation of the process, in parallel to an ongoing machining process. Such a solution allows to avoid control errors resulting from false alarms or imperfect algorithms [11]. In this case, it is also possible to limit the use of expensive sensors that require frequent calibrations and are impractical in assembly.

There is also a third approach to the study of the above-mentioned issues, based on the construction of a virtual environment that would reflect the machining conditions as accurately as possible without delving into the physical processes occurring in the machining zone and without possessing a mathematical model of the process [12]. It allows to conduct tests simulating the course of the machining process, including the process using the active AC strategy. A work [13] where the author developed a virtual model that simulates the occurrence of cutting forces in order to optimize the material removal rate and the tool's durability, may serve as an example.

Virtual simulators of computerized numerical control (CNC) systems are now able to accurately reflect the reaction of the control system to a change in the input parameters. The synchronous motion actions that are available in the latest generations of CNC machine tools provide the user with a much larger repertoire of functions interfering with the course of the programme which, until recently, required the use of advanced, expensive hardware and software solutions. One of the most interesting functions is the ability of the end user to activate their own advanced AC strategies. However, the implementation of this type of solutions has always required a number of costly and time-consuming production plant trials in order to readjust the variable parameters of the adopted control strategy to the specific conditions and requirements of the machining process. There are many factors influencing the machining process, such as: the type of material, its machinability, the size and irregularity of the allowance distribution, the geometry and wear of the tool's blade, lubricating and cooling conditions of the tool's blade, blade wear, the form of the chip, the rigidity of the machine tool – mounting holder – workpiece – tool system, the shape of the machined surface, the selected processing parameters and more. In addition, the functionality of an AC strategy is influenced by some of the features of the computerized numerical control system, and especially the interpolator's cycle time, which has a definitive influence on the speed of the system's response to changes in machining conditions. This time usually varies between 0.02s and 0.005s. Adjusting an AC system usually takes place at the expense of temporarily excluding a given machine tool from the production process. As a result, despite the potential possibilities existing in this area, AC is not implemented or the implemented applications are not optimized.

Software simulating the machine tool's control system on a PC is a significant facilitation for the operator, programmer or technologist operating the CNC machine. In the versions that are currently available, full compatibility between the virtual working environment of the simulator and the computerized numerical control systems has already been achieved. This means that after executing and installing the image of the machine tool's control system on a PC, we obtain an almost identical environment as in the system installed on the machine tool.

The TRACE function available in modern SINUMERIK controllers grants access to the behaviours of the system variables of a machine tool, in addition to making it possible to archive these behaviours for later analysis. The “TRACE” function enables the dynamic logging of data directly on machine tools, as well as on PC simulators. The “TRACE” is an oscilloscope function that supports you when optimizing, troubleshooting and analysing machines. When selecting the “TRACE” function in the operating area "Diagnostics", the list view is opened to insert variables, whose signals are to be graphically displayed in the trace view. A dedicated “Session type” should be used for the following variables: NC, PLC, servo variables, drive parameters. As such, it is possible to analyse the behaviours of the drives’ loads relative to the changing parameters of the machining process and setup data. This function can be used to support machine manufacturers, end users or service personnel in activities such as: troubleshooting, location of errors, analysis of the performance of machines, analysis of the performance of processes, comparative analysis and tuning. It should be emphasized that such a type of software suite is also an excellent teaching instrument.

2. VIRTUAL TESTING OF ADAPTIVE CONTROL STRATEGIES

Activating the function of AC during rough turning offers various benefits, including the possibility to fully use the potential of the machine tool and cutting tool, maintenance-free operation over long periods of time, increasing productivity, reducing irregular interruptions in the machine tool's work, which, in turn, leads to an increase in the overall equipment effectiveness (OEE) index [14] and reduces tool costs. Currently, research is being conducted on intelligent systems which achieve the level of expert systems, allowing for the optimization of machining parameters using fuzzy control strategies [15].

The tested strategy of adaptively controlling rough turning is designed to keep the load on the selected drive (main or feeds) at the L_{set} level chosen by the machine's operator. The L_{set} value should be chosen taking into account the machine tool's capabilities and the tool used. In the first step of the algorithm, we calculate the relative load on the L_R drive, as the ratio of the current, filtered value of the load on the L_f drive to the given L_{set} load (1).

$$L_R = {}^{L_f}\!/_{L_{\text{set}}} \tag{1}$$

The form of the filter has been defined by the formula 2:

$$L_{f_k} = \alpha L_{f_{k-1}} + (1-\alpha)L_k, \tag{2}$$

where: L_{f_k} – represents the filtered signal in step k, $L_{f_{k-1}}$ – represents the filtered signal in step k–1, L_k – represents the signal read in step k, α – a regulating factor from the range [0, 1].

This type of the filter was used, for example, in the work by [16]. The selection of parameter α will affect the sensitivity of the curve variation. If α is low, the filtering effect is small. If α is high, the filtering result is good, but there is a slight shift in the phase. Figure 1 illustrates the result of filtering for α = 0.9.

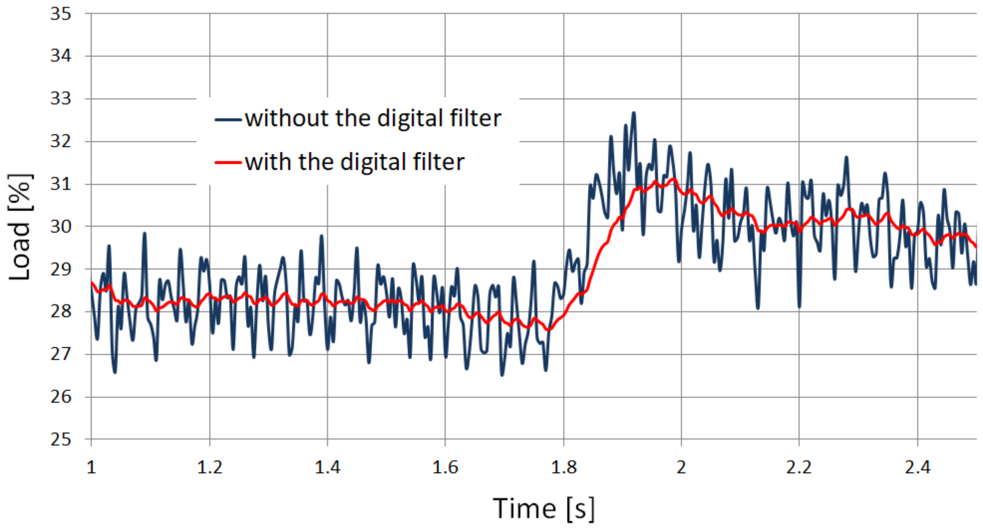

Fig. 1. Feedback signal of the drive load

In the next step, the C_F correlation coefficient should be specified (3). The path of this correlation is illustrated by Figure 2. C_F takes values from the range of real numbers between –1 and 1. Positive values mean the possibility of increasing the feed, negative values mean the need to reduce the feed. The *b* parameter appearing in equation (3) makes it possible to control the aggressiveness of the proposed AC strategy. It has no significant influence on the duration of the processing cycle. In the last step of the tested strategy, is calculated the new value of software-based feed correction O_N (4). The path of this correlation is illustrated in Fig. 3.

$$C_F = \begin{cases} 1 - \sqrt{e^{-b\left(1-\frac{1}{(L_R+0.001)}\right)^2}} & if\ L_R \le 1 \\ \sqrt{e^{-b(1-L_R)^2}} - 1 & if\ L_R > 1 \end{cases} \tag{3}$$

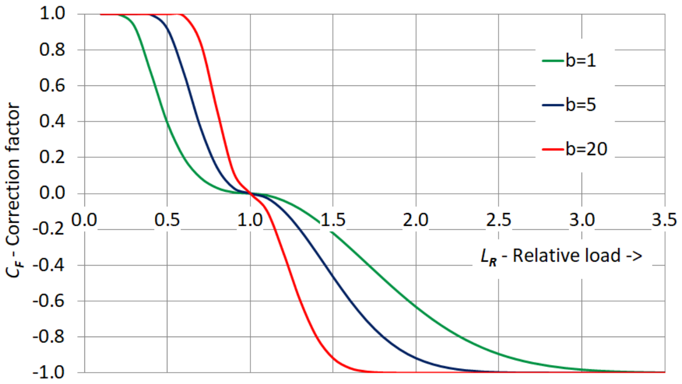

Fig. 2. The values of the correction coefficient depending on the *b* parameter

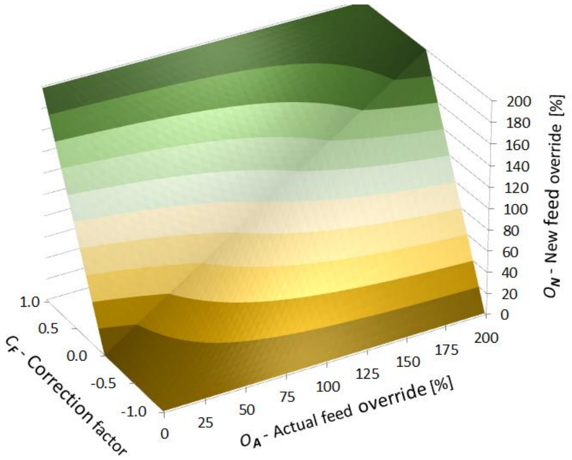

Fig. 3. Software-based feed corrector depending on its current value and the calculated correlation coefficient

Equation 4 takes into account the previously calculated C_F correction coefficient and the current value of the O_A software correction. The fuzzy functions of the soft product and the logical sum have been used to aggregate the C_F and O_A values. The constant 200 results from the assumption that the automatically calculated software-based feed corrector cannot exceed 200% of the given feed.

$$O_N = \begin{cases} (C_F + 1)O_A & if\ C_F \le 0 \\ 200\left(\frac{O_A}{200} + C_F - \frac{O_A C_F}{200}\right) & if\ C_F > 0 \end{cases} \tag{4}$$

Simulation tests have been carried out for a pass with a varying allowance shown in Fig. 4. The selection of the correction coefficient, the load on the drive and the software feed corrector have been analysed at three characteristic points of the pass P_A, P_B and P_C.

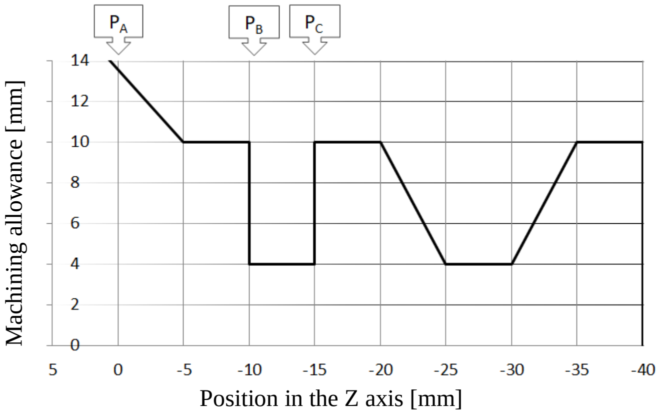

Fig. 4. Size of machining allowance in the conducted tests

The P_A point is the point of the cutting tool first penetration into the material, where the highest step-load on the drive usually occurs. It should be taken into consideration that with the active AC function, when the tool approaches the material, the feed rate will be 200% in relation to the feed rate set for a given pass. At the P_B point, there occurs a rapid decrease in allowance, while at the P_C point, there occurs a rapid increase in machining allowance. The tests have been carried out for 3 values of the *b* parameter, i.e. 1, 5, 20. The value of the expected L_{set} drive load has been set at the level of 25%, which guarantees the drive's smooth operation. Figure 5 shows the formation of the analysed values.

The relaxation time means the return time of a perturbed system into stability. The relaxation times obtained, keeping at to approximately 0.4 s, should be considered acceptable while taking into account that in the case of rough turning on heavy machine tools, the rotational speed rarely exceeds 100 revolutions per minute. Until now, the proposed strategy has been used in cases of heavy regeneration machining of wheelsets, as well as roughing machining of groove rollers used in the smelting industry. In both cases, the turning diameter was very large and amounted to between 600 and 1200 mm, the depth of cut equalled up to 7 mm, the feed totalled up to 6mm per revolution and the material was very difficult to machine (e.g. heat-resistant cast iron). This is where the value of between 30 and 90 revolutions per minute comes from. It may be noticed that the increase of the *b* parameter accelerates the reaction at point A, while at points B and C it leads to a reduction of the amplitude of the drive load's vibrations. However, the above conclusion cannot be generalized, as each case should be treated individually. A significant increase in the *b* parameter will lead to inefficiency of the AC strategy. On the other hand, decreasing the *b* parameter leads to more gentle changes in the software-based feed corrector.

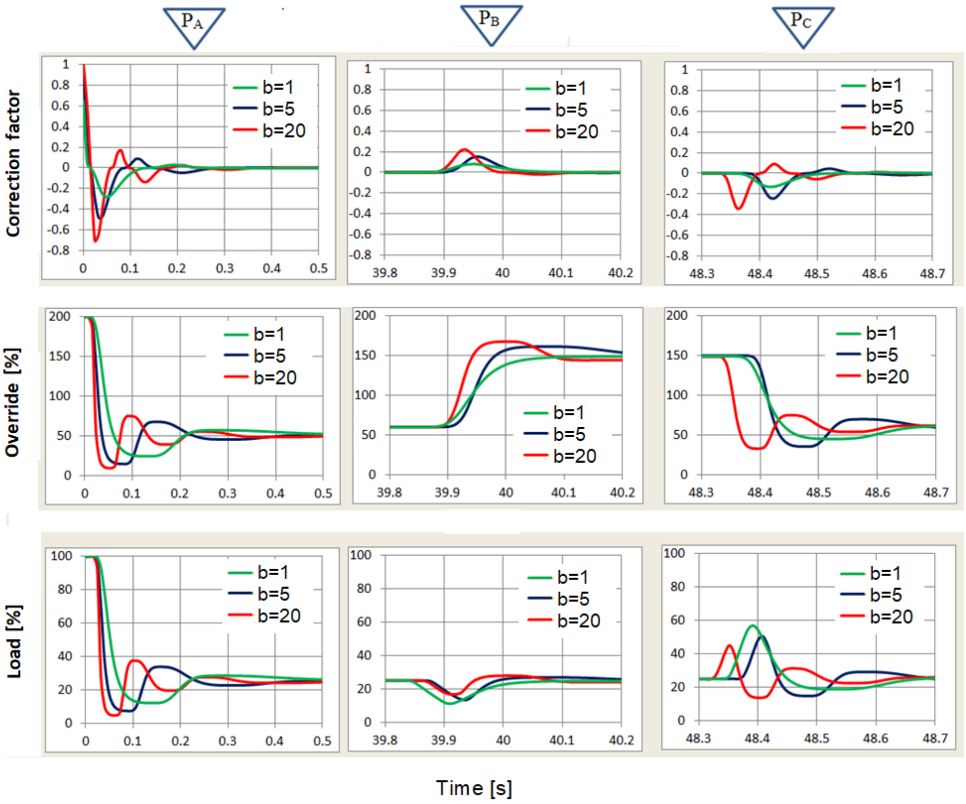

Fig. 5. The values of the correction coefficient, drive load and the software feed corrector at the points of step changes in the removal resistance

Figure 6 shows the results of 3 experiments carried out for the allowance from Fig. 3, but for variable L_{set} load drive values, setting at 10%, 25% and 40% respectively. The given L_{set} load values analyzed in the experiment should be treated as low, normal and high load values respectively. The drive load for L_{set} equalling 10% and 25% remained at the set level.

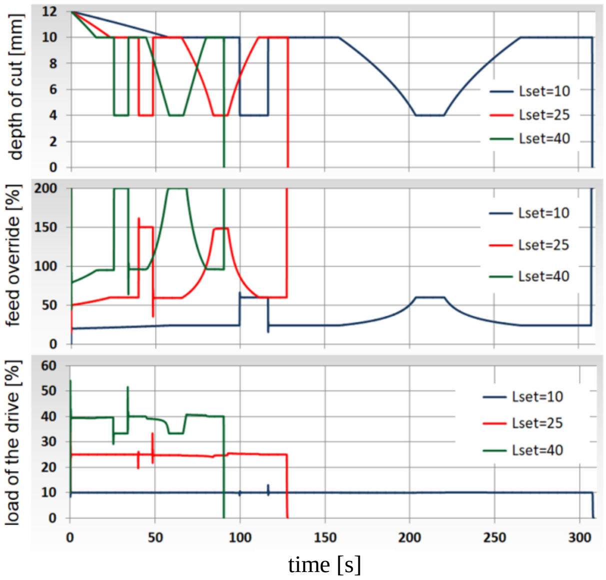

Fig. 6. The drive load and the software feed correction for different L_{set} values

Only at points P_A, P_B and P_C short-term, but acceptable deviation from the set value may be observed. In the case of L_{set} = 40%, for a small machining allowance, the set load values could not be achieved, although the feed corrector value was 200%. In such a situation, if the tool allows it, the given feed rate should be increased.

Generally, a significant influence of L_{set} on the duration of a machining pass may be observed. L_{set} = 10%, 25% and 40% amounted to 310 s, 130 s and 90 s, respectively. That is why an additional series of tests was carried out in order to determine the impact of L_{set} on the duration of the machining cycle more precisely. The tests were performed for two types of drives, with the power of drive of an M_2 machine tool being two times higher as the power of drive of an M_1 machine tool. Figure 7 illustrates the results of these analyses, which clearly indicate that this influence increases for small L_{set} values.

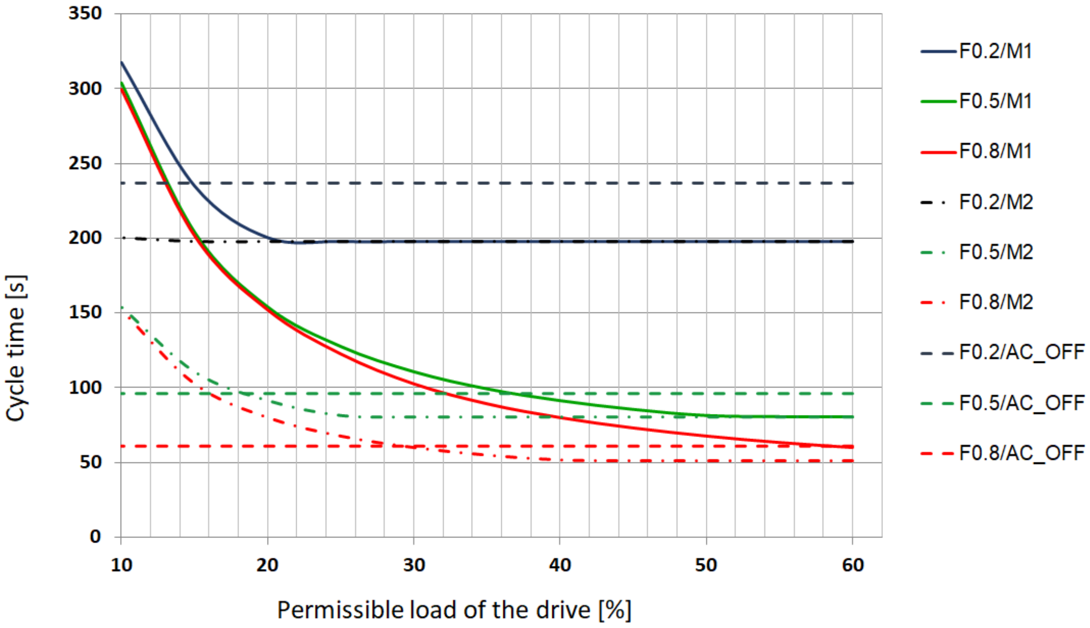

Fig. 7. Cutting cycle times for different given feed values and different capacities of M_1 and M_2 machine tools

However, this is a situation that is often encountered in a production plant environment because heavy machine tools often have a large power reserve, and the limiting factor is almost always the strength of the cutting plate.

For the tested allowance distribution (according to Fig. 4), with a correspondingly high L_{set} load given, the reduction in the cycle time amounted to approximately 20%. On the basis of trials carried out in the industry, a cycle time reduction of 45% was obtained for underfloor wheel lathes working on axle sets, and even 60% for rough turning of groove rollers. In the case of turning axle sets, there occur long periods with a small allowance, which explains the results. In the case of machining grooves in mill rolls, such a significant reduction in time results from a large number of short passes made by the tool. Thus, sections which constitute the tools run-ons and run-offs are subject to acceleration. Considering the long periods of time it takes to complete the machining of groove rollers, savings can amount to as much as several hours of a machine tool's work per day.

3. CONCLUSION

The expected, increasingly higher level of automation of means of production enforces the implementation of increasingly more sophisticated machining strategies, using the innovative possibilities of modern, computerized numerical control systems. The effects of implementing changes into the machining process are difficult to predict in advance and their identification, as well as tuning the operating parameters of a control system directly at the production plant can cause downtimes at the workplace and other losses in tools and materials. That is why opportunities to test the implemented innovations outside of the production plant, in a virtual reality, are being sought.

The developed strategy of adaptively controlling rough turning is characterized by its fast response time, combined with a short relaxation time as a result of changing the cutting depth, changing the feed and changing the machinability of a material. It allows to protect the drive system of the machine tool, it does not allow to set the cutting resistance parameters so as to exceed the acceptable values for the tool used and, at the same time, it also allows to take full advantage of the cutting capabilities of a tool. Another advantageous effect of using AC is releasing the operator of a machine tool from the duty of constantly tracking the machining process, thus enabling him to work on multiple posts. Implementations of the developed AC strategy in a production plant environment fully confirm the above-mentioned effects. The results obtained are particularly significant in cases of heavy machining, characterized by variable allowances and short passes.

The conducted practical experiments confirm the usefulness of autonomous, virtual simulators in planning the process of removal machining. Obtaining such a quality of the method of AC in production plant conditions would require the expenditure of large amounts of time and money. Nevertheless, in the author opinion, the future lies in the integration of simulation models with systems controlling and monitoring the course of the process and their effective cooperation in the duration of a machining cycle. Further research in the context of developing the proposed adaptive feed control strategy in rough turning should also include research on the influence of a high level of drive load on the durability of a machine tool.

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