Adaptive Process Control System of Fine Turning with the Use of Vibroacoustic Signal on CNC Machines

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Abstract. One way to improve the quality and accuracy of machining is a method based on intervention in the process course. Adaptive control is a promising direction of process control. The creation of machines of high accuracy and rigidity, high resistance tool, the development of active control has led to the fact that the role of the dominant factors that generate processing error, were random factors and primarily such as the fluctuation of the allowance and hardness of the workpiece material, as well as the wear of the cutting tool and the condition of the equipment. The actions of these factors are the main reason that prevents the quality improvement and processing productivity. The aim of this work is to study the possibility of using the vibroacoustic signal as an information source for the structure and algorithm development of the finishing turning process adaptive control system.

It is established in the work that the signal generated by the technological processing system is random when finishing turning parts from hard-to-process materials. As an information signal for the technological processing system diagnosis, the most promising will be the use of an acoustic signal that directly accompanies the process of parts mechanical processing. Experimental dependences of roughness parameters and vibration signal parameters on cutting conditions (tool feed, spindle speed) and tool wear are presented. The calculations carried out in the work showed that there is a correlation between the vibration signal parameters and the parts surface roughness parameters. The correlation coefficient between these functions reached 0.75...0.85. Therefore, by controlling the level of the vibroacoustic signal, it is possible to estimate the output parameters of the machining process.

On the basis of the conducted researches the adaptive control system structure variant is offered, the information source for which is the vibrations Converter occurring in technological system.

1. Introduction

Adaptive control systems are designed for almost all machine tools types. The greatest use of adaptive control systems found in lathes, milling, grinding machines and machines for deep drilling.

Adaptive systems are used to equip universal machines and machines with varying degrees of automation, including CNC machines. CNC cutting machines are most convenient for equipping them with adaptive systems, since many control units are common. Thus, stepless-adjustable feed drives and the main motion and logic blocks of the CNC system with some modification can be used in the machine adaptive system.
The basis of technological process adaptive control is the knowledge of qualitative and quantitative relationships between the operating factors, process parameters, technological system properties, operating modes and process output indicators. Studies [1-3] have shown that the technological processing system is nonlinear, dissipative, stochastic.

The parts processing adaptive control process on machines can be considered as a solution of two tasks: timely receipt with the required accuracy of information about the various parameters deviations that affect the process course and timely introduction of appropriate amendments to the values functionally related to the controlled value.

2. Relevance
One of the main purposes of adaptive control in general, and in the automated production conditions in particular, is to increase the equipment productivity. Improving the machining process performance is associated with the adaptive control problem solution, that is control in the machining process all the necessary input and output parameters.

Typically, the adaptive systems currently in use are designed for a specific machine or system. Process regulation is carried out on certain indicators, the values of which must be set experimentally.

The main thing in the roughness parameters management in the automated production conditions is to ensure real profile continuous measurement.

The most widespread, both in our country and abroad received automatic control system of precision machined parts. For example, in [4] we consider the reducing contour errors problem in the complex curved surfaces processing on multi-axis CNC machines. The same authors investigate the method of contour error precompensation in real time [5]. In articles [6,7] the adaptive sliding mode contouring control and the combined by sliding mode contouring control and the disturbances observer is considered.

Adaptive control in systems with numerical control and high-speed coordinate measuring machines is used to solve the problem of minimizing circuit errors [8]

The most important machine parts quality indicators include the parts surface layer quality, which is characterized by the roughness parameters, waviness, surface microhardness, as well as residual stresses. Despite the surface layer parameters importance the control systems of these settings has received insufficient attention.

Most of the works devoted to adaptive control systems, consider the limit control system, compared with optimal control systems, especially designed to provide a given surface layer quality. It is necessary to note the works of foreign scientists Coppel, R.; Abellan-Nebot, J. V.; Siller, H. R.; Rodriguez, C. A.; Guedea, F. The paper [9] describes the adaptive control optimization in micro-milling. This system uses optimal regulation to assess the cutting tool wear in the parts quality terms and the cutting conditions appropriate adaptation.

The acoustic diagnostics idea is based on the assumption that the specific state of the technological processing system should correspond to a purely individual acoustic radiation. Acoustic characteristics are a reflection of the most significant processes occurring during cutting. It is believed that acoustic radiation is elastic energy that is released in a solid body during deformation and destruction. It is necessary to note the acoustic radiation complexity as a phenomenon caused by the micro and macro processes interaction in the cutting zone, the functioning of other units in the system in which elastic vibrations are excited [10,11].

The surface of the finished part is the addition result of many movements and bears the imprint of all processes occurring in the technological system. Any change in the technological system state is manifested in the resulting profile texture.

The choice of acoustic radiation as an information source characterizing the technological process course is determined by the task for which the adaptive system is created. In this case, the main requirement is an unambiguous relationship presence between the output and the required parameters.
Adaptive systems of both limit and optimal control, designed to improve the finishing efficiency, mainly solve the compensation for errors problem caused by force and temperature deformation and tool wear.

3. Problem
This work purpose is to develop the structure and algorithm of the finishing turning process adaptive control system. The finishing process is characterized by a particularly large number of stochastic factors that must be taken into account. Technological system reliable operation is provided by the following tasks solution: identification, optimization, feedbacks organization.

4. Theoretical Part

4.1. Oscillation Sources Identification
The paper [12] demonstrates the oscillatory processes complexity occurring in the technological system. For effective management it is necessary to identify the nature of these fluctuations. When turning in dynamic conditions, two types of vibration can be distinguished: vibrations caused by the machine design and vibrations caused by the cutting process. Figure 1 shows a typical spectrogram of a vibroacoustic signal. As can be seen from the spectrogram, the maximum power is concentrated in the frequency range from 0 to 20 kHz.

![Figure 1. Treatment of steel 45KHN, tool T15K6, V=900 rpm, S=0.097 mm/Rev.](image)

The energy of the vibration signal frequency is distributed unevenly. The spectrogram shows areas with elevated signal levels, both discrete components and broadband vibration noise. A very wide range of vibration frequencies excite the acoustic noise of machines, resonant vibrations of rotating stationary parts. At work [13] revealed that the main fluctuations caused by the machine design, are in the range up to 4 kHz. Vibrations occurring during turning occupy the spectrum band from 8 to 12 kHz. With high-speed cutting, the oscillation frequency is shifted to a range of 13 to 15 kHz.

For the machine SuperJobber 500 frequency vibration, the source of which is the machine design, not beyond 4 kHz.

Spectra analysis revealed that the most sensitive spectrum band to changes in cutting conditions at high-speed turning by mineral ceramics and synthetic materials is in the range from 14 to 16 kHz, and for final turning at speeds of not more than 250 m/min in the band from 4 to 8 Hz.

Spectra analysis carried out during the vibration signal registration in the X, Y and Z Directions revealed their identity.
5. Experimental Results
To determine the oscillations frequency generated by the tool, the vibration source identification was carried out by comparing the vibration signal spectra obtained during the processing of steel samples (45KHN) by a cutter with a soldered plate T15K6, the main angle in terms of \( \phi = 45^\circ \) and a radius at the top \( r = 1 \) mm; the Feed value in the study was \( S = 0.07 \) mm/Rev; cutting depth \( t = 0.25 \) mm; cutting speed \( V = 500 \) m/min.

To determine the spectrum band, depending on the cutting conditions, the part was processed from 45KHN, a cutter with a plate material T15K6, the main angle in terms of \( \phi = 45^\circ \) and a radius at the top \( r = 1 \) mm; cutting Modes varied as follows: \( S = 0.01...0.1 \) mm/Rev; \( t = 0.25...1.0 \) mm; \( V = 90...500 \) m/min.

These oscillations records cannot be presented as a deterministic functional dependence. Simple realizations recording is not a visual information material for research because of the large amount of information.

5.1. The Roughness Parameters and Vibration Signal Dependence Study from the Feed
The vibration signal power dependences on the feed obtained at different cutting speeds were investigated. To establish the relationship between the arithmetic mean deviation \( Ra \) and the vibroacoustic signal power, a correlation analysis was carried out, which showed that the closest relationship was observed between these values along the \( Y \) axis, the coefficient of which is equal to \( r_{XY} = 0.8 \). On the other two axes the correlation coefficient is: on the \( Z \) axis \( r_{YZ} = 0.65 \), on the \( X \) axis \( r_{XZ} = 0.6 \).

The cross-correlation calculations between the surface roughness profile and the vibroacoustic signal amplitudes are shown in fig. 2.

![Figure 2](image)

**Figure 2.** Calculation the cross-correlation coefficients of the surface roughness profile and vibration signal recording.

It has been found that the cutting process generates mainly vibroacoustic signals in the range of 14 to 16 kHz. When using the octave filter with average frequency 8 kHz, the correlation coefficient increased to \( r_{XY} = 0.98 \) on the \( Y \) axis, \( r_{YZ} = 0.7 \) on the \( Z \) axis, \( r_{XZ} = 0.85 \) on the \( X \) axis.

It is established that with increasing longitudinal feed value the arithmetic mean deviation of the \( Ra \) profile and the vibration signal output value \( Sw \) increases.
5.2. The Roughness Parameters and Vibration Signal Dependence Study from the Cutting Speed

It is known that with increasing cutting speed increases processing capacity. The required cutting speed choice is determined by the cutting tool required resistance and the requirements for accuracy and the treated surface roughness.

Only that part of the vibration signal, which is caused by the processing process (cutting process), with signal frequency from 8 to 14 kHz, was processed.

As a studies result it was found that with increasing cutting speed, the arithmetic mean deviation of the Ra profile decreases monotonically. The obtained empirical dependences do not contradict the theory, since it is proved that with increasing cutting speed, the roughness decrease height parameters. The vibration signal power value Sw decreases with increasing cutting speed.

5.3. The Roughness Parameters and Vibration Signal Dependence Study on Tool Wear

The need to develop effective technical solutions in the field of cutting tool wear control during processing is due to the fact that this factor has a significant impact on the machining process output parameters and in particular on the treated surface roughness. The main problem here is that the real spread of technological factors that affect the tool life in the production environment does not allow to reliably predict wear using theoretical or semi-empirical relationships. Wear diagnostics using vibroacoustics in this sense is a very promising direction, especially within the framework of the methodological concept used in this work, because it is possible to develop solutions for specific processing conditions (equipment, tooling and parts).

During the experiment, it is necessary to find out the dependence of the vibration signal and the roughness parameters on the cutting tool wear. This experiment was planned and conducted as a persistent. The vibration signal, roughness and tool wear parameters were monitored during the study. The wear chamfer dimensions were measured on the MIM-6 tool microscope.

The recorded vibroacoustic signal is subjected to filtration, the intention to leave only that part which is generated by the current turning process. In the studies course it was found that the signal generated by the worn tool is significantly different from the signal that was created an unworn cutting edge, what does not contradict other studies [14,15].

As an experiments result, it was found that at the wear chamfer width values to 0.38 mm, the vibroacoustic power decreased, this is due to the tool burnishing, the establishment of the tool-workpiece pair optimal roughness. At the wear chamfer width values from 0.38 to 1.83 mm, the vibroacoustic signal power values increased slightly, which corresponds to the normal wear zone, and at the wear chamfer width values exceeding 1.83 mm, the vibroacoustic signal power changes were significant and catastrophic wear was observed.

A similar nature of the dependences was observed for the arithmetic mean deviation of the Ra profile.

5.4. Adaptive Control System Structure Development

Finishing turning process control has its own characteristics associated with the conditions specifics in which it is carried out:

- small removable allowances (5-20 microns) and, accordingly, reducing the cutting tool wear intensity;
- small (units of micrometers) size tolerances, increasing the control and measurement operations responsibility degree, which practically leads to an increase in their duration and makes commensurate with the processing time;
- the increase in the thermal disturbances influence due to the fact that the deformation magnitude caused by them of the machine structural elements is commensurate with the size tolerance.

The control specificity in this case is that it is important to determine not the pre-adjustment pulse value, but the moment when it must be entered. Since to reduce accidental releases probability, it is advisable to center the machining process to the tolerance field middle.
Thus, the machining process behavior prediction in the near future becomes particularly relevant, which will streamline the procedure control and measurement operations in the optimizing direction their frequency. If the white noise or the thermal transition process is over, the processing mode is stabilized and the control and measurement operations performance becomes practically impractical, since the individual random emissions recorded in their course cannot serve as a basis for the correction and subsequent control introduction to the system reaction to it. In this case, taking into account the processing conditions specifics, it will be more rational to implement automatic control of the technological processing system state using appropriate equipment, so the control channel organization by perturbation. Therefore, for more efficient machines use, it is necessary to solve the problem of creating a reliable apparatus for the machining process technological diagnosis, as well as an approach to process control based on adaptation [16].

The constant gradient or oscillation within the specified limits reflect the stability of the machining process and eliminate the need for manufactured parts measurements, thereby significantly increasing the equipment productivity. The growing fluctuations magnitude or a significant temperature drift emergence in the reference point will be the stationarity conditions violation signal and determine the measurement time [17,18].

Thus, in the precision processing conditions, it is expedient to implement a combined control of the technological system accuracy (Fig.3), the control channel on the deviation of which will be used mainly in the transient thermal mode, and the control channel on the perturbation mainly in the conditions of its stationarity.

![Figure 3. Combined precision machining control block diagram.](image)

The scheme shown in figure 2 is a variant of the adaptive control system (ACS). The information source for the adaptive system is a vibration converter, provides an output signal about the vibrations occurring in the process system. The adaptive system includes the main modules: module "Precision model", module for cutting conditions calculation, modules for corrective actions calculation and their formation (decision-making unit).

The module "Precision model" is designed to build a surface roughness three-dimensional model. The initial data for this model are the surface roughness parameters Ra, Sm, regulated by the part drawing.

Output unit technological cutting parameters used for cutting modes calculation, given the restrictions.
As a subsystem of the adaptive control system that combines the calculation and formation corrective actions modules in the "Decision-making unit", which allows to evaluate the surface roughness and tool wear during processing, a device for controlling the cutting process, designed on the obtained dependencies basis is used.

The device is made in the form of a separate hardware-software complex connected to the CNC system. The device operation algorithms are implemented by hardware and software. The block diagram control system algorithm is shown in Fig. 4.

Studies [19-22] have shown that effective methods for obtaining a decision-making device with maximum accuracy in machining process stochastic terms are the use artificial neural networks and fuzzy logic methods.

![Figure 4. The algorithm block diagram.](image)

For tasks suitable microcontrollers "Microchip" by "PICmicro" (PIC) or "Atmel" by "ARM".

But at application of these controllers there is a need for external "binding". It’s necessary to create a board, hardware and software drivers that connect the controller to other system parts. In addition, the programming language is quite complex and it is time-consuming to implement complex mathematical functions. The information processing speed (the controller frequency is about 16 MHz) and memory amount (32 KB) is clearly not enough for the correct operation the designed adaptive control system. To the implemented tasks the ideal candidate would be an ordinary personal computer. It has high speed, allows to solve wide range problems, is able to implement mathematical calculations in various programming languages. But the device must be compact and installed on the machine.

This problem can be solved by using a Single-Board computer, such as Raspberry Pi (fig. 5).

It combines the microcontrollers and personal computers advantages:
- high-performance processor with 4 cores and 1.2 GHz.
- compactness – sizes up to 150 mm.
- 256 to 1024 MB RAM, sufficient for most operating systems, including Windows 10.
- flexible configuration and programming
- easy programming
- the presence of most popular communications – USB, HDMI, VGA, Ethernet, Audio out and others.

Thus, for the proposed device manufacture, the most promising is the use a Single-Board computer.
6. Conclusion
The studies identified the most sensitive to changes in cutting mode spectrum band, the dependence roughness parameters and vibration signal power from the cutting conditions and tool wear.

The block diagram adaptive control system of technological system and algorithm one is developed. The control system allows to take into account the specifics the finishing turning as a nonlinear stochastic process. The hardware implementation variant control device, which allows to implement the control algorithm hardware-software method.

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Figure 5. Single-Board Raspberry Pi computer.
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