**Improvement of Monitoring and Control System Algorithms for the Cutting Process on Computer Numerical Controlled (CNC) Lathes**

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**Abstract**.  The article presents an analysis and direction for improving the monitoring and control system on CNC lathes. Informative indicators of monitoring and control systems are analysed. The direction of improvement is determined based on measuring vibration and thermoelectromotive force (thermo-EMF). A description is provided of the operating principle of the Interlock Control and Monitoring System (ICMS) for the cutting process on CNC lathes. Developed algorithms for the ICMS operation in "learning" and "monitoring" modes based on vibration level and thermo-EMF measurements on CNC lathes are presented. These algorithms were developed with consideration for their integrated operation. The results of experimental research conducted on a robotic complex based on the 16K20F3S32 CNC lathe with a 2P22 control system are presented. The experiments were carried out under the following cutting conditions: cutting speed in the range of 20 m/min to 52 m/min, with constant feed rate S = 0.25 mm/rev and cutting depth t = 1 mm. All parameters of the experimental study of the developed algorithms are considered in conjunction with the control system based on thermo-EMF measurement. The optimal range of vibroacoustic oscillations was determined, with a maximum frequency not exceeding 20 kHz, ensuring a steady-state cutting process on the 16K20F3S32 CNC lathe with 2P22 control. The maximum cutting speeds and tool life for material St. 5 have been determined: Vₘₐₓ = 28 m/min, T = 120 min and Vₘₐₓ = 60 m/min, T = 100 min (at feed rates of S = 0.2 mm/rev and S = 0.4 mm/rev, respectively). The results of implementing the monitoring and control system algorithms on the NT-250 CNC lathe (SZS2GH) at the Navoi Machine-Building Plant in the Republic of Uzbekistan are also provided. Machining productivity increased by 8–10%, product cost decreased due to optimal cutting mode selection, and machining process stability and reliability were ensured. Downtime was reduced by preventing unplanned events or emergencies.

**Keywords:** CNC lathe, cutting speed, thermos electromotive force, interlock control and monitoring system, algorithm, cutting modes, multi-parameter control and management system

# INTRODUCTION

The machining process on CNC lathes is a key stage in forming the quality characteristics of parts. However, at present, the control of deviations in the cutting process from a stable state, the prevention of emergencies, and the measures to limit the impact of their consequences are the responsibility of the CNC machine operator. Therefore, objective automatic decision-making algorithms for the most critical situations are not available.

To increase the likelihood of obtaining reliable information about the machining process, it is necessary to improve the control and management algorithms on CNC lathes [1].

On CNC lathes, vibration is one of the parameters used for diagnosing the cutting tool during the machining process. The diagnostics are based on measuring the vibration parameters of system components during cutting over a wide frequency range.

Based on this informative indicator, various monitoring and control systems for the cutting process on CNC lathes have been developed. One such system is the Interlock Control and Monitoring System (ICMS), which is a subsystem of the multiparameter monitoring and control system used on CNC lathes.

Thus, this study aims to improve and integrate the ICMS and thermoelectric EMF algorithms with the cutting process on CNC lathes.

# LITERATURE SURVEY

At present, the cutting process is accompanied by vibrations of varying frequency, amplitude, and intensity. Vibration is mainly caused by the unbalanced properties of the workpiece material, surface irregularities of the machined part, and the random distribution of microhardness within the workpiece material [2, 3]. These factors affect chip formation, the surface quality of the machined part, and the performance of the cutting tool. Researchers have analysed various methods for monitoring and eliminating tool vibration during metal cutting on CNC lathes. Under certain cutting conditions and amplitude-frequency parameters, vibrations can be beneficial, as they facilitate plastic deformation of the material during chip formation. However, in other ranges of these characteristics, vibrations may lead to fatigue chipping of the cutting edge, accelerated wear, and even tool breakage during CNC lathe operations.

The problem of vibrations is particularly relevant when machining low-rigidity workpieces. A typical example of such machining is the turning of slender shafts. Their occurrence can be minimised by appropriately selecting the machining parameters [4].

Currently, vibration as an informational indicator is widely used in various processes on CNC machines. For example, in the analysis of CNC machines using monitoring systems, vibration during automatic tool change is studied [5]. Research is also being conducted to obtain high-quality vibration signals using empirical mode decomposition as an effective and adaptive noise filter [6].

A promising approach in turning operations is the use of more advanced methods based on topological data analysis and similarity measures of time series using discrete time warping [7].

One of the key issues in CNC turning is the selection of appropriate sensors. A wide range of signals-such as vibration, acoustic emission, and cutting force, can be captured for this purpose. These signals are then used to extract features correlated with the monitored parameter [8]. A recent development is the implementation of condition monitoring systems that utilize commercially available accelerometers combined with control and monitoring infrastructure, enabling the assessment of performance in measurement or production systems [9, 10]. Experimental studies have shown that the vibration amplitude of the tool is lower at the initial stage of cutting and gradually increases as the tool wears, reaching significant levels toward the end of the tool’s service life. Based on this, a damper has been developed that can adapt according to the amplitude of tool wear [11].

The analysis has shown that one of the promising directions for signal analysis and the subsequent development of a system to critically reduce the impact of vibrations is the method of regulating the spindle rotation speed and varying the spindle speed during operation [12, 13].

In this regard, research has been conducted on the application of this factor. Under automated production conditions, where operator involvement is minimal, obtaining reliable information about the cutting process becomes a highly important task. Therefore, acquiring additional accurate data on the cutting process is essential. One of the informative indicators is the thermoelectric electromotive force (thermo-EMF) generated during cutting.

The physical principles of the thermo-EMF method are associated with both the fundamental processes of chip formation in the workpiece material and the properties of the cutting tool material. This makes it possible to diagnose tool wear, evaluate the quality of the machined surface, and develop methods for rapid optimisation of cutting parameters. Based on thermo-EMF measurements, systems have been developed for process diagnostics and adaptive control, which contribute to improving cutting performance on CNC lathes [14, 15, 16, 17, 18].

The control and monitoring system developed based on thermo-EMF measurements for CNC lathes can function effectively only within the limits of the adequacy of the machining process to the mathematical model on which the system is built.

A promising direction is the research and development of a multiparametric control and monitoring system for the cutting process, based on integrating the thermo-EMF measurement system with the ICMS system, which is based on vibration (oscillation) level measurements, for CNC lathes.

Accordingly, a set of tasks has been defined for developing a multiparametric control and monitoring system for machining processes on CNC lathes [19].

To achieve this goal, an analysis of the ICMS operation is carried out using algorithmic processes, taking into account the features of the combined functioning of the two systems. This approach will allow the development of algorithms for a multiparametric control and monitoring system for machining processes on CNC lathes.

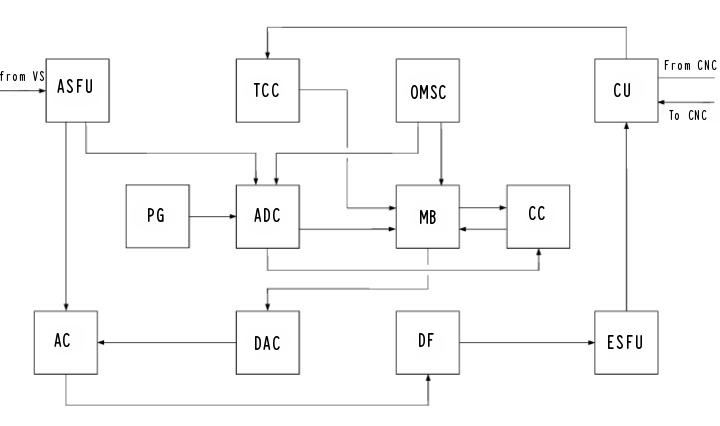
# SYSTEM ARCHITECTURE

To support decision-making for preventing emergencies and minimising their consequences, an ICMS system for the cutting process has been developed based on vibration level measurements on CNC lathes. This system operates independently, fulfilling its assigned tasks following the developed operating algorithms and the corresponding software and mathematical support for CNC lathes.

The ICMS system enables detection of deviations from the stable course of the cutting process based on vibration level analysis, and it sends a control signal to stop the feed of the lathe’s carriage and call the operator for further decision-making (see Fig. 1).

The ICMS system is based on the following principles:

* Vibration sensor captures specific information about the cutting process;
* Measured data is compared with a predefined reference value;
* Deviations from the normal cutting process are identified;
* If the measured value exceeds the reference threshold, the carriage feed is halted (blocked), and the CNC machine operator is notified.



**FIGURE 1.** Functional diagram of the Interlock Control and Monitoring System

where: VS – vibration sensor; ASFU – acoustic signal formation unit; TCC – technological command counter; OMSC – operating mode selection circuit; PG – pulse generator; ADC – analogue-to-digital converter; MB – memory block; CC – code comparator; AC – analogy comparator; DAC – digital-to-analogue converter; DF – digital filter; ESFU – "emergency" signal formation unit; CU – CNC communication unit.

This system has been implemented on a robotic complex based on the 16K20F3S32 CNC lathe with a 2P22 control unit, integrated with a computer, and operates in the “learning” and “monitoring” modes.

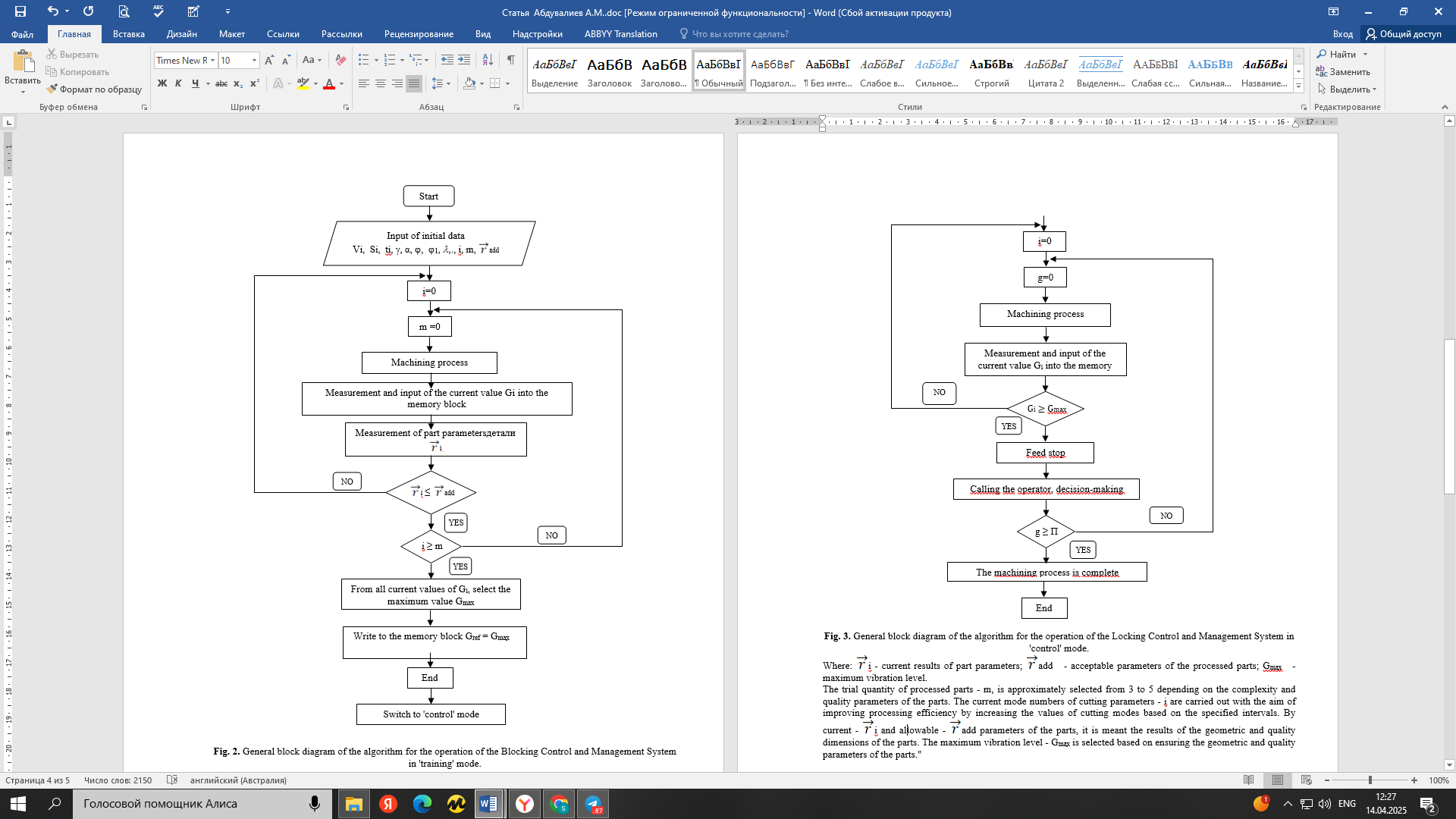
The multiparametric monitoring system consists of two main components: a subsystem based on thermo-EMF measurements and an ICMS subsystem based on vibration level measurements using a vibration sensor and control board. The vibration sensor is housed in a metal casing composed of a base and a threaded probe, with a piezoelectric element installed at the end of the probe. The main component of the ICMS is the control board, which directly monitors the machining process and issues an “emergency” signal when necessary.

The primary task of the ICMS is to detect the critical condition of the cutting tool for its replacement and to restore the operational readiness of the CNC machine. It measures the vibration level parameter and makes decisions regarding tool replacement or adjustments to the technological process.

The decisions made significantly affect the effectiveness of the ICMS. In this case, decisions are limited to halting the machining process and shutting down the 16K20F3S32 CNC lathe. This prevents emergencies, damage to the workpiece, or failure of the CNC machine. Due to the high speed of decision-making, the ICMS control loop is implemented directly through the machine's electrical automation system.

Tool condition recognition based on vibration level signals received from the cutting zone is carried out using the vibration sensor and the CNC unit. The reception and processing of information occur in real time during the cutting process. The high sampling rate of the sensor allows it to register changes in diagnostic indicators both during gradual tool wear and in the event of sudden failures such as breakage or chipping.

The ICMS operates in two modes: “learning” and “monitoring”.  
Before starting a batch of parts, the system enters the “learning” mode (see Fig. 2). A trial set of workpieces is machined, during which current values of thermo-EMF and tool wear on the flank surface are recorded into the memory block under defined cutting conditions. The third monitored parameter is the vibration level value Gi. Thus, achieving the allowable accuracy of the part parameters and production efficiency is ensured through the use of a multiparametric monitoring system (measuring three parameters) on CNC lathes.

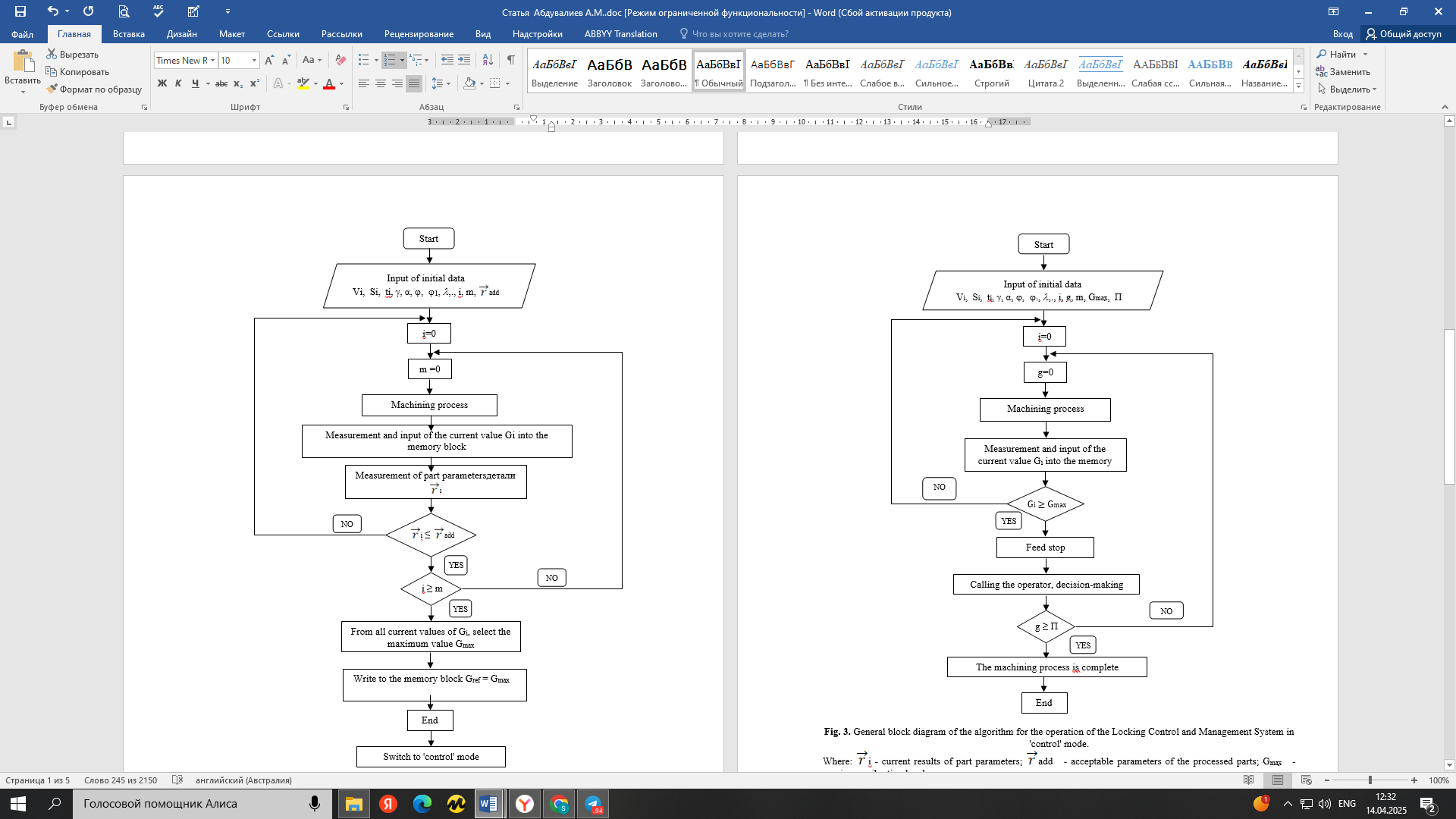


**FIGURE 2.** General block diagram of the algorithm for the operation of the Interlock Control and Monitoring System in 'training' mode

where: Vi, Si, ti – current cutting parameters (namely, cutting speed, feed rate, and cutting depth) adopted during the development of machining processes and ensuring the quality characteristics of the batch of machined parts; ℽ, α – front and back rake angles of the cutting tool; ϕ, ϕ1 – main and auxiliary cutting-edge angles of the tool in the plan view; *λ* – inclination angle of the main cutting edge of the tool;i – current index numbers of the cutting parameters; m – number of test parts being processed;   
Gi - current value of vibration level during machining; – generalized indicator of permissible values for the current monitored parameters of the parts; Gi – current value of the vibration level during machining; i - generalized indicator of the values of the current monitored parameters of the parts.

The current - and permissible parameters of the parts refer to the results of the geometrical and quality dimensions of the parts.

Gmax - maximum vibration level during machining is selected based on ensuring the geometrical and quality parameters of the parts; Gref - reference value of the vibration level during machining.



**FIGURE 3.** General block diagram of the algorithm for the operation of the Interlock Control and Monitoring System in 'control' mode

In this regard, based on the functional diagram of the Interlock Control and Monitoring System (ICMS), algorithms for its operation in "training" mode (Fig. 2) and "control" mode have been developed and improved, taking into account the operation of the control and management system based on measuring thermo EMF (Fig. 3).

Where: i - current results of part parameters; add - acceptable parameters of the processed parts; Gmax - maximum vibration level. The trial quantity of processed parts - m, is approximately selected from 3 to 5 depending on the complexity and quality parameters of the parts. The current mode numbers of cutting parameters - i are carried out with the aim of improving processing efficiency by increasing the values of cutting modes based on the specified intervals. By current - i and allowable - add parameters of the parts, it is meant the results of the geometric and quality dimensions of the parts. The maximum vibration level - Gmax is selected based on ensuring the geometric and quality parameters of the parts. After the completion of the 'training' mode, the batch of parts is launched into the ICMS in 'control' mode (Fig. 3): where: g – the current number of processed parts in the batch, within the specified time interval; Gi – the current vibration level, measured at the current time value; П – the total number of parts being processed in the batch of the specified type. The ICMS operates based on the mathematical model underlying the developed system for three situational cases of the cutting process. Considering the joint functioning of the two systems, the case is considered when the cutting tool experiences forced vibrations (oscillations) in the conditions of a stationary and normal cutting process on CNC lathes. In this regard, based on the developed algorithms, experimental studies were conducted on a robotic technical complex based on the 16K20F3S32 lathe with CNC 2R22. The experiments were conducted under the following cutting conditions: cutting speed in the range v from 20 m/min to 52 m/min, with constant feed rates S = 0.25 mm/rev and depth t = 1 mm. All parameters of the experimental studies of the developed ICMS algorithms are considered in their integrated operation with the monitoring and control system based on thermo-EMF measurement.

# RESULTS AND DISCUSSIONS

Based on the developed algorithms, experimental studies were carried out on a robotic system equipped with the 16K20F3S32 CNC lathe (model 2R22). The experiments were conducted under the following cutting conditions: cutting speed v ranged from 20 m/min to 52 m/min, with a constant feed rate S=0.25 mm/rev and cutting depth t=1 mm. All parameters of the experimental studies involving the developed ICMS algorithms were considered in conjunction with the simultaneous operation of the control and monitoring system based on thermo-EMF measurements [3]. Using the developed algorithms, experimental research was conducted on the 16K20F3S32 CNC lathe (model 2R22), and the optimal range of vibroacoustic oscillations was identified, having a maximum frequency of no more than 20 kHz, ensuring a steady-state cutting process. Values of thermo-EMF, maximum cutting speed, and tool life were determined under the specified machining conditions (see Tables 1 and 2). As a result of the experiments, the following values were obtained: At a thermo-electromotive force value of E3=3.8 mV, the maximum cutting speed was Vmax=28 m/min, the tool life was Т=120 min, and tool wear reached hз=0,55 mm (see Table 1).

**TABLE 1**. Results of Experimental Studies Feed Rate S=0.4 mm/rev. Material: St. 5

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Cutting speed, V, m/min | 20 | 24 | 28 | 32 | 36 | 40 | 44 | 48 | 52 | 56 |
| Thermo-electromotive force, mV | 3 | 3.4 | 3.8 | 4.1 | 4.2 | 4.25 | 4.25 | 4.3 | 4.35 | 4.35 |
| Tool wear hз, mm | 0.45 | 0.5 | 0.55 | 0.6 | 1 | 1.3 | 2 | 2.4 | - | - |
| Tool life Т, min. | 125 | 125 | 120 | 75 | 28 | 15 | 10 | 5 | - | - |

At E4=4.0 mV: Vmax = 60 m/min, Т=100 min, hз=0,7 mm (table 2)

**TABLE 2.** Results of Experimental Studies Feed rate S=0,2 mm/rev. Material: St. 5

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Cutting speed, V, m/min | 48 | 52 | 50 | 60 | 64 | 68 | 72 | 76 | 80 | 84 |
| Thermo-electromotive force, mV | 3.4 | 3.6 | 3.8 | 4 | 4.1 | 4.15 | 4.16 | 4.16 | 4.16 | 4.17 |
| Tool wear hз, mm | 0.4 | 0.5 | 0.55 | 0.7 | 0.9 | 1.1 | 1.5 | 2 | - | - |
| Tool life  Т, min. | 120 | 120 | 120 | 100 | 70 | 45 | 15 | 5 | - | -- |

# ADVANTAGES

The developed algorithms will serve as the basis for conducting comprehensive research aimed at creating a multiparametric control and monitoring system consisting of two integrated subsystems: the Interlock Control and Monitoring System (ICMS) based on vibration level measurements and the control and monitoring system based on thermo-EMF measurements.

The application of this multiparametric control and monitoring system, which utilises two diagnostic indicators, vibration and thermo-EMF, will enhance the reliability and accuracy of information acquisition and enable the determination of optimal cutting parameters on CNC lathes.

# APPLICATIONS

The developed algorithms for the Interlock Control and Monitoring System (ICMS), operating in “learning” and “monitoring” modes based on vibration level measurements, and integrated with the control and monitoring system using thermo-EMF measurements, can be applied to CNC lathes at machine-building enterprises.

These algorithms were tested on the 16K20F3S32 CNC lathe, model 2R22. Based on the experimental research conducted, the optimal range of vibroacoustic oscillations was identified, with a maximum frequency not exceeding 20 kHz, ensuring a stable cutting process.

The methodology for determining maximum cutting speeds that provide optimal tool life can be used to assess the machinability of new parts on CNC lathes.

The results have been implemented on the NT-250 CNC lathe (SZS2GH model) at the Navoi Machine-Building Plant in the Republic of Uzbekistan.

CONCLUSION

Algorithms have been developed for the operation of the Interlock Control and Monitoring System (ICMS) in "learning" and "monitoring" modes, based on vibration level measurements and taking into account the integrated operation with the control and monitoring system based on thermo-EMF measurements.

On the 16K20F3S32 CNC lathe, model 2R22, the optimal range of vibroacoustic oscillations was selected, with a maximum frequency not exceeding 20 kHz, ensuring a steady-state cutting process.

The multiparametric control and monitoring system, based on the integrated operation of the two subsystems, has increased the reliability and accuracy of information regarding the machining process.

The developed algorithms will serve as the foundation for further research aimed at creating algorithms for a multiparametric control and monitoring system, functioning jointly based on the thermo-EMF measurement system and the vibration-based Interlock Control and Monitoring System for CNC lathes.

The maximum cutting speeds and tool life for material St. 5 were determined:  
Vmax=28 m/min, Т=120 and Vmax=60 m/min, T=100 min (at feed rates of S=0.2 mm/rev and S=0.4 mm/rev, respectively).

As a result of implementing the Interlock Control and Monitoring System algorithms on the NT-250 CNC lathe (SZS2GH model) at the Navoi Machine-Building Plant in the Republic of Uzbekistan, machining productivity increased by 8–10%, product cost was reduced through optimal cutting mode selection, and the machining process became more stable and reliable. Downtime was also reduced by preventing unplanned events or emergencies.

**FUTURE SCOPE**

In the future, the integration of artificial intelligence (AI) and machine learning (ML) algorithms into the Interlock Control and Monitoring System (ICMS) will enable more accurate pattern recognition of abnormal machining conditions. This will help CNC systems make predictive decisions without relying solely on fixed thresholds.

The use of cloud-based data storage and analysis platforms will provide the capability to collect and evaluate machining data from multiple CNC lathes across different facilities. This will open opportunities for remote diagnostics and centralized optimization of cutting parameters.

Further research will be focused on expanding the ICMS to cover additional measurable indicators such as acoustic emission, tool tip temperature, and cutting force. These parameters, when integrated with vibration and thermo-EMF data, will create a more comprehensive multi-sensor monitoring framework.

The system's adaptability can be improved by implementing real-time feedback loops that adjust cutting parameters dynamically based on instantaneous sensor data. This would significantly enhance the precision and responsiveness of the cutting process.

With the development of Industry 4.0 and cyber-physical production systems, the ICMS and thermo-EMF-based control modules can be embedded within fully autonomous manufacturing environments. Such systems will facilitate zero-defect manufacturing and predictive maintenance. Another promising direction involves developing user-friendly interfaces and visualization tools that can provide intuitive feedback to operators about system status, anomalies, and recommended corrective actions.

Experimental validations of the current algorithms can be extended to a wider range of CNC machine models and machining materials. This would help generalize the algorithms and increase their applicability in diverse industrial scenarios. Collaborative efforts with industrial partners could lead to the development of standardized protocols and modular control systems that are easier to retrofit into existing CNC infrastructure without major redesigns.

Further development of digital twins for CNC machining processes can provide virtual environments where new control algorithms can be safely simulated and tested before physical implementation. Lastly, the continuous evolution of sensor technology, particularly in miniaturisation and sensitivity, will enhance the system's ability to detect subtle anomalies, further boosting the efficiency, reliability, and safety of CNC machining operations.

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