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INVESTIGATION OF PROCESSES IN HIGH-SPEED EQUIPMENT USING CNC CAPABILITIES

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Abstract
Improving the accuracy, reliability and performance of high-speed technological systems is one of the most pressing challenges in modern industry. The process of improvements in machine tools is permanent because of growth in requirements for the parts quality. The HSM process progress may depends on specific characteristics of particular machine. In this connection, there is a need to carry out investigations in real equipment. The possibility of in-process parameters registration using CNC capabilities is considered. Hardware and software solutions are proposed. The software capabilities for data processing, analyzing and displaying a large number of graphs are shown.

Keywords:
CNC; High-speed equipment; Parameters recording

1 INTRODUCTION

Metal processing with chip removal today is the most important parts production method in mechanical engineering. Improving the accuracy, reliability and cutting performance is one of the most pressing problems in the industry. Due to the constant increase in the requirements for the quality of machined surfaces, the process of improvement of the machine equipment is permanent.

A modern machine tool is integrally formed with the CNC system, which can be endowed with various functions. The machine must be equipped with a flexible and intelligent control system associated with the production control system. Software complexity is not a regulatory indicator. Quite complex algorithms that taking into account the dynamic processes occurring in the machine systems can be used in the control process. One of the directions of the CNC development for modern machining equipment is the creation of systems based on a personal computer (PC) [Chen 2015], [Rogelio 2015], which makes it possible to use the entire set of computing possibilities and communication capabilities of modern technology.

The increasing complexity of metal-cutting equipment, the use of HSM technologies, the need to take into account the dynamic processes occurring in the machine systems, necessitates conducting research on these processes both in general and on specific instances of equipment [Boerlage 2004], [Herranz 2005], [Jiang 2010].

The creation of specialized experimental setups for the algorithms studying and equipment control processes is applicable to the research of a limited number of problems. High-speed processing optimizing results may differ significantly for different equipment instances of the same type. For example, the information data of CNC machine tool based on the controller tuning operation are investigated for a smart productivity in position control mode [Chang 2016]. [Downey 2016] is describe the task of real-time monitoring CNC tool wear through the use of three sensor technologies: force, acoustic emission and vibration.

This circumstance determines the need to develop a software and hardware complex (SHC) for the study of algorithms and processes in CNC machines, providing research directly on the process equipment.

2 CNC-BASED SOFTWARE AND HARDWARE COMPLEX

The aim of the work is to provide an analysis of control algorithms, processes in machine systems and machining processes on metal cutting equipment. An approach is proposed to supplement the CNC structure with specialized hardware and software that allows recording a complete set of equipment functioning parameters.

2.1 Requirements to the software and hardware complex

The following tasks and requirements for software and hardware complex are defined.

It is most rational to use a CNC system as the basis for creating complex for researching on real equipment. It requires integrating additional hardware and software into the CNC system.

The CNC system should provide not only the convenience of working in the main mode (equipment control), but also provide the ability to integrate additional hardware and software necessary to perform research tasks. CNC system must have a network connectivity to a network to share results of experiments. From this point of view, the most suitable is the PC-based CNC architecture. Such systems provide flexible interface and allow using local and global networks connections.

At the application layer the number and composition of application sections, which are called a control tasks [Sosonkin 2005], determine the CNC system architecture. Such tasks include geometrical (servo drives control); logical (electro-automatic control); technological (maintenance or optimization of the technological process parameters); dispatching (control of other tasks at the application level); terminal (dialogue with the operator, system states displaying, NC programs editing and verification); communication (information exchange with the enterprise management system). The SHC must ensure the possibility to receive and save information about the performance of the algorithms and all above tasks. The software should provide the ability to display, analyze and process a large number of registered parameters.

At creating the PC-based CNC system, it is necessary to consider the specificity of real-time mode implementation. The real-time term implies that the behavior of the computing system is predictable and the time that spended on a particular procedure does not exceed a predetermined limit [Sosonkin 2005]. This means that a computer system can use time to perform the same action, the duration of which depends on various circumstances, but time is limited. The SHC for investigation of algorithms and processes should provide the ability to measure the actual duration of the processes occurring in the control system. For these purposes, an independent high-precision hardware real-time counter should be implemented.

The CNC system controls a large number of parameters, but in order to analyze a technological process or other processes occurring in equipment, it may be necessary to register various signals and data from external devices. To facilitate data analysis, it is necessary to be able to manage the data receiving by external measuring devices synchronously with internal data receiving. The process of collecting and recording data is carried out parallel with the equipment control process and should not affect it.

A SHC has been developed, that can be operated as part of various types of equipment.

2.2 Hardware

The hardware of the complex is a two-level CNC system, in which tasks control is distributed between two PCs (Fig. 1). Communication between PCs build on industrial IoT technology.

Operator panel unit contains a PC, which operates by the Windows operation system.

The real-time unit contains a CPU module and FPGA-based specialized modules connected to the internal bus: discrete signal input-output modules, motor controllers, feedback modules. Reliability, safety and fault tolerance of this modules and all hardware is provided by methods based on using of specialized analysis techniques [Kharchenko 2014].

Separation of tasks between levels of the control system ensures maximum efficiency and 1000…2500 Hz frequency of the control cycle.

Using a PC as CPU module allows simultaneously provide eight-axis control, register the required number of parameters and process the data of additional devices, which are connected to the complex.

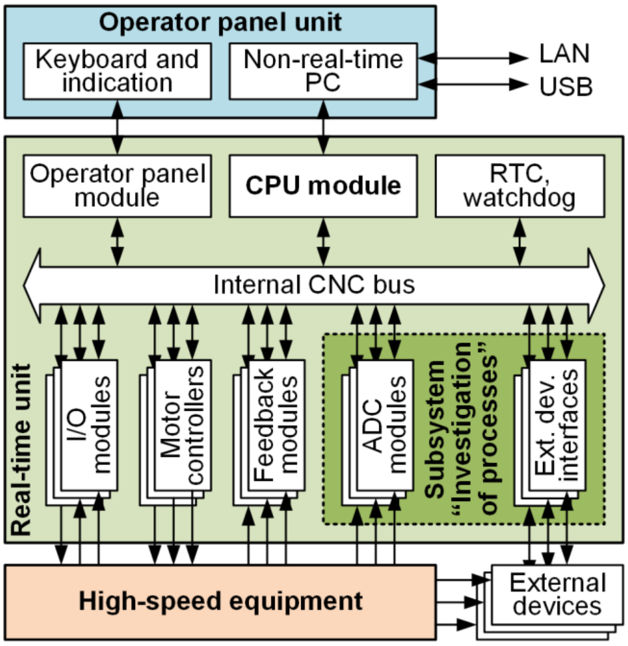

Fig. 1: CNC hardware structure including subsystem “Investigation of processes”.

The data exchange between the specialized modules and the CPU module provide the high performance and reliability, which is best suited for record a large amount of external signals and internal CNC variables.

The SHC hardware in addition to CNC hardware including special ADC modules and external device interfaces.

Thus, any machine tool or process technological equipment, which is supplied a CNC with specialized hardware expansion can be considered as a research facility. Conducting a technological experiment on a real machine, and not on experimental setup, allows to obtain the most reliable and valuable results.

2.3 Software

The SHC software distributed according to hardware structure. Windows PC performs terminal, communication and, partially, technological control tasks. The real-time unit operates under a real-time OS and provides dispatching, geometric, logical and technological tasks.

All processes, performed in the real-time unit are controlled by commands, generated by the Windows PC and transmitted by the communication network.

The real-time unit software (Fig. 2) consists of two equivalent subsystems: “equipment control” part and “process investigation” part. "Control core" carried out control of all parts via commands sent over the virtual network. Control of each machine tool units implemented through software “logic devices”. “Logic devices” are grouped to “virtual controllers”. Data exchange between virtual controllers and physical interfaces implemented via the address space transformation.

The software contains a “data storage management” module that collects data and stores it in “data storage”. Various signals and data from all CNC modules and controllers, external devices and internal parameter values can be registered to “data storage”. The “data storage management” module provides two parameters registration modes: manual and emergency.

In the manual mode initialization and completion of data storage is performed by the operator inputted commands and transmitted from the operator panel unit to the real-time unit or contained in NC program.

3 INVESTIGATION OF ALGORITHMS AND PROCESSES

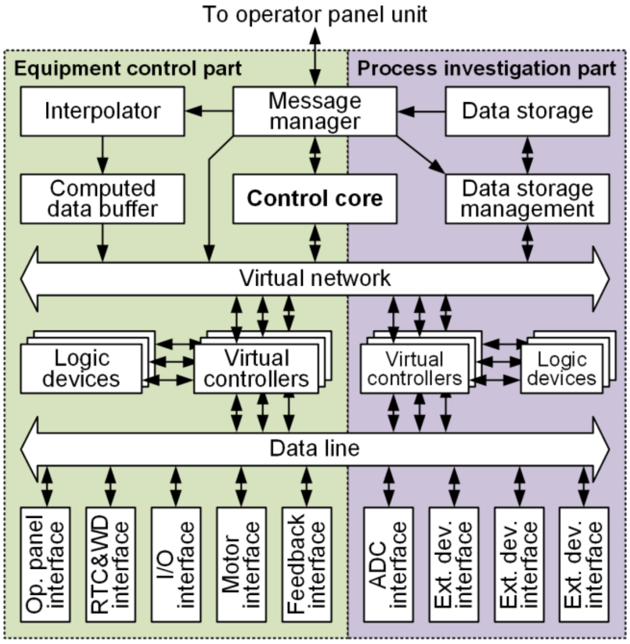

Fig. 2: CNC real-time unit software structure.

Data registration is performed at each system cycle. Data registration duration is about one minute. Up to 300 variables can be registered for each controlled axis. The data set is determined by the system configuration. The specific data set stored in a specific experiment is described in the file header. It helps for subsequent data processing of different hardware configurations. This mode is useful for study of algorithms and various processes of investigated equipment.

Emergency mode is used for data saving in case of detection errors in equipment control processes, such as failures of axis drives, spindle, hydraulic or other critical systems. CNC is switched off the machine tool power supply and start process of saving registered data to file. The file contains the operation data, received for one minute before a fault and few seconds after it. This file is used to debug the control algorithms and fault diagnostics.

Experimental data processing software (Fig. 3) allows visualizing large number of registered parameters, performing mathematical operations, extremum detection, data transform, such as time domain to frequency domain conversion, filtering etc. There is a possibility to export the data for further processing in external software.

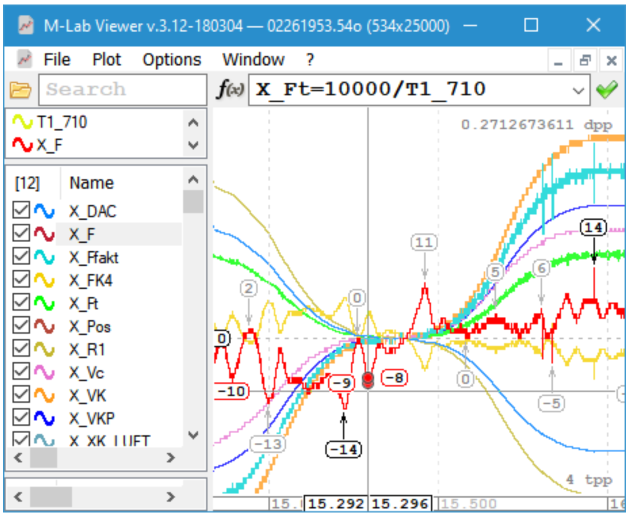

Fig. 3: Experimental data processing software.

The SHC allows to get information about any data into the CNC system and to carry out the registration technological process data and equipment processes; allows investigating and optimizing of CNC algorithms for all control tasks.

Consider a few examples of the SHC using.

3.1 Investigation of the equipment functioning

The developed SHC allows investigating the functioning of the equipment during its operation. To do this, it is possible to save the parameters automatically when an error occurs or by operator command at any time.

Analysis of the causes of equipment failure

Fig. 4 shows a simple example of the analysis of the emergency parameters registration data file, which was saved when equipment was switched off due to an error. This file contains the values of 534 CNC system variables for 25,000 control cycles.

In the position A it can be seen that the Z coordinate error signal goes from state 0 to state 8, which means the excess of the allowable position error. For 221 cycles up to this point the operator has selected the "coordinate Z manual movement" command (pos. B), after which the logical device "Z coordinate" issued manual control command (pos. C) and increasing speed signal (pos. D) is formed. This increases the value of position mismatch (pos. E). The "Feedback module" is operating normally and does not detect any encoder error signals. The Z coordinate drive does not report an error too. Therefore, it can be assumed that the error in this case is caused by incorrect configuration of the position controller parameters. When error exceeds an allowable value, the error signal goes to the appropriate state (pos. A), the logic device "Z coordinate" goes into the "off" state (pos. F), the logic unit "Power Supply" starts procedure of emergency stop of equipment (pos. G). The Z coordinate drive receives a logical zero of "enable control" signal (pos. H) an "equipment shutdown" signal is set (pos. I), the drive power is switched off (pos. J). Through 514 cycles after the error is detected, the "coordinate Z manual movement" command of is disabled – operator deselect command on the keyboard.

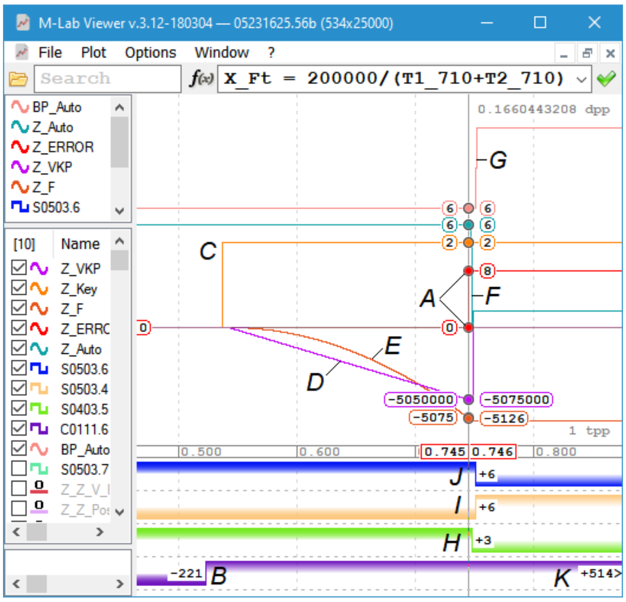

Fig. 4: An example of the emergency data file analysis.

This example demonstrates the ability to fully track the time sequence of all events occurring before and after the moment of error detection. The values of all SHC variables and the equipment state are available for research, which makes it possible to track the interaction of software with equipment, to identify the cause of the error. Similarly, using the developed CNC software and hardware, various situations arising in the equipment can be analyzed, which greatly simplifies the troubleshooting process and minimizes equipment downtime.

Analysis of axis movement errors

At experimental study of contouring accuracy for CNC machines is an important opportunity to analyze changes in the kinematic parameters of the tested equipment organs [Conway 2013], [Schraeder 2014]. Fig. 5 shows an example of changes in control signals, motion parameters and the following error of X axis of machine tool arising during circular interpolation execution.

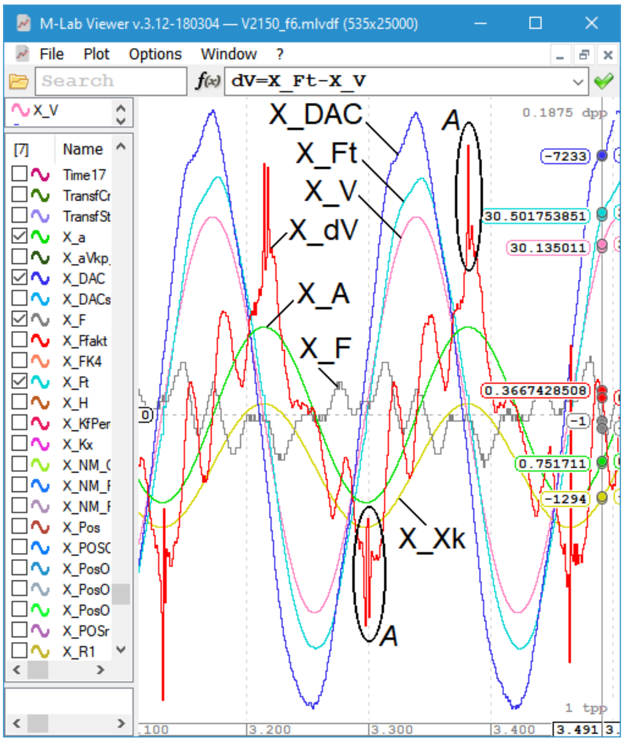

Fig. 5: Axis motion during circular interpolation execution.

The velocity error X_dV is the value of distortion of the actual velocity X_FT relative to the command velocity X_V. This distortion is the cause of the following error X_F - deviation of the actual position from the command position X_Xk. Graph X_DAC shows the change of the control code transmitted to the servo drive. There is a correlation between the velocity error X_dV and the specified acceleration X_A. This indicates an underdetermined or disabled acceleration feedforward. Character of velocity error oscillations means bad-quality tuning of the damping and gain parameters of position loop. Velocity error value at the moments of the motion direction change (pos. A) indicates the presence of the servo drive dead zone.

3.2 Investigation of dynamic characteristics

An experimental study of dynamic characteristics can be performed in two ways: a study of response of the step command or a study of movement while performing harmonic command with different frequencies. A step command can be obtained by executing a NC program with linear movement of the axis under study when setting an heightened value of acceleration.

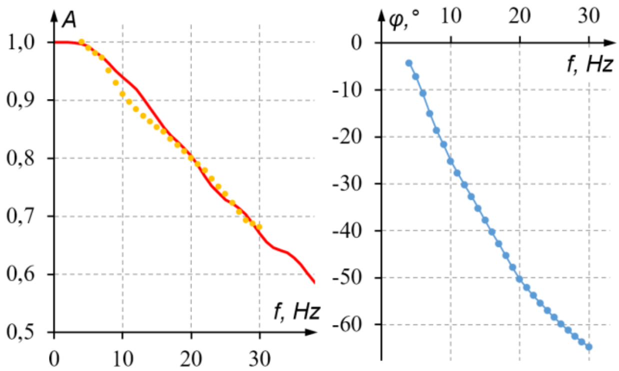

Fig. 6: The frequency characteristics of the open-loop system.

Harmonic command can be formed using circular interpolation, in which each of the axes is moved according to harmonic law.

The frequency characteristics of the open-loop system

Using of high-speed processing technologies needs to take into account the dynamic characteristics of the servo drives of the tool machine. One way to study the dynamic characteristics is to determine the frequency characteristics of servo drives. Fig. 6 shows the results of study of the frequency characteristics of the open-loop system with velocity feedforward control without position feedback loop.

Amplitude-frequency characteristics obtained by various methods. The solid line shows the spectrum of step response of the servo drive. The dots show the response to the harmonic command. The results showed that good response to commands provides at frequencies up to 5 Hz. Increasing the frequency of the command leads to a distortion of the actual velocity. The passband of the drive under study in terms of the amplitude ratio of 0.707 is 28 Hz. The phase delay within the passband does not reach the maximum permissible value of 90°.

Study of contouring accuracy

Fig. 7 shows the initial conditions of a study of contouring accuracy along a circular path depending on the frequency of the harmonic reference and the method of controlling a closed-loop system with position feedback. To correctly determine the dependences, disturbing factors arising during cutting were excluded, and the movement of the milling machine organs without processing the part was investigated. The actual position of the organs was determined by feedback from the machine. The radius of the circle R was defined as a function of frequency f.

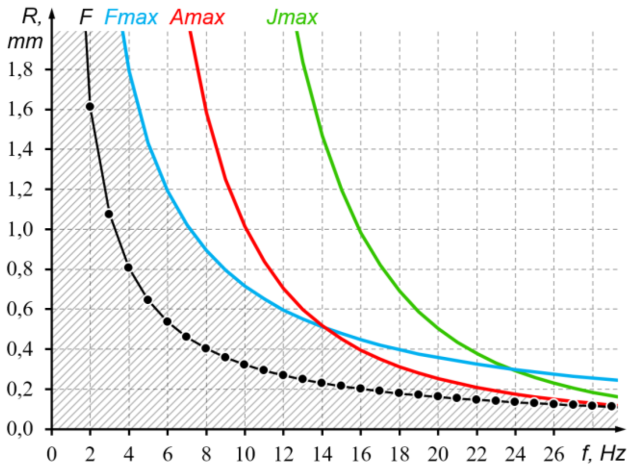

Fig. 7: Initial conditions of contouring accuracy study along a circular trajectory.

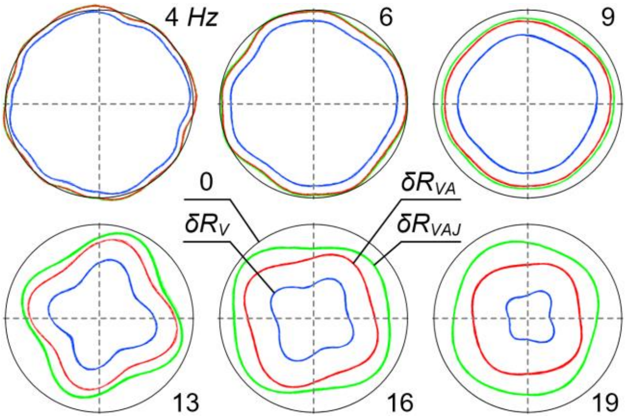

Fig. 8: Results of contouring accuracy study along a circular trajectory.

The experiment was carried out at a constant feedrate F < Fmax, chosen in such a way that, when moving around the circle, the limits of acceleration Amax and jerk Jmax are not reached. Used P controller with feedforward loop of velocity (V-feedforward), velocity and acceleration (VA-feedforward), velocity, acceleration and jerk (VAJ-feedforward).

Fig. 8 shows the evaluation of the circularity test performed for various frequencies. Even at low frequencies of the order of 4 Hz, the V-feedforward gives an unacceptably large value of the radius error δR. The use of VA- or VAJ-feedforward provides higher positioning accuracy, which indicates a significant effect of acceleration. The jerk effect is not significant, so the behavior of VA- and VAJ-feedforward remains almost the same up to a frequency of 6 Hz. An increase in the influence of jerk and a corresponding difference in the behavior of the VA- and VAJ-feedforward appear at a frequency of 9 Hz. The value of the jerk is 114 m/s^3. A further increase of the frequency (13 Hz and higher) leads to an increase and an excess of the permissible error level for all types of controller. In this case, the smallest error is ensured when using VAJ-feedforward.

Thus, while limiting the permissible error δR, the maximum permissible feed rate change depends on the feedforward composition and is much less, than the drive bandwidth determined by studying the frequency response of an open system. Accordingly, to ensure accuracy, it is necessary to limit the frequency of feed change. A SHC study allows to determining the appropriate limitations for specific equipment.

3.3 Investigation of high-speed processes

In modern high-speed equipment trend of combining different processes, not only cutting, but also, for example, laser cladding. Processes investigation to implement combined technologies require high-speed parameters recording and process control.

Pressure signals registration

The process of the pressure changing at the pulse action in the pneumatic valve system channel of the technological equipment for different frequencies of the generated pulses and different values of pressure has been studied (Fig. 9). The SHC subsystem designed for high frequency signals recording is used for this investigation. Subsystem allows recording data at a frequency of 1 MHz, which is three orders more than the control cycle frequency. The study found the formation of rarefaction wave (pos. A) in the investigated channel with parameters, which are taken into account by the CNC system during forming the commands of control process.

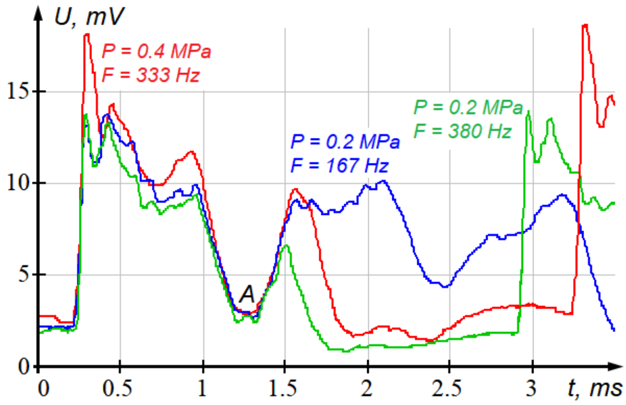

Fig. 9: The process of the pressure changing at the pulse action in the pneumatic valve system channel.

Investigation of vibrations during milling

Fluctuations in machine tools affect the accuracy and quality of machined surfaces, the durability of tools and machine elements. One of the methods for studying vibrations is the analysis of it acoustic emission [Downey 2016], [Bejaxhin 2019]. Acoustic emission in the machining process comprises information about a cutting process, motor operation, spindle rotating, etc. Each process causes vibrations in a narrow frequency band, the amplitude of which describes the process. The coincidence frequency of these oscillations with the natural frequencies of the system will lead to resonance oscillations.

Investigation of acoustic vibrations of the cutting process was performed on a milling machine tool. The rotational frequency of the spindle from 2,500 to 23,000 rpm is used in this investigation.

This investigation allowed determining the spectrum structure of the acoustic emission in the various operating modes for a particular machine (Fig. 10). On the frequency characteristics, natural oscillations are noticeable in several frequency ranges. As the spindle speed increases, some harmonics coincides with the natural frequencies of the equipment. Analysis of the acoustic emission spectrum showed that the most sensitive to the resonance of first, second, sixth and eighth harmonics of the spindle speed.

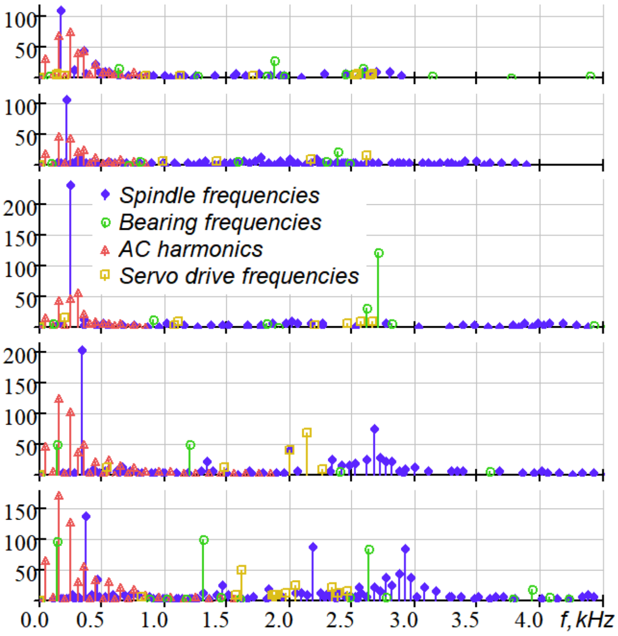

Fig. 10: Structure of spectrum of the acoustic emission in the various operating modes.

Thus, at frequencies 9,000...10,000 rpm is observed amplification of the oscillations at the second harmonic, at 15,500...17,500 rpm increases at the fundamental frequency oscillations and eighth harmonic at frequencies above 20,000 rpm in the range of resonance are sixth and eighth harmonic. The specified spindle speeds are undesirable for use in processing on the investigated equipment.

The results of such studies can be used to develop a methodology for choosing rational processing modes for specific parts on specific equipment.

4 SUMMARY

The paper considers the possibility of providing an analysis of the algorithms and processes of functioning of high-speed equipment. An approach that involves the addition of the CNC structure with specialized hardware and software and allows recording a complete set of equipment functioning parameters is proposed.

A software and hardware complex integrated with a PC-based CNC system that implements the proposed approach has been developed. The complex allows registering data of the technological process, parameters of the equipment operations and internal variables of the CNC system. Parameter registration can be performed both at the frequency of the control cycle and at higher frequencies

The examples of the SHC use for the analysis of failure causes, analysis of axis movement errors, investigation of dynamic characteristics of servo drives, investigation of high-speed processes are shown.

The complex is operated as part of the equipment of various types.

The proposed approach has greatly simplified investigation of various processes on specific high-speed equipment.

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