KAUNAS UNIVERSITY OF TECHNOLOGY
MECHANICAL ENGINEERING AND DESIGN FACULTY

AUGIS RIMKEVIČIUS

DEVELOPMENT AND INVESTIGATION OF EFFECTIVENESS AND PREVENTIVE MAINTENANCE SYSTEMS FOR NUMERICAL CONTROL MACHINES

Master's Degree Final Project

Supervisor
Assoc. prof. dr. Saulius Baskutis

KAUNAS, 2017

KAUNAS UNIVERSITY OF TECHNOLOGY
MECHANICAL ENGINEERING AND DESIGN FACULTY

DEVELOPMENT AND INVESTIGATION OF EFFECTIVENESS AND PREVENTIVE MAINTENANCE SYSTEMS FOR NUMERICAL CONTROL MACHINES

Master’s Degree Final Project
Industrial Engineering and Management (621H77003)

Supervisor
(signature) Assoc. prof. dr. Saulius Baskutis
(date)

Reviewer
(signature) Assoc. prof. dr. Inga Skiedraitė
(date)

Project made by
(signature) Augis Rimkevičius
(date)

KAUNAS, 2017

KAUNAS UNIVERSITY OF TECHNOLOGY

Faculty of Mechanical Engineering and Design
(Faculty)
Augis Rimkevičius
(Student's name, surname)
Industrial Engineering and Management - 621H77003
(Title and code of study programme)

"Development and investigation of effectiveness and preventive maintenance systems for numerical control machines"

DECLARATION OF ACADEMIC INTEGRITY

2017 June 13
Kaunas

I confirm that the final project of mine, **Augis Rimkevičius**, on the subject "Development and investigation of effectiveness and preventive maintenance systems for numerical control machines" is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarized from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by law) have been paid to anyone for any contribution to this thesis.

I fully and completely understand that any discovery of any manifestations/case/facts of dishonesty inevitably results in me incurring a penalty according to the procedure(s) effective at Kaunas University of Technology.

(name and surname filled in by hand) *(signature)*

Rimkevičius A. Development and investigation of effectiveness and preventive maintenance systems for numerical control machines. Master's thesis project / supervisor prof. Dr. Saulius Baskutis; Kaunas University of Technology, faculty of Mechanical engineering and design, department of Industrial engineering.

Research field and area: Technological Sciences, Production Engineering

Keywords: *technologies, equipment, monitoring system, tool wear, vibration, bearing defects.*

Kaunas, 2017. 50 p.

SUMMURY

A large part of metal processing companies are faced with inefficient labor and low productivity problems, which could be solved by the system that observes metal working machine tools conditions. In order to create such a system, it is necessary to explore the physical quantities – vibrations resulting from metal-working, acoustic noise from cutting tools wear and diagnosis resulting from bearing defects.

The aim of this research project: to develop and to investigate labour effectiveness and preventive maintenance system for numerical control machines.

To carry out the overview of the monitoring system and analyse the state of technological equipment and various technical parameters.

Tool wear process in the CNC milling machine was investigated. For the experiment was used four different milling cutters with different diameters (5, 10, 12 and 16 mm) were selected for low carbon steel, aluminium and stainless steel manufacturing. The manufacturing modes for each milling cutter were calculated and adapted in the processing programme. Piezoelectric accelerometers and microphone were selected for vibrations and sound level measurements.

For each tool in different frequency components are set the value of vibration and sound pressure levels. Different frequency bands established machine tool spindle corps vibration levels and sound pressure levels.

Rimkevičius A. Staklių darbo efektyvumo ir prevencinės diagnostikos sistemos kūrimas ir tyrimas. Magistro baigiamasis projektas / vadovas doc. dr. Saulius Baskutis; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas, Gamybos inžinerijos katedra.

Mokslo kryptis ir sritis: Technologiniai mokslai, Gamybos inžinerija

Reikšminiai žodžiai: technologijos, įranga, monitoringo sistema, įrankio dilimas, vibracijos, guolių defektai.

Kaunas, 2017. 50 p.

SANTRAUKA

Didelė dalis metalo apdirbimo įmonių susiduria su neefektyvaus darbo ir mažo našumo problema, kurią išspręsti galėtų sistema, stebinti metalo apdirbimo staklių ir įrankio būklę. Siekiant sukurti tokią sistemą, būtina ištirti fizikinius dydžius – vibracijas, atsirandančias metalo apdirbimo metu; akustinį triukšmą, atsirandantį nuo nusidėvėjusio įrankio ir guolių pažeidimų diagnostika.

Magistrinio darbo tikslas: sukurti ir ištirti staklių darbo efektyvumo ir prevencinės diagnostikos sistemą.

Atlikta apžvalga apie stebėsenos (monitoringo) sistemą ir išanalizuota technologinė įranga bei jos techniniai parametrai.

Ištirtas įrankio dilimas naudojant programuojamas frezavimo stakles. Eksperimentui buvo naudojama keturių skirtingų tipų ir skirtingų skersmenų (5, 10, 12 ir 16 mm) frezos. Naudoti trys skirtingi metalai – aliuminis, mažaanglis plienas ir nerūdijantis plienas. Kiekvienai frezai gamybos rėžimai buvo apskaičiuoti ir pritaikyti apdirbimo programoje. Vibracijoms ir garso slėgio lygiui matuoti buvo parinkti pjezoelektriniai akselerometrai ir mikrofonas.

Kiekvienoje skirtingoje dažnių dedamosios dalyje buvo nustatyta įrankio vibracijų ir garso slėgio lygio vertė. Skirtingame dažnių ruože nustatytas staklių suklio korpuso vibracijų ir garso slėgio lygis.

KAUNAS UN IVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:
Head of
Production engineering
Department

(Signature, date)

Kazimieras Juzėnas
(Name, Surname)

MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme INDUSTRIAL ENGINEERING AND MANAGEMENT

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Development and investigation of effectiveness and preventive maintenance systems for numerical control machines

Approved by the Dean Order No.V25-11-8, 21 April 2017

2. Aim of the project

Analyze the monitoring system integration into industrial equipment; Do research of tool wear; Analyze of bearing diagnostic methods and defects.

3. Structure of the project

Introduction;
Literature review;
Project research on vibration and acoustic noise;
Experimental data and results;
Research of bearing data and results;
Conclusions;
Literature;
Accessories.

4. Requirements and conditions

Analyze and select the sensors, which can be adapted to the necessary tools to determine the state of measurement parameters; Monitoring system integration into industrial equipment; Describe tool wear process and types of wearing; Examine bearing diagnostic methods and defects; Analyze systems capable of a set of metal processing tool condition; Investigate the vibration and acoustic noise levels in the CNC milling machine tool environment. Set work tool addictive with different diameters cutter mills.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2017 June 13 st.

Student	Augis Rimkevičius *(Name, Surname of the Student)*	*(Signature, date)*
Supervisor	Saulius Baskutis *(Position, Name, Surname)*	*(Signature, date)*

Table of contents

INTRODUCTION

Metal industrial development over the past few years increased a lot of. There is a large demand for CNC machine centers in metal industry. More and more companies integrate the flexible manufacturing technologies, accordingly rose and their requirements. The main feature of such centers is a constant load, this machine is working continuously to ensure the highest possible device efficiency and at the same time the supply of profits. This means that any machine downtime due to its poor technical condition and organization of processes leads to significant losses, which significantly affects the competitiveness of the company. For this reason, manufacturers are interested in installing smart metal processing machine technical condition monitoring systems. It allows monitoring the devices operating parameters, changing trends and timely report on the current and future potential defects even in their initial stage of development. Such systems can be implemented as a technological device in development stage. In any case, the cost of such equipment technical condition monitoring system installed is small compared to the potential losses, which might arise from an accident at a facility.

The main goal of such system is to detect defects at the earliest stage of their development and accept optimal solution, for example, a planned period of time and procedure. In the practical diagnosis do not always succeed to notice acoustic noise and cannot modulate the required information, such as working cutting tool or bearing technical condition characteristic of a signal. This noise depends on a number of possible factors, such as: environment which employs a device operating modes, the geometric dimensions of the device, changing work settings, and so on. Diagnosing one or the other device defects, which are strongly developed, is important in making necessary decisions in identifying one element that causes the defect, such as tool wear or spindle bearings, which can irreversibly affect other expensive items. This not only results in significant downtime and damage repair, but often negatively affects development and installation of production quality. To avoid such damages it is necessary to optimize the use of diagnostic tools, adapting them to the specific monitoring device and determining how one or another potential defect would affect the measurement hardware signal recording and analysis. Such investigations should be carried out in different physical defect modelling, which require appropriate deliberately damage both node elements, how much we want to identify defects in the design of the diagnostic system. It is not feasible due to the high material costs and the time required for each potential defect to physically realize and explore the real system.

Work objective: to develop and to investigate labour effectiveness and preventive maintenance system for numerical control machines.

Project Tasks:

1. To analyze and select the sensors, which can be adapted to the necessary tools to determine the state of measurement parameters;
2. To analyze the monitoring system integration into industrial equipment;
3. To select the necessary equipment that will be used for research;
4. To describe tool wear process and types of wearing;
5. To examine bearing diagnostic methods and possibly of arising defects;
6. To analyze systems capable of a set of metal processing tool condition;
7. To investigate the vibration and acoustic noise levels in the CNC milling machine tool environment. Set work tool addictive with different diameters cutter mills.

1. LITERATURE REVIEW

In industry, manufacturing processes requires continuous monitoring status. The monitoring system allows monitoring processes and to collect the necessary information to process and organize, present findings and possible forecasts for working process of CNC machines. Modern monitoring systems from different equipment receive data and processes, the following information as a state of the view in real time. Functionality of these systems is adjusted according to the specific needs of the client. The monitoring system implementation not depends on the equipment, devices and sensor manufacturer.

Machinery and equipment condition monitoring and fault diagnosis of defects prevention is an integral part of the modern manufacturing process component. Modern monitoring systems facilitate the organization of the company; there is the possibility of preventing equipment maintenance, avoiding downtime, and minimizing equipment disorders for random numbers. Therefore, monitoring is a useful investment with wide practical benefits [1].

Monitoring – in the broad sense is the state of monitoring. In a narrow sense, it can be a specific type of monitoring, such as monitoring of mechanical systems, structures monitoring and so on. When monitoring specific processes, such as vibration – it comes to mechanical vibration monitoring systems, namely vibration monitoring processes [2].

Surface treated with various types of milling cutters, drills, which significantly determines the status of the final product quality. Unsuitable tool machining process starts to heat up from excessive loads, metal processing modes and causes vibrations. This leads to uneven surfaces rout and inaccurate product dimensions.

In order to determine the condition of the tool with the two physical quantities measurements is vibrations and sound. The measurement of physical quantities is numerous individual systems capable of monitoring a physical phenomenon, as well as different sensors, which converts them to analogue or digital signals. According to these signals it can be seen, what operates the most vibrations and sounds [3].

The main goal installing such systems is to detect defects at the earliest possible stage of their development and adoption of an optimal solution, such as a planned repair time and procedure. In the practical diagnosis do not always succeed on a wide variety of noise that hides us and modulates the required information, such as the bearing technical condition characteristic of a signal. This noise depends on a number of possible factors, such as environment employing a device operating modes, the geometric dimensions of the device, changing work settings, and so on. This not only results in significant downtime and repair damage, but often affects the quality of production. To avoid such damages it is necessary to optimize the use of diagnostic tools, adapting them to the specified device and monitoring to determine how one or another potential defect would affect the measurement hardware signal recording and analysing [4; 5].

1.1 Technologies, equipment and monitoring tools overview

The monitoring systems are used in various industries. This is especially true in areas, where the use of complex and expensive equipment, whose failure has a significant negative impact on the entire enterprise productivity and competitiveness of the company. One of these is active cutting tool, where efficient production is difficult to imagine without modern numerically controlled machine tools, robots and manipulators is metal processing.

Modern technology allows the development level of a fundamental change in metal and other materials, machining processes, management and monitoring of the principles, and measures that work more efficient, environmentally friendly and save energy resources.

There are two main processes, monitoring systems: active and passive. Systems are required for active sensors that are detected, for example, the sawing process instabilities electronic controls would make it possible to transmit controllers, interacting with a mechanical device technology system. In active control systems data cables and power transmission are required. User use control system friendly for environment, but their application in industry is not widespread. Passive management system does not need to be sophisticated equipment, but so far in the market can be found just a passive vibration damping equipment [2; 6; 24].

Wireless active management (monitoring) system – is a micro sensor networks deployment into production modules (machines, devices, tools, workpieces). Such systems allow monitoring of machine tools vibration levels of the cutting parameters and register them. Such data analysis and appropriate action ensures smooth cutting process in optimal mode, it makes it possible to inform about the need to change tools, mounting equipment operational reliability (e.g., if enough force recorded details of the situation and so on.), thus, significantly reducing the downtime of spoilage volume production [6].

Figure 1.1 shown in this project is a multi-monitoring (monitoring) system, which will monitor and analyse the state of technological equipment and various technical parameters. The monitoring system will include rotating parts of the machine vibration measurements, focusing on the bearing diagnostics, temperature of the cutting area and other machine heat source measurement, hydraulic and pneumatic machine system parameters, in particular, the pressure measurement, machine tools, electric power consumption measurement, cutting tool wear, gear cutting plates, resource experiments.

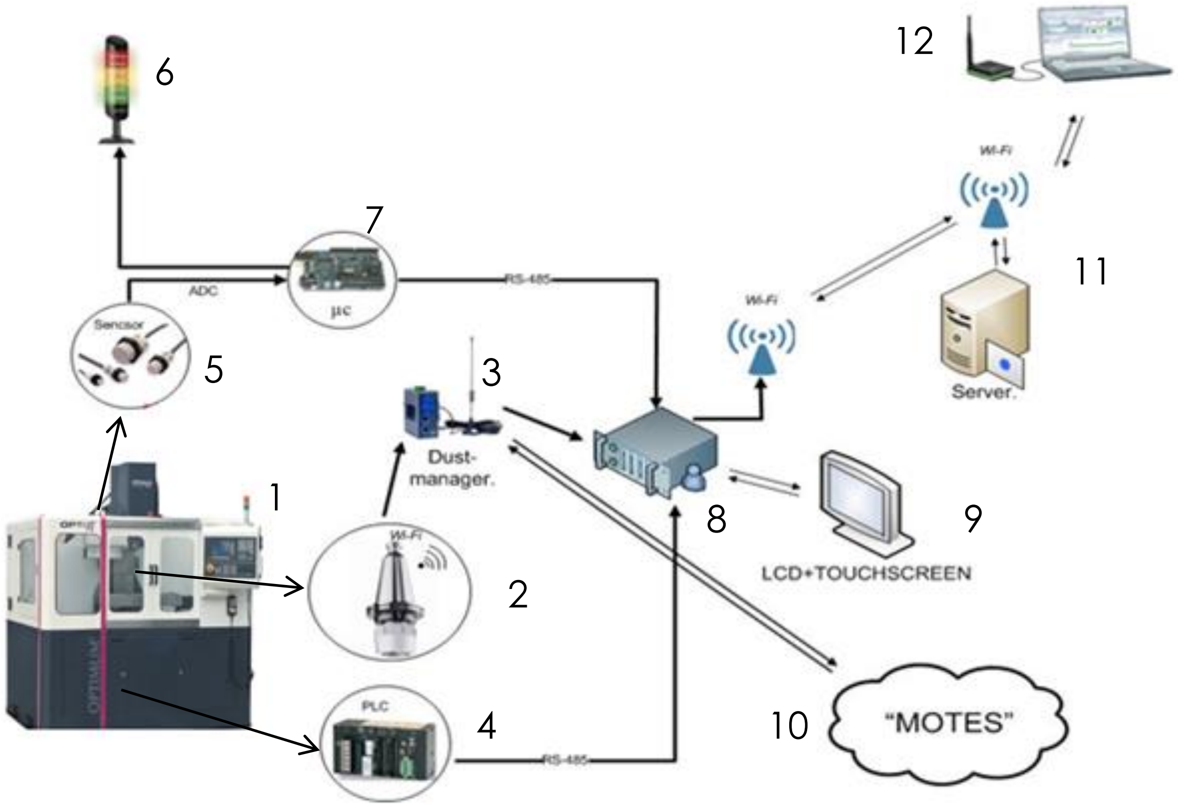


Fig. 1.1. Components of developed monitoring system: 1 – CNC metal cutting machine, 2 – "smart" tool with built-in sensors and wireless connecting module, 3 – software designed to communicate with "smart" tool, 4 – PLC controller of machine, 5 – sensors and recording additional machine parameters, 6 – telltale lights visually presenting simplified information about the machine's working state, 7 – the micro-controller, collecting information from the sensors transmitting information to a computer and controls the telltale lights, 8 – the main computer system, processes data and provides information on the displey and in the server, 9 – an information display, 10 – additional wireless modules of "smart" tools, 11 – Server, 12 – a personal computer with Internet access [1].

1.1.1 Similar devices and sensors overview

In order to monitor the sound of the machine and vibrations of the device is required, which can be fixed to the rotating axis of the CNC machine. It should be easily integrated into the machine or tool holder on it. It is also important to take into account the fact that the metal-working environment is not suitable for measurement method, because the environment is exposed to high-pressure jet of the emulsion. One of the factors that characterize the state of the tool is the main spindle sound increase in environment. This is due to increased resistance, the tool exposed to the same treatment modes. These variations can capture the sound sensors built on main spindle direction of rotation.

Depending on the requirements equipment analysis and comparison of similar devices is made.

System that can recognize a bad tool and inform the user, was not found in literature, but developed experimental models which are not available for public sources.

For this purpose to carry out the investigation, it is needed to choose the necessary equipment. Equipment will consist of three main components: microphone, vibration sensors and data processing machine.

The microphone is used for noise detection. The device should be small and easily mounted on the CNC machine table.

Vibration sensors must be kept to a smaller size (up to 4 x 4 mm) that it can be integrated on spindle non-rotating part.

Data processing machine software allows to perform FFT, CPB the intensity of the noise analysis and to create noise maps. The meter is used with a computer, which collects measurement data and calculations.

1.1.2 Microphone types

Microphones divided into four main types [7]:

- condenser microphone;
- electret condenser;
- dynamic (moving-coil microphone);
- piezoelectric.

Several different types of microphone are in use, which employ different methods to convert the air pressure variations of a sound wave to an electrical signal. The most common are the dynamic microphone, which uses a coil of wire suspended in a magnetic field; the condenser microphone, which uses the vibrating diaphragm as a capacitor plate, and the piezoelectric microphone, which uses a crystal of piezoelectric material. Microphones typically need to be connected to a preamplifier before the signal can be recorded or reproduced [8].

Dynamic microphones are best suited for handling fairly high volume levels, such as electric amplifiers or drums. They do not require any external power or batteries and they have no internal amplifier.

Condenser microphones use a capacitor (a thing that stores electricity) to convert acoustic energy (things wiggling back and forth) into electric energy (electrons zipping around inside some wires).

Ribbon microphones are considered to be the most natural sounding microphones ever made. They use a type of aluminium called duralumin (the “ribbon") that is placed between the poles of a magnet in order to produce voltages. The ribbon is very thin and allows the microphone to respond to sound very quickly [9].

1.1.3 Vibration measurement techniques

Industrial machinery-induced vibrations are key indicators of machine and tool longevity and quality of manufactured products. The monitoring systems, which can record and monitor tool cutting time resulting from changes in vibration, can detect possible measures, to avoid possible discrepancies in the product or major failures in the CNC machines, which would bring the company huge losses. Vibration analyses - a tool to help determine the condition of the machine or tool, which will not allow discrepancies occur in the products and will help to prevent unexpected machine failures.

Vibrations are defined with three parameters: speed, acceleration and displacement. These parameters are mathematically related, the vibrations can identify all sensors to measure speed, acceleration and displacement. The sensor depends on the vibration frequency and the sensor output level.

Vibrations can be measured by using piezoelectric sensors or accelerometers.

A piezoelectric sensor works on the principle of conversion of energy in mechanical and electrical energy forms. When a polarized crystal is put under pressure, some mechanical deformation takes place in the polarized crystal, which leads in the generation of the electric charge.

The generated electric charge or the mechanical deformation can then be measured using a piezo sensor [10].

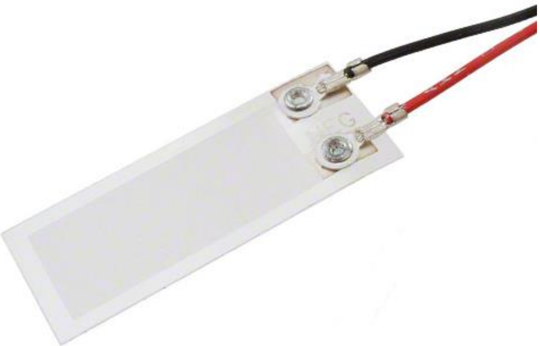


Fig. 1.2. Piezoelectric sensor

The most common piezoelectric sensors are used in closed mechanisms such as gearbox.

Accelerometers are devices that measure acceleration, which is the rate of change of the velocity of an object. They measure in meters per second squared (m/s^2) or in G-forces (g). A single G-force for us here on planet Earth is equivalent to 9.8 m/s^2, but this does vary slightly with elevation (and will be a different value on different planets due to variations in gravitational pull). Accelerometers are useful for sensing vibrations in systems or for orientation applications [11].

Fig. 1.3. Common uses and Industrial accelerometers [11]

Accelerometers are electromechanical devices that sense either static or dynamic forces of acceleration. Static forces include gravity, while dynamic forces can include vibrations and movement.

Generally, accelerometers contain capacitive plates internally. Some of these are fixed, while others are attached to miniscule springs that move internally as acceleration forces act upon the sensor. As these plates move in relation to each other, the capacitance between them changes. From these changes in capacitance, the acceleration can be determined [11].

1.1.4 Data processing equipment

Data processing is the development and implementation of technology that automatically processes data. This technology includes computers and other electronic communications that can collect, store, process, prepare and distribute information. Automated data processing is too quickly and efficiently process large amounts of information with minimal human resources, and shares it with a select audience.

There are various types of equipment used in the testing of noise, vibration, and harshness.

Analysers are electronic devices which can quantify and assess noise and vibration. Many of these devices are portable.

Shakers and controllers provide signal analysis and control of vibrational noise. Shakers can be built for a range of different vibrational forces from small (25lbf) to very large (1000lbf).

Noise dosimeters are specialized sound level meters intended to measure exposure of a person to noise over time.

Electromagnetic acoustic transducers (EMATs) are transducers for non-contact sound generation and reception using electromagnetic mechanisms.

Dynamometers measure force, moment of force, or power. In the case of NHV testing, dynamometers simulate motors and other mechanical devices to test vibration and noise characteristics.

Sound level meters are devices used to measure sound pressure levels. They are used for quantification of almost any noise in noise pollution studies.

Microphones are recording devices that can be used to test noise and sound levels from most sources.

Analysis software includes all computer programs and tools that provide interface and allow manipulation of outputs from recorded and testing devices [12].

1.2 Tool wear and types

Tool wear is the inevitable cause tool failure in the machining process. The extent of tool wear has a strong influence on dimensional accuracy and surface finish obtained. The gradual wear of the tool occurs at three principal locations of a cutting tool. According to this cutting tool wear is classified into three categories [13]:

- Flank wear;
- Crater wear;
- Corner wear.

Flank wear is due to work hardening. Flank wear occurs at the tool flanks, where it contacts with the finished surface, as a result of abrasion and adhesion wear. The cutting force increases with flank wear. It affects the great extent of mechanics of cutting. The flank wear region is known as wear land and is measured by the width of wear land. If the width of wear land exceeds 0,5 – 0,6 mm the excessive cutting forces cause tool failure [13].

Crater wear happens on the tool face at a short distance from cutting edge by the action of chip flow over the face at very high temperature. The crater wear is mainly due to diffusion and friction. They are commonly observed where the continuous chip is formed (usually in the plastic material). In the brittle material, the chip formation in the shape of a small segment, this loosely fragmented chip has low abrasive action on the surface as compared to the continuous chip formation. The depth of crater measures the crater wear; the surface measuring instrument can measure it. The cutting edge may break from tool due to excessive cratering [13].

Corner wear occurs at tool nose radius. Corner wear shortens the cutting tool, cause a significant dimensional error in machining. It is considered as part of flank wear since there is no distinguishing boundary between them [13].

Cutting tool wear classification presented in Figure 1.4.

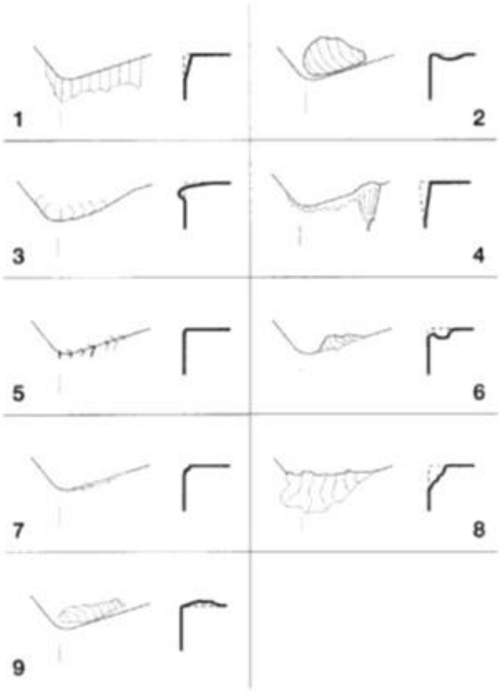


Fig. 1.4. Cutting tool wear classification of different wear factors: 1 – side wear, 2 – crater wear, 3 – plastic deformation, 4 – carving wear, 5 – thermal cracking, 6 - mechanical fatigue cracking, 7 – shavings, 8 – crack, 9 – ridge formation [14].

The side cutting edge wear occurs on a surface abrasion. The rear surfaces of both the Primary and Secondary and peaks are subjected to a rounding of the workpiece and moving particles Figure 1.5. Wane side surface, due to increased friction changing the basic form of the cutting edge, thus deteriorating the machined surface quality, dimensional accuracy decreases.

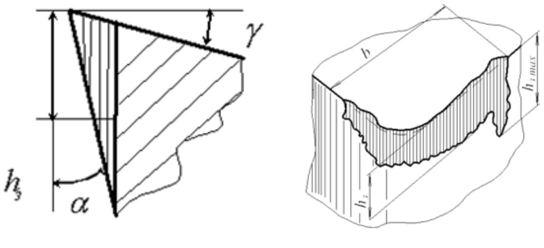


Fig. 1.5. Basic rear surface abrasion: h_3 - Bound wear width, γ - the main front angle, α - the main rear angle, length of the wear bound [14].

Processing fragile materials occurs in the rear face of the wear of the tool, such as iron, which generates a break shaving. When processed steels, the rear face of the wear dominates when the thickness is small offcuts at low rear angle. The front surface of a crater wear caused abrasive wear or diffusion wear. The crater formed when the material of the tool on the front surface is eliminated hard abrasive particles to the workpiece. Exposure diffuse or shavings tool preheated in the front surface Figure 1.6.

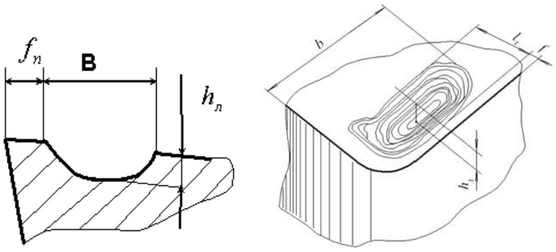


Fig. 1.6. The front surface of the crater wear: *B* – width of the crater, *hn* – the crater depth, *fn* – bulkhead (the distance from the cutting edges to the crater) width, *ln* – crater width [14].

The front surface of the wear happens when processed tacky metals, such as titanium. Front face wear not immediately at the cutting edge, but in a distance fn of the cutting edge. The resulting crater working tool is deepening and expanding away from the cutting edge. Crater depth increases in proportion to the working time of the tool, the tool wear with the exception of the initial period. The front surface of the crater width B increases slightly and the lintel width fn decreases. The durability of the tool or the period of time between regrinding depends precisely on this lintel. This lintel dissolved, the cutting tool loses its properties. Large crater abrasion tool changes the geometry of the cutting part, weakens the cutting edge hinders the formation of shavings.

The wear on the cutting tool gets a change of shape and cutting tool loses its properties. The tool cutting edge wears on the friction surface and the machined shavings. Intensive wears on the rear surface of the tool.

The entire blade wear period can be divided into three stages. The first stage is the initial stage of wear. Rapid wear of the tool, because the tool cutting edge improperly work. Rounded up to the optimum size with a sharp cutting edge, equalize individual roughness, spalling and honing traces. Dimensional size of wear is characterized by initial attrition polling.

The second – the normal (steady) abrasion step is characterized in that during tool wear evenly. Tool wear characterized by linear dependence wear knee. For this period, the wear curve of a straight line inclined at an angle α with respect to the X axis. At this stage, the tool wear is largely dependent on the tool and workpiece materials, cutting conditions, process systems rigidity.

The third phase is the most intense wear. This catastrophic wear period during which the cutting edge may crumble, tool breakage. At this stage, the cutting edge decomposes. Therefore, in order to keep the cutting tool that is suitable for further use, it needs sharpening or change an existing new cutting plate.

Figure 1.7 shows the wear curve of the blade according to the cutting path length. Curve 1 in the graph shows three wear phases and curve 2 does not have the initial wear. This can be achieved smoothly consummate cutting edges and surfaces.

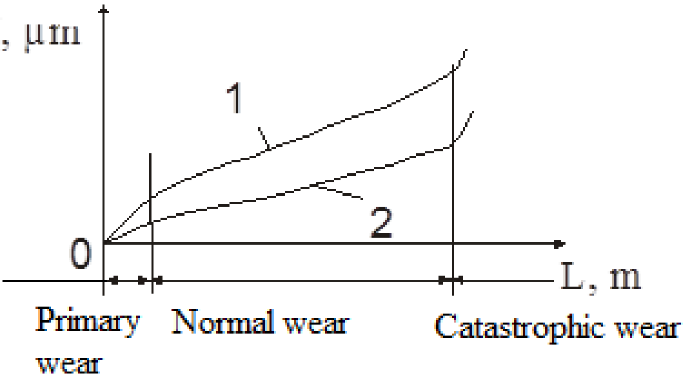


Fig. 1.7. Blade wear stages [14]

For the tool wear variable received systemic error. In order to reduce the possible, it is recommended to choose the right material toolbar, consummate cutter cutting edges, selected economical modes (speed, feed, depth of cut), stabilize the cutting mode (to be as constant as possible the cutting force), timely change and sharpening tools and align machines.

The cutting conditions greatest impact comparative abrasion has a cutting speed. Research shows that the processing of iron, comparative steel wear justifies the smallest cut of 100 ... 200 m/min. Cutting depth has little impact on the comparative abrasion. The greater the angle of the rear of the tool influence. When the angle is lower wear increases. When workpiece material harder, the comparative attrition higher. Dimensional tool wear is the most important reason, which after a certain time not reaches the required dimensional accuracy of the workpiece.

1.3 Metalworking machine spindle bearings diagnostic

Spindle unit metalworking machine tool’s is the final key motion and is designed to drive the tool or the workpiece holding device for fixing. Spindle assembly quality directly affects the reliability of the entire device, production accuracy and productivity. Simple spindle assembly, as shown in Figure 1.8 consists of the spindle, its supports and the motion transmission mechanism. Modern programmable machine tool, wherein the spindle rotates at high speeds in particular motion actuator including the motor itself is directly integrated in the spindle unit Figure 1.9.

Fig. 1.8. Milling machine spindle [4]

Machine-tool spindle unit during operation of the tool or workpiece transmit the torque required for the cutting process to realize. Main motion drive power is transmitted to the spindle unit can be up to 150 kW, spindle speeds in milling rolling bearing is 30000 rev/min and above, cutting force reaches 30000 N.

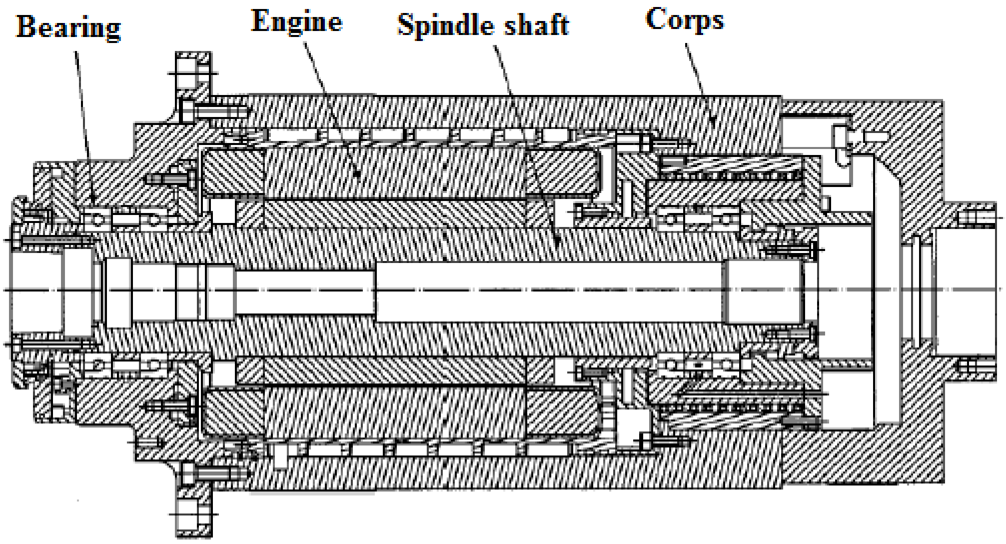


Fig. 1.9. Spindle unit with integrated motor schema [4]

Spindle assembly system damage severely affected by the vibration. Therefore, in order to diagnose and monitor the status of the system and its components defect trends, it is appropriate to investigate node vibro – acoustic environment and its changes.

1.3.1 Spindle assembly vibration sources

Machine-tool spindle unit vibrational environments are separate elements and processes of vibration as a whole. The main sources of vibration system are:

1. Spindle shaft disbalance;
2. Engine and referred to vibrations caused;
3. Random vibration components for manufacture and assembly inaccuracies;
4. Elements of the system resonance operation mode of operation;
5. Workpiece during cutting caused by vibration;
6. Bearing system and its defects vibration.

Vibrations on the environment and work alongside other devices can be ignored, since the machines are usually isolated by special vibrations depressants platforms. From the above sources of vibration, the vibration caused by the spindle shaft and bearing systems disbalance defects related to technical system corresponding node failures. It is precisely this type of vibrations that are isolated and analysed as a diagnostic information technical condition monitoring systems. All other vibration sources are an integral part of the device and its operating modes share and influence will be independent of the device in question technical condition [4; 5].

1.3.2 Spindle bearing system

When working with metal working machines, the biggest responsibilities and requirements have a bearing spindle mechanism consisting of the bearing system. It must provide a high – speed rotation options, to be able to withstand high dynamic and static loads and have a long service life. Usually high speeds stem used in ceramic radial – axial ball, roller and conical bearings Figure 1.10.

These types of bearings are widely used in metalworking machine spindle unit, as they have a sufficient accuracy, the maximum withstand load and the spindle rotation speed. In addition, their relatively low cost compared with a hydrostatic, aerostatic or magnetic bearing. Angular contact bearings are designed to withstand the possibility of external loads in axial and radial directions. These types of bearings are coupled in order to increase support rigidity and strength. Bearing assembly shown as an example in Figure 1.11.

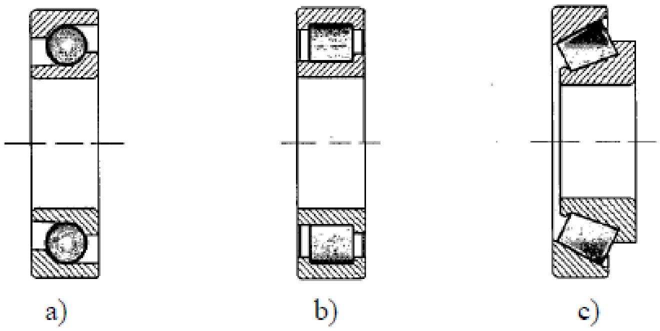


Fig. 1.10. Radial - axial bearings: a) the ball; b) the roller; c) the cone [5]

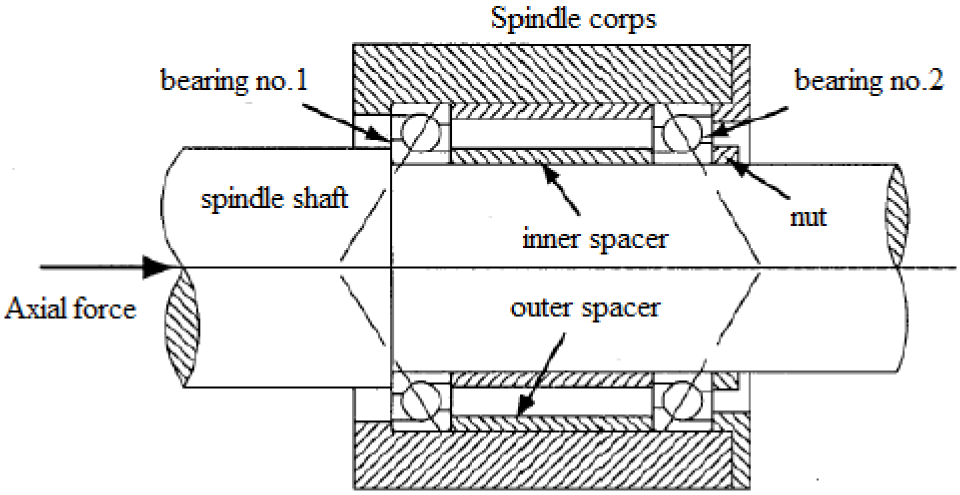


Fig. 1.11. Bearing mounting example [16]

The main difference between the usual destination and spindle bearings used in the system is that the latter has a high precision class and has the axial backlash adjustment. Axial backlash adjustment allows you to change the bearing rolling elements and rings clamping voltage. Depending on the operating conditions during mounting spindle unit is formed or the preliminary tension or slack. If voltage is formed rolling element being pressed into the elastic ring the tracks are a number of operations increases the spindle unit hardness and resistance to vibration also, increased accuracy and rotation. Occurrence of at least one bearing element of the unit rapidly increases the amplitude of vibration and the rotating tool or workpiece deviation, which has been lost, is required metalworking machine production accuracy.

1.3.3 Bearing vibration sources

Antifriction bearings excited vibration by their very nature was divided into four main groups:

1. Construction vibration;
2. Vibration due to manufacture tolerances;
3. The vibration due to operation of properties;
4. Other vibration.

Construction vibration occurs in all rolling bearings and virtually unavoidable. Each bearing element is a separate body with a specific weight and form, thus turning them running centrifugal force and inertia. Rolling member strikes his ring tracks simultaneous excitation of the bearing construction own oscillations. The vibration of the bearing element depends on the dimensions, materials, and rotational speed [4; 5].

The second group of vibration caused by the inaccuracy of the bearings elements. This is the bearing rings waviness, roughness of tracks and other forms of discrepancies. Such vibration has a random nature and is hard to evaluate. Speaking about vibrations on the operating characteristics, bearing wear and various defects caused by vibrations. In bearing units defects dramatically increases the structural vibration level, it appears as sudden load pulses. Since this particular group of vibrations is analyzed to determine the technical condition, their properties and the evaluation methods must be examined in detail [2].

The other vibrations include hydrodynamic and turbulent phenomena bearing lubrication. Generally vibro – acoustic environment they do not have a significant impact because they will also be ignored.

1.3.4 Bearing defects

Bearings are among the most accurate mechanical engineering elements. Their production complies with very strict quality requirements and conditions specified by the manufacturer of bearings can be operated for a very long time. The working conditions are never be ideal, bearings seldom realize their full potential for resource respect.

Roller bearing life directly depends on the accuracy of their production, storage, handling, load and operating conditions [5; 25].

Under the FAG bearings studies is made up of bearing defects cause of the diagram according to their frequency of occurrence of different types of machinery Figure 1.12. All bearing defect causes some of their inherent vibration components of the spindle. Proper measurement and these vibrations can be analyzed with sufficient accuracy to determine the type of fault current, its development and the cause. For this purpose, many methods are developed allowing for the installation's technical condition and to diagnose existing and potential faults, and thus to act as the technical condition of the objective monitoring.

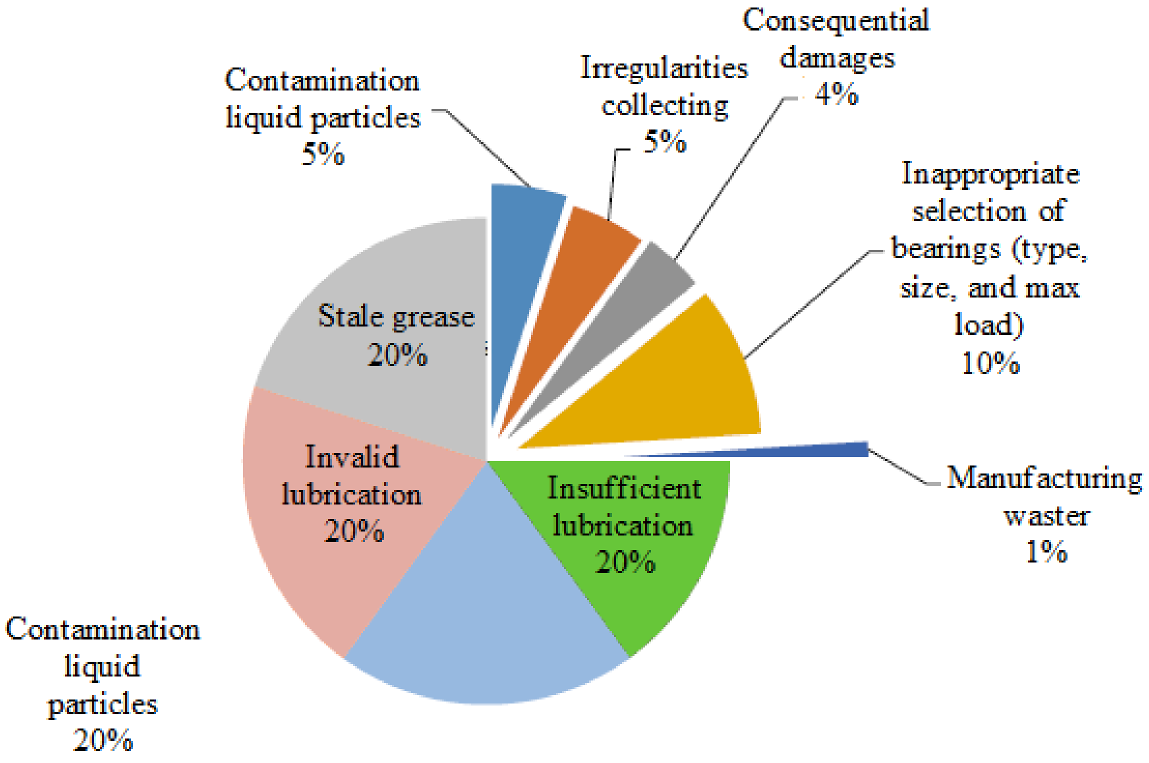


Fig. 1.12. Bearing failure causes according to the frequency of occurrence [4; 5]

Having dealt with the metalworking machine structure and during the conditions sources of vibrations, it can be said that the main spindle assembly defects of the rotor imbalance and bearing race system damage repaired. Therefore, creating a vibration signal model will be limited to this particular nature vibration modelling.

1.3.5 Spindle unit diagnostics and monitoring

Technical diagnostics – this branch of science researches the technical state of the system and identification methods. The main task is to determine whether the technical system is damaged or undamaged, if broken – where place and why, and if is not broke – it is how much time it has to be operated by the failure or how to avoid it. There is always the aim to capture the failure of an earlier stage of its development. This task is solved in three stages [6]:

1. Technical data about the state of the system assembly.
2. The data collected by the information received, processing and analysis.
3. Decision-making in determining the technical condition of the repair duration and scope.

Over the past decades technical diagnostics highly advanced non-destructive diagnostic systems technical direction. Creating technical diagnostic systems and methods, allows the determination of the technical state of the object without dismantling. This day is the most prevalent vibration, acoustic and thermovisual technical condition assessment methods.

Metalworking machine tool spindle assembly fault diagnosis tests are also widely used in the world and this moment is created by a number of operating, and diagnostic systems used. It was approved various diagnostic methodology in order to find the optimum and most effective means of machine diagnostics and technological quality condition monitoring.

Vibration spectrum analysis method is considered the technical system of vibro – acoustic signal emitted by the research. The measured signal from the time domain to the frequency domain translated and analysing the frequency spectrum. Spectral vibration analysis usually applies fast Fourier transform (FFT), and the correlation is calculated to determine a unilateral and mutual correlation function [6; 15; 26].

Spectral analysis can identify the individual hardware system defects while and rolling bearing faults. Knowing arouse bearings working frequencies; it is possible to identify the nature of vibrations and determine the bearing and the particular structural element defect.

1.4 Chapter Summary

Review of literature analogues on the market. Most of the devices on the market do not perform state analysis of the tool. To examine, discuss and compare the market in tool wear, monitoring system, bearing diagnostic and vibration sensors. Given the technical requirements of the selected device satisfies all the requirements of the acoustic measuring accelerometer frequencies. Discuss the types of microphones, vibration measurement techniques, data processing equipment and metalworking machine spindle bearings diagnostic.

The measuring device is in the range from - 0 to 6,4 kHz. The device is very small in size, which allows it to integrate the tool in the working part.

Proper vibration sensor is a three-axis accelerometer, reaching 250G measurement range.

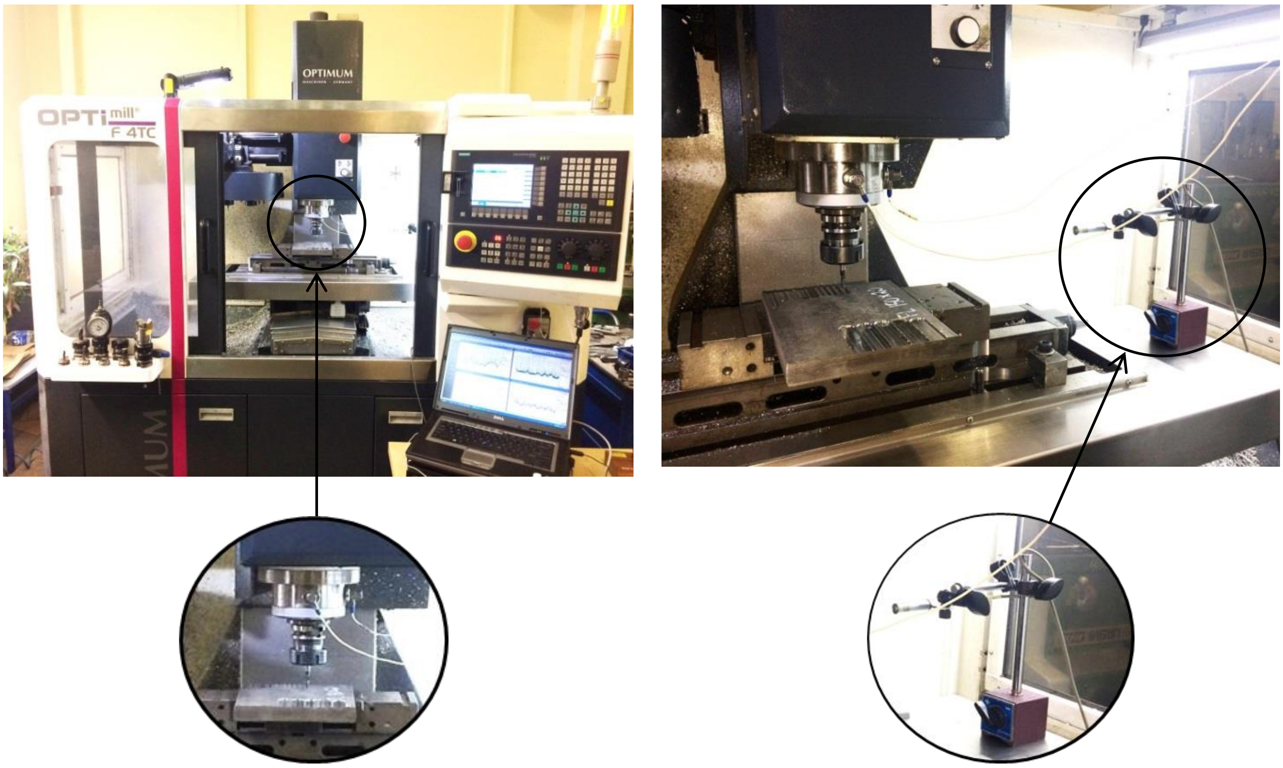
2. PROJECT RESEARCH ON VIBRATION AND ACOUSTIC NOISE

The purpose of this chapter is to investigate the vibration and acoustic noise levels in the spindle machine tool environment. Determine the dependence of the work tool, wear of different work tools.

In modern metal working companies there are many devices with rotary and mechanical systems. Most of them - modern machining centres with complex computer controlled systems and executive precise mechanisms of technological opportunities. The main feature of the metal working centres - constant and continuous work to ensure maximum device performance. Working devices such conditions happening faster depreciation of machinery and tools, this is directly related to product quality and accuracy. Not the last place is occupied by the developer and the machine monitors the workers skills. All of these factors influence the quality of the manufacturing process, parts machining accuracy, surface roughness and other quality parameters. Therefore, technical condition of equipment monitoring, without interrupting the production process is one of the most modern technical diagnostic tasks [5 – 7].

Modern metal processing CNC machines and parts of the technical condition monitoring is often based on vibration measurement and analysis. However, modern production process to perform vibration monitoring of the parameters is not possible by traditional means. It is therefore necessary to look for new, modern methods of measurement, less influencing and characterizing the production process machinery and equipment conditions [5; 16].

One of the possible experimental measurement techniques is vibration and acoustic noise measurements on spindle machine tool environment. The comparisons of measurement data to determine the correlation of diagnostic parameters and the change trends, which makes it possible to determine the state of the spindle bearings and work tool wear. Finding vibration and acoustic noise level dependencies, machine tool spindle environment was carried out an experimental study. The experiment was carried out in CNC machine OPTI mill F4TC environment. CNC milling machine OPTI Mill F4TC tool (mill) excitation of vibration were measured on the hull transverse spindle (acceleration 1) and longitudinal (acceleration 2) directions. Acoustic Noise measured at 1 meter from the cutter. Transducer and microphone positions for the measurement time are shown in Figure 2.1. a), b). Measured in a modular precision vibration and noise meter Pulse 3560 frequency bands 0...800 Hz and 0...6,4 kHz using two oscillation measurement sensor type 751-100 and microphone pre-amplifier 4189 with the (Bruel&Kjear) [22].



a) b)

Fig. 2.1. Vibration transducer (a) and microphone (b) position during the measurement.

The workpiece used in the experiment was chosen with dimensions 150x130x20 mm, of mild steel (EN 1.0037) Figure 2.2. Chemical composition and mechanical properties is presented in table 8.

Steel - iron and carbon alloy containing up to 2% carbon and manganese (0.3 ... 1.8%), silicon (12:15 ... 1.1%), sulphur (up to 0.06%) and phosphorus (up to 0.07%) impurities. Steel mechanical properties and chemical composition are key indicators for judging the quality of steel and suitability for use. The most important mechanical properties: strength, elasticity, plasticity, brittleness, hardness.

Fig. 2.2. Workpiece of steel with dimensions 150x130x20mm

For the experiments were used four cutters with different diameters Ø5, Ø10, Ø12 and Ø16. Tools with diameters Ø5 mm are shown in Figure 2.3. Tools with diameters Ø16 mm are shown in Figure 2.4.

Fig. 2.3. Ø5 diameter cutters examples

Fig. 2.4. Ø16 diameter cutters examples

Table 2.1 Low carbon steel (EN 1.0037) chemical composition

Low carbon steel	C	Mn	P	S
1.0037	0.17 – 0.20	1.40 – 1.40	0.045	0.045

Material designation: C – carbon; Mn – manganese; P – phosphorus; S – sulphur.

Table 2.2 HOLEX (202080) cutter mill working modes for low carbon steel (1.0037).

	Ø5 mm	Ø6 mm	Ø8 mm	Ø10 mm	Ø12 mm	Ø16 mm
S rev/min	6050	5470	4540	3630	3020	2270
F mm/min	517	517	517	517	517	517

The lengths of the tools measure is presented in Table 10.

Table 2.3 the cutters of different diameters in length.

Cutter No.	⦰16 cutter	⦰12 cutter	⦰10 cutter	⦰5 cutter
1	0091527586 = 94.573mm	79.471mm	74.576mm	58.006mm
2	0091554520 = 93.149mm	79.581mm	74.664mm	57.923mm
3	0091616726 = 93.086mm	79.393mm	74.569mm	57.986mm
4	0091584724 = 93.255mm	79.543mm	74.697mm	58.001mm
5	0091616726 = 92.932mm	79.604mm	74.566mm	58.028mm

Laser machine Precitool was used to measure the cutters length with set of 400 basic. The system can automatically measure the five tool parameters: length, diameter, radius, and two corners. It has installed C.R.I.S. system, which allows measuring the maximum tool diameter. The system accuracy of < 2 micrometres, the installation error of + / - 1 mm.

The measuring machine to be used for measurement of metal working machine tools geometry parameters. Tools are checked by the suitability. The measuring machine Figure 2.5 is adapted to the manufacturing place, so you can quickly and accurately check processing tools.

Fig. 2.5. Measuring machine Precitool set basic 400 [21].

For the vibration and acoustic experiments were used Bruel & Kjaer Pulse 3560 system Figure 2.6, microphone Figure 2.7, 751 – 100 Endevco vibration sensor Figure 2.8.

Portable Pulse processing unit 3560 has a vibration and noise measurement and analysis system. It consists of four independent vibration and noise measuring four independent channels. Comes with 751-10, 751-100 accelerometer type and 4189-type microphones to 20 kHz. The software allows to perform FFT, CPB, and the intensity of the noise analysis and to create noise maps. The meter is used in conjunction with a computer, which collects measurement data and calculations performed.

Technical Specification: Frequency range: 0 – 25.6 kHz; Input Voltage: 7 range from 7.071 mVpeak to 7.071 mVpeak [21].

Microphone technical specification:

- Dynamic range: 16.5 – 134 dB;
- Frequency range: 20 – 20000 Hz;
- Inherent noise: 16.5 dB A;
- Lower limiting frequency – 3 dB, 12 Hz;
- Pressure coefficient – 0.01 dB/kPa;
- Sensitivity – 50 mV/Pa [8].

Diesella RT-0162 roughness meter technical specification:

- Roughness parameter: Ra, Rq, Rz, Rt, Rp, Rv, Ry, RS, RSm, RSk, Rz (JIS), R3z, Rmax,
- Measuring system: Metric mm, imperial inch
- Measuring range: Ra: 0.005 µm - 16 µm and Rz: 0.02 µm - 160 µm
- Pick-up measuring range: ±20 µm, ±40 µm, ±80 µm
- Cut-off length: 0.25 mm / 0.8 mm / 2.5 mm / Auto [20].

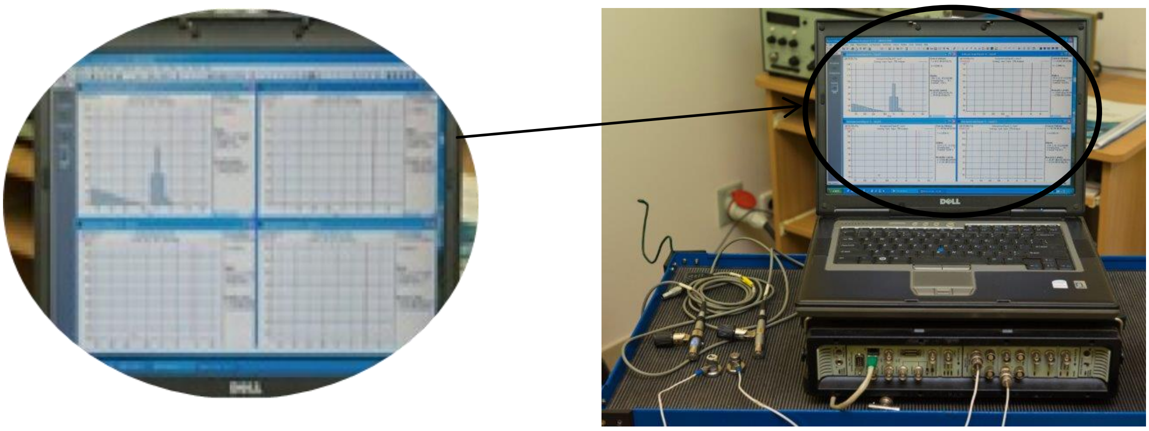


Fig. 2.6. Pulse Multi-analyser system type 3560

Fig. 2.7. Microphone up to 20 kHz

Fig. 2.8. Vibration sensor Endevco 751-100

After milling experiments were checked milled material surface roughness. It was used for surface roughness meter Diesella RT-0162, which is presented in Figure 2.9

Fig. 2.9. The surface roughness meter Diesella RT-0162

Roughness measurement process is shown in Figure 2.10.

Fig. 2.10. Milled surface roughness measurements procedure

Flowchart consists of five main parts: the x and y axes of vibration sensors, microphones, machine tool spindle and the data processing unit Figure 2.11.

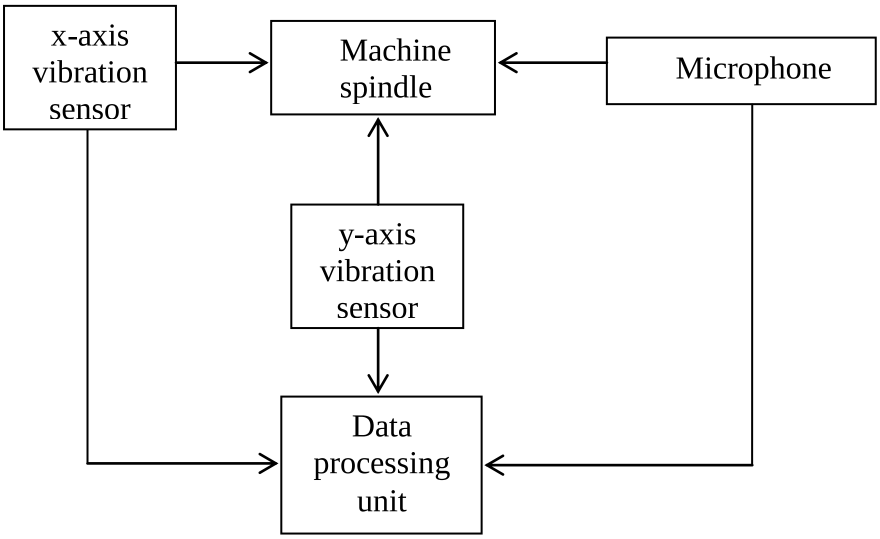


Fig. 2.11. Flowchart

3. EXPERIMENTAL DATA AND RESULTS

Measurements performed at processing of the product. Machining currently used new and worn cutter mill with the three cutting edges. Milled is steel product. Operating mode: the rotational speed of 1000 rev/min, cutting depth 2 mm, feed rate of 300 mm/min. Acoustic noise and vibration oscillogram and spectra are provided only 0 ... 800 Hz frequency band. All the measurement results are presented in Tables 2 and 3.

The experiment was carried out in three modes: free movement, new milling workpiece and worn cutters. Measurements available proceeding to perform CNC milling machine OPTI Mill F4TC tool tray insert cutter and set spindle rotation speed of 1000rev/min. The experiment was generated acoustic noise and vibration in the longitudinal direction oscillogram Figure 3.12 – 3.13 and the spectra of the frequency range of 0 Hz to 800 Hz Figure 3.14 – 3.15. As shown in Figure 4 spectrum frequency range 0 ... 800 Hz is visible in a small (2.67 mm/s^2) 16.6 Hz speed component. A similar component of the visible spectrum and the acoustic noise (43.8 dB). Measured machine tool spindle corps vibrations average value (TQM) – 152 mm/s^2 and measured sound pressure level of the average – 72.2 dB.

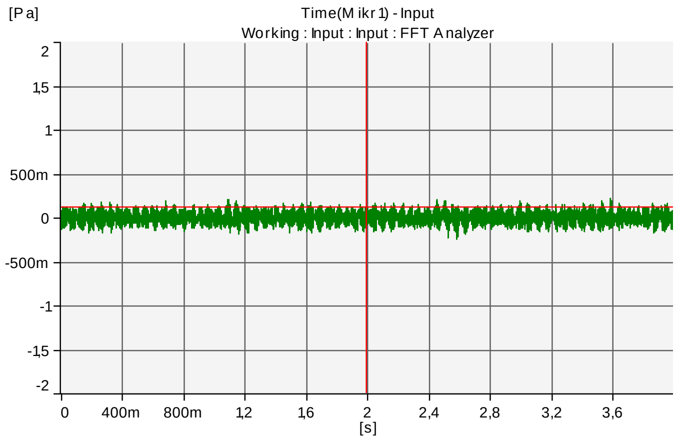


Fig. 3.1. Acoustic noise oscillogram. Free movement

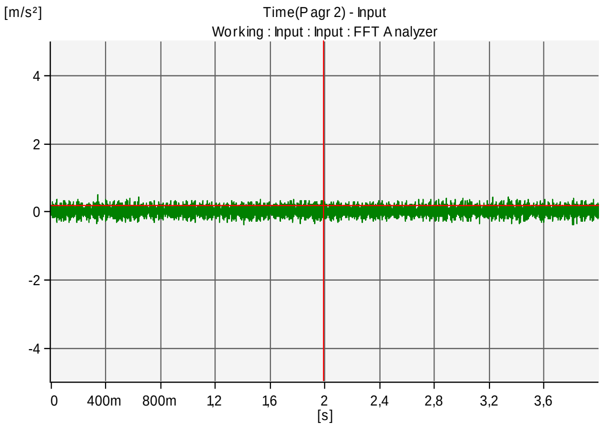


Fig. 3.2. The oscillogram of vibration in longitudinal direction. Free movement

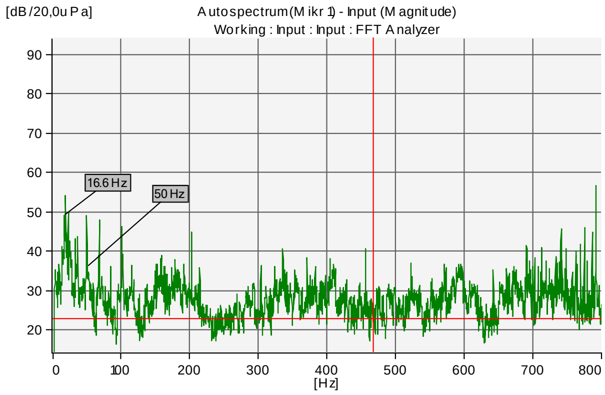


Fig. 3.3. Acoustic noise spectrum frequency range 0 ... 800 Hz. Free movement

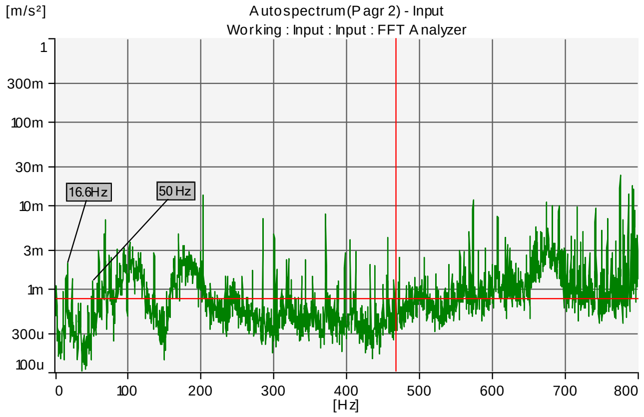


Fig. 3.4. The vibration in the longitudinal direction range of the frequency range of 0 ... 800 Hz. Free movement

3.1 Results with new cutter tool milling

The next stage of the experiment carried out at the new cutter mill and the steel workpiece milling operation. Operating mode is similar. Free movement: spindle rotation speed of 1000 rev/min, cutting depth of 2 mm, the feed rate of 300 mm/min. The measurement was recorded acoustic noise and vibration in the longitudinal direction oscillogram Figure 3.5 – 3.6 and the spectra of the frequency range of 0 Hz to 800 Figure 3.7-3.8.

As shown in Figure 8. Spectrum, frequency range 0 ... 800 Hz is visible elevated (35.9 mm/s^2) 16.6 Hz speed component. A similar component used of the visible spectrum and the acoustic noise (51.5 dB). These spectra saw milling cutting edges 50 Hz component which vibrations in the longitudinal direction is 73.2 mm/s^2, acoustic noise spectrum - 82.6 dB. Measured machine tool spindle corps vibrations average value (TQM) is 1.29 m/s^2, the measured sound pressure level of the average - 85.2 dB.

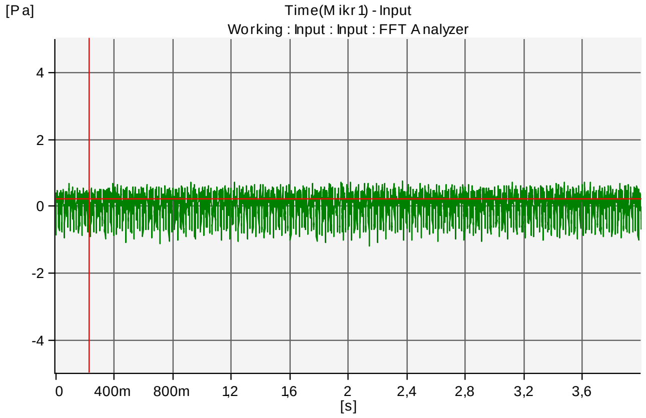


Fig. 3.5. Acoustic noise oscillogram. New cutter mill.

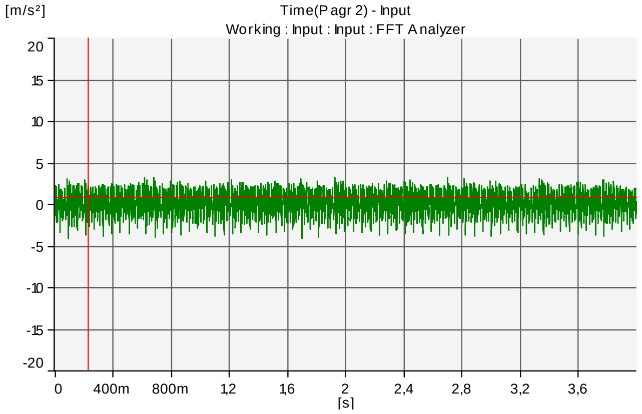


Fig. 3.6. The oscillogram of vibration in longitudinal direction. New cutter mill.

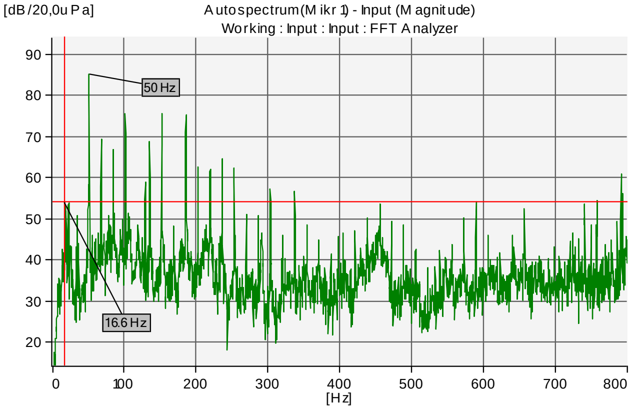


Fig. 3.7. Acoustic noise spectrum frequency range 0 ... 800 Hz. New cutter mill.

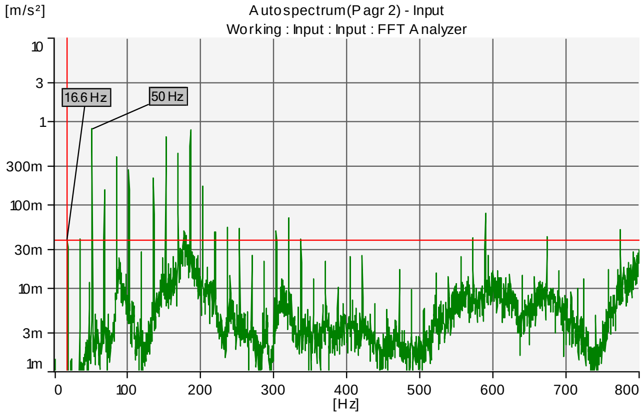


Fig. 3.8. Vibration in the longitudinal direction range of the frequency range of 0 ... 800 Hz. New cutter mill.

3.2 Results with worn cutter tool mill

The third stage of the experiment, a new milling cutter replaced in most worn. Milling machine operating mode settings are left unchanged: the spindle rotation speed of 1000 rev/min, cutting depth of 2 mm, the feed rate of 300 mm/min. Recorded acoustic noise and vibration in the longitudinal direction oscillogram and spectra of the frequency range from 0 to 800 Hz are shown in Figure 3.8 – 3.11. When routing template worn cutter Figure 3.9 – 3.10 written in oscillogram can see an increase in overall noise and vibration levels. Figure 3.11 shown acoustic noise in the spectrum of visible increased 16.6 Hz (56 dB) and 50 Hz (87.4 dB) components. Their increase can be seen in Figure 3.12 depicted vibration spectrum. Increase 16.6 Hz (60.1mm/s^2) and 50 Hz (1.0 m/s^2) component.

The fourth stage of the experiment is worn mostly cutters changed to No.5 cutter diameter Ø5 mm. Modes to keep the same. The written acoustic noise and vibration in the longitudinal x-direction and the oscillogram spectra over the frequency range of 0 to 6.4 kHz are shown in Figure 3.17 – 3.18. Routing template Ø5 cutter Figure 3.13 – 3.14 written in oscillogram can be seen in the increase in overall noise and vibration levels. Figure 3.17 – 3.18 shown with the acoustic noise level of the total visible spectra respectively 8.22 MPa and 29.7 MPa. Total acceleration level to 3.75 m/s^2 and 6.13 m/s^2 Figure 3.15 – 3.16

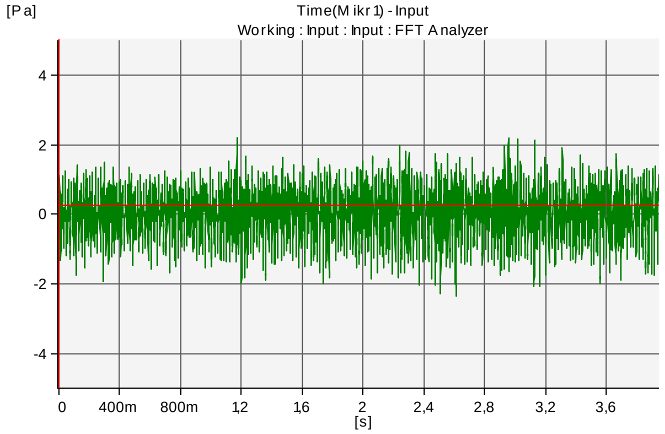


Fig. 3.9. Acoustic noise oscillogram. Worn cutter

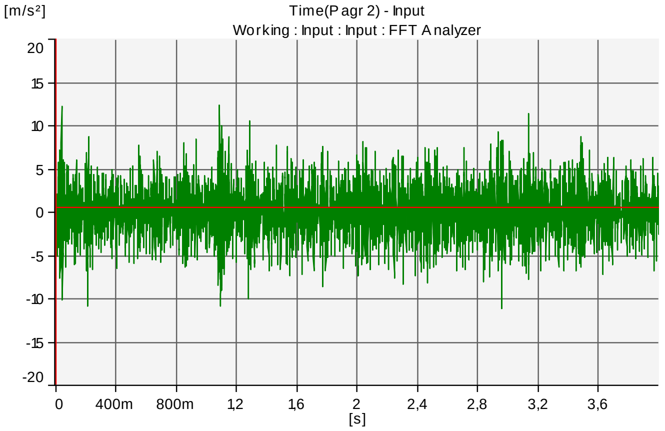


Fig. 3.10. The oscillogram of vibration in longitudinal direction. Worn cutter

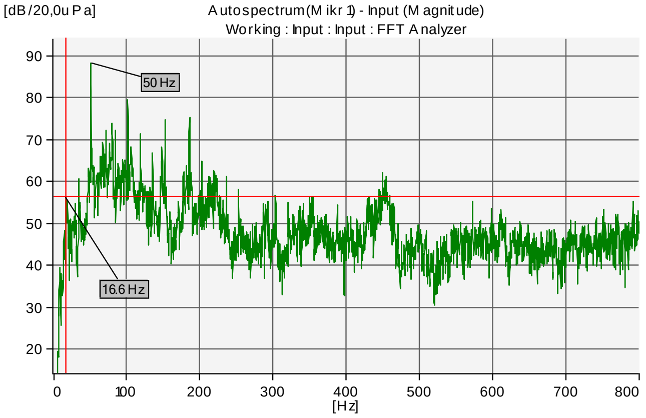


Fig. 3.11. Acoustic noise spectrum frequency range 0 ... 800 Hz. worn cutter mill

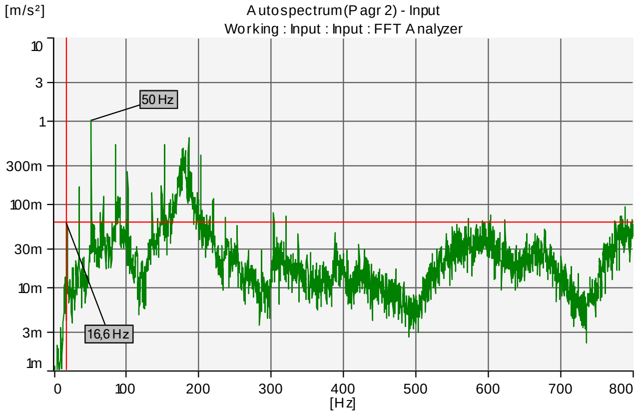


Fig. 3.12. The vibration in the longitudinal direction range of the frequency 0 ... 800 Hz. worn cutter mill

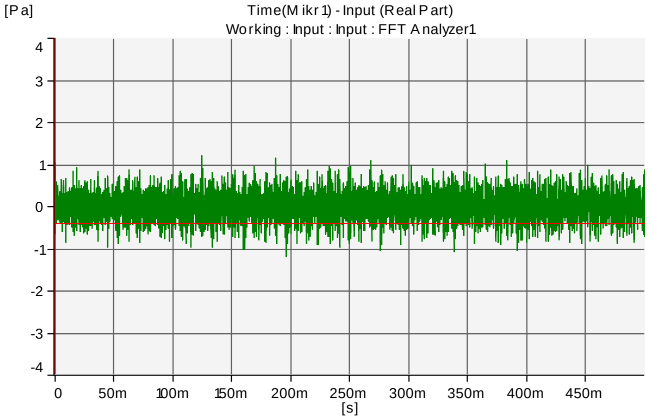


Fig. 3.13. Tool No.5, Ø5mm diameter cutters oscillogram acoustic noise in the X direction

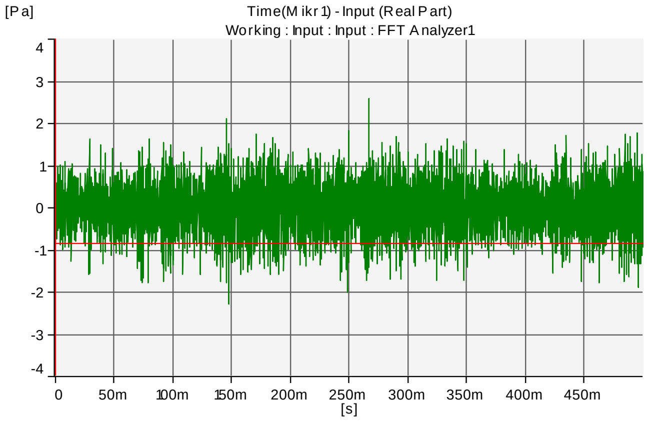


Fig. 3.14. No.3, Ø5 mm milling oscillogram acoustic noise in the X direction

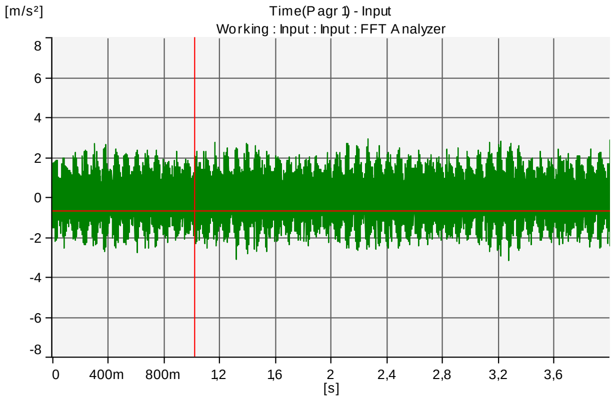


Fig. 3.15. No.5, Ø5 mm milling acceleration oscillogram in the X direction

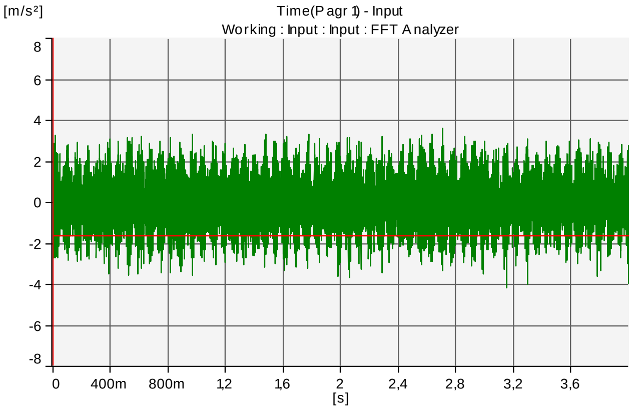


Fig. 3.16. No.3, Ø5 mm milling acceleration oscillogram in the X direction

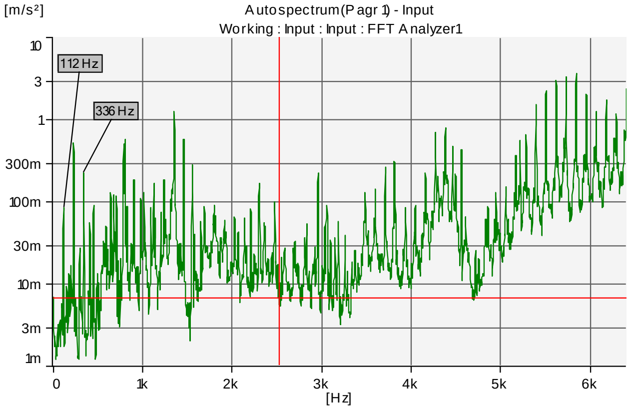


Fig. 3.17. No.5, Ø5 mm diameter cutter oscillogram acceleration in the X direction frequency range 0 ... 6.4 kHz.

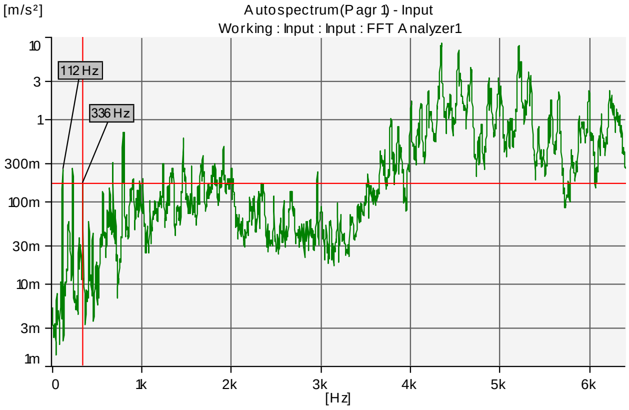


Fig. 3.18. No.3, Ø5 mm diameter cutter oscillogram acceleration in the X direction frequency range 0 ... 6.4 kHz.

3.1 – 3.8 tables of machine spindle body vibration levels (TQM), and sound pressure levels are measured over the frequency range 0 ... 800 Hz and the frequency range 0 ... 6.4 kHz.

Table 3.1 Machine spindle housing vibration values (TQM) and sound pressure levels

Measurement No.	Frequency range 0 ... 800 Hz			Frequency range 0 ... 6.4 kHz		
	Acceleration 1	Acceleration 2	Microphone	Acceleration 1	Acceleration 2	Microphone
	m/s^2	m/s^2	dB	m/s^2	m/s^2	dB
	Free movement					
1	0.21	0.12	70.7	0.26	0.20	71.6
2	0.21	0.12	72.5	0.28	0.18	74.2
3	0.22	0.12	73.3	0.27	0.18	77.2
	New cutter mill					
1	0.40	1.29	85.3	1.10	1.91	88.1
2	0.44	1.22	85.1	1.24	1.93	87.7
3	0.41	1.18	84.4	1.19	1.95	87.3
	Worn cutter mill					
1	1.24	2.75	91.3	2.87	6.57	94.2
2	1.12	2.60	90.5	2.50	3.93	92.7
3	1.10	2.58	90.7	2.91	4.77	93.7

Table 3.2 Machine spindle housing vibration values (TQM) and sound pressure levels (cutter Ø5)

Measurement No.	Frequency range 0 ... 800 Hz			Frequency range 0 ... 6.4 kHz		
	Acceleration 1X	Acceleration 2X	Microphone	Acceleration 1X	Acceleration 2Y	Microphone
	m/s^2	m/s^2	dB	m/s^2	m/s^2	dB
	Free movement					
	0,21	0,12	70,7	0,26	0,20	71,6
Cutter mill ø05, steel workpiece P1 S6050 rev/min T517 mm/min S1mm;						
1	1.47	0.68	81.1	22.5	11.1	86.6
2	1.05	0.89	80.8	3.68	3.09	82.2
3	1.18	0.53	77.8	29.7	21.8	90.0
4	0.97	0.66	80.3	17.9	8.91	84.6
5	0.87	0.66	80.9	8.22	7.95	83.6

Table 3.3 Machine spindle housing vibration values (TQM) and sound pressure levels (cutter Ø10)

Measurement No.	Frequency range 0 ... 800 Hz			Frequency range 0 ... 6.4 kHz		
	Acceleration 1X	Acceleration 2X	Microphone	Acceleration 1X	Acceleration 2Y	Microphone
	m/s^2	m/s^2	dB	m/s^2	m/s^2	dB
	Free movement					
	0.21	0.12	70.7	0.26	0.20	71.6
Cutter mill ø010, steel workpiece P1 S3630 rev/min T517 mm/min S1mm;						
1	1.19	0.88	81.8	149.0	125.0	99.2
2	1.06	0.95	79.8	135.0	126.0	96.0
3	0.71	0.42	78.1	151.0	61.7	98.3
4	0.92	0.52	80.1	110.0	105.0	98.7
5	3.88	2.31	86.4	45.1	47.4	94.6

Table 3.4 Machine spindle housing vibration values (TQM) and sound pressure levels (cutter Ø16)

Measurement No.	Frequency range 0 ... 800 Hz			Frequency range 0 ... 6.4 kHz		
	Acceleration 1X	Acceleration 2X	Microphone	Acceleration 1X	Acceleration 2Y	Microphone
	m/s^2	m/s^2	dB	m/s^2	m/s^2	dB
	Free movement					
	0.21	0.12	70.7	0.26	0.20	71.6
Cutter mill ø016, steel workpiece P1 S2270 rev/min T517 mm/min S1mm;						
1	3.29	1.66	89.7	6.42	4.62	90.5
2	3.22	1.21	88.3	4.94	3.36	88.6
3	2.20	0.68	85.0	3.29	2.20	85.7
4	1.80	0.82	80.7	2.82	2.11	82.3
5	2.53	1.11	84.8	3.15	2.31	84.9

Table 3.5 Vibration value (TQM) and sound pressure levels at 112Hz and 337Hz frequency (Cutter Ø5)

Cutter No.	Cutter diameter Ø5 mm workpiece steel - S					
	Rotation speed 112 Hz (spindle)			Cutter 3 cutting edges 337 Hz frequency		
	X	Y	Microphone	X	Y	Microphone
	m/s^2	m/s^2	dB	m/s^2	m/s^2	dB
1	0.39	0.087	79.9	0.099	0.117	67.7
2	0.195	0.12	79.2	0.16	0.065	65.9
3	0.246	0.021	72.9	0.158	0.132	71.8
4	0.128	0.094	77.5	0.159	0.114	69.7
5	0.087	0.166	79.9	0.225	0.076	66.8

Table 3.6 Vibration value (TQM) and sound pressure levels at 112Hz and 337Hz frequency (Cutter Ø10)

Cutter No.	Cutter diameter Ø10 mm workpiece steel - S					
	Rotation speed 112 Hz (spindle)			Cutter 3 cutting edges 337 Hz frequency		
	X	Y	Microphone	X	Y	Microphone
	m/s^2	m/s^2	dB	m/s^2	m/s^2	dB
1	0.427	0.083	68.4	0.745	0.631	80.4
2	0.258	0.13	70.6	0.401	0.555	77.2
3	0.266	0.066	56.3	0.41	0.136	77.2
4	0.286	0.071	75.5	0.469	0.138	76.7
5	0.504	0.255	82.3	0.831	0.246	78.1

Table 3.7 Vibration value (TQM) and sound pressure levels at 112Hz and 337Hz frequency (Cutter Ø16)

Cutter No.	Cutter diameter Ø16 mm workpiece steel - S					
	Rotation speed 112 Hz (spindle)			Cutter 3 cutting edges 337 Hz frequency		
	X	Y	Microphone	X	Y	Microphone
	m/s^2	m/s^2	dB	m/s^2	m/s^2	dB
1	0.254	0.019	84.6	0.844	0.315	83.4
2	0.192	0.062	81.8	0.979	0.313	82.2
3	0.267	0.08	76	0.598	0.148	77
4	0.082	0.03	69.8	0.571	0.166	76.3
5	0.103	0.045	71.8	1.12	0.245	81.3

Table 3.8 Machine spindle housing vibration average value (TQM) and mean sound pressure levels

	Frequency range 0 ... 800 Hz			Frequency range 0 ... 6.4 kHz		
	Acceleration 1	Acceleration 2	Microphone	Acceleration 1	Acceleration 2	Microphone
	m/s^2	m/s^2	dB	m/s^2	m/s^2	dB
Free movement	0.21	0.12	72.2	0.27	0.18	74.3
New cutter mill	0.42	1.23	84.9	1.18	1.93	87.7
Worn cutter mill	1.15	2.64	90.8	2.76	5.09	93.5
ø5 cutter mill	1.11	0.7	80.2	16.4	10.6	85.4
Ø10 cutter mill	1.55	1.02	81.2	118.02	93.02	97.4
Ø16 cutter mill	2.61	1.1	85.7	4.12	2.92	86.4
Signal change (worn and new milling cutter signal ratio)	2.76	2.15	1.97	2.35	2.64	1.95

The measurements carried out were determined sound pressure levels and the machine tool spindle corps vibration dependence on milling quality. These dependencies are shown in the (Figure 3.19 – 3.20) the results shows, that the analysis of fundamental frequencies of 16.6 Hz - spindle speed, and 50 Hz - milling cutting edge frequency correlated both vibration and acoustic noise measured result.

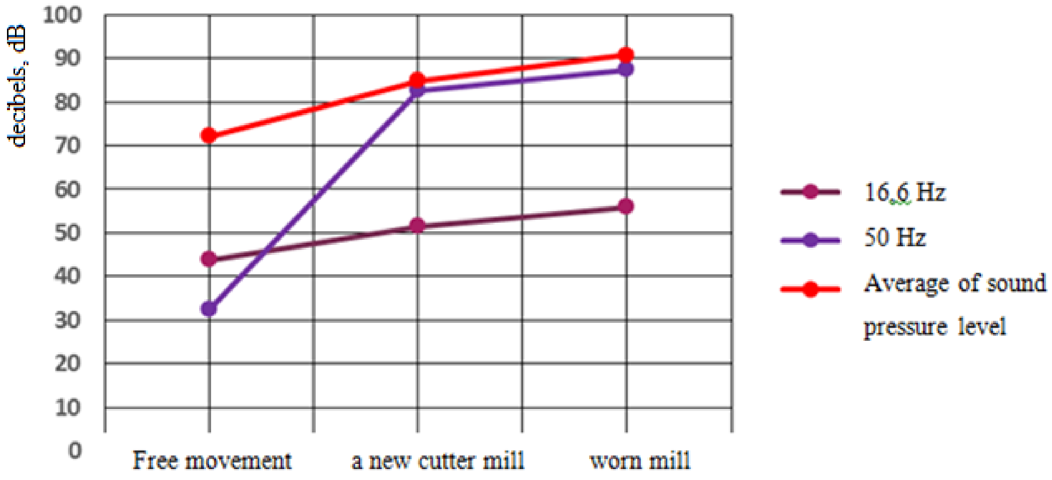


Fig. 3.19. CNC machine sound level dependence from milling cutters quality

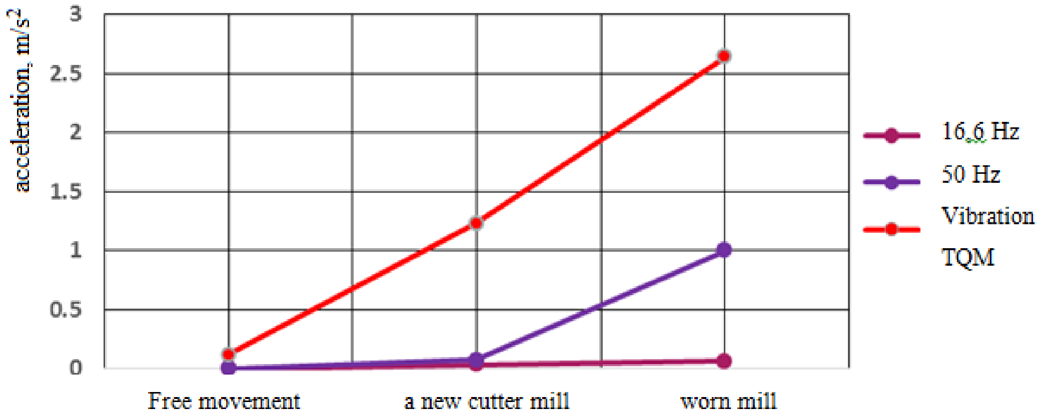
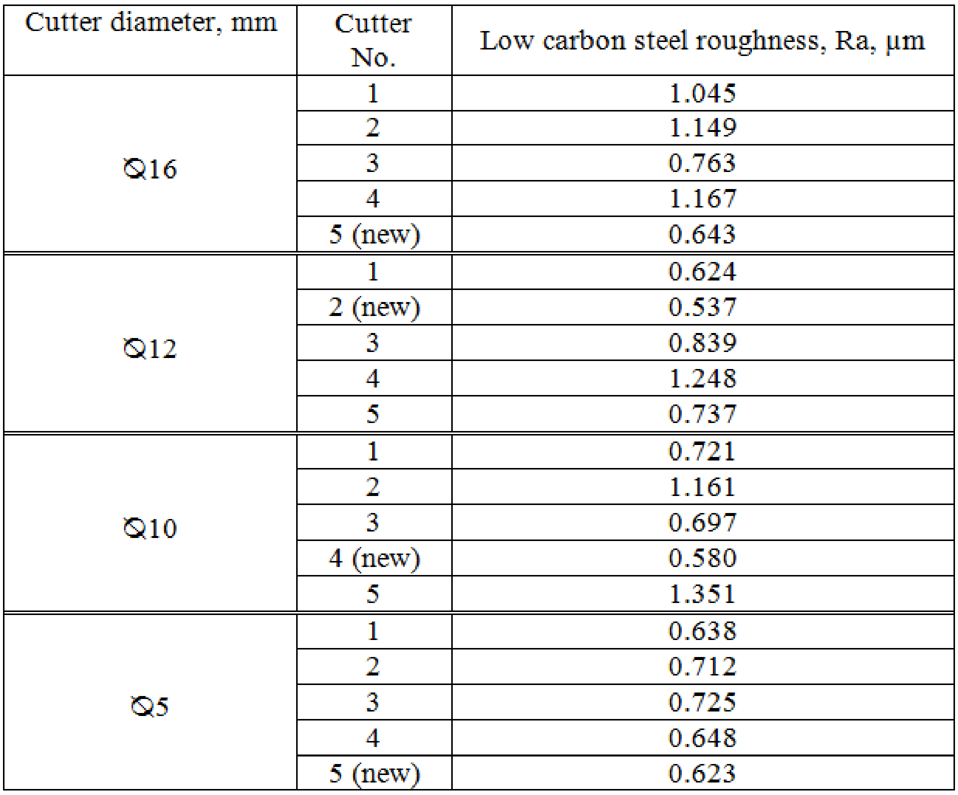


Fig. 3.20. CNC machine vibration, acceleration dependence from milling cutters quality

Surface roughness results added to Table 3.9.

Table 3.9 Results of surface roughness measurements.



Cutter diameter, mm	Cutter No.	Low carbon steel roughness, Ra, µm
Ø16	1	1.045
	2	1.149
	3	0.763
	4	1.167
	5 (new)	0.643
Ø12	1	0.624
	2 (new)	0.537
	3	0.839
	4	1.248
	5	0.737
Ø10	1	0.721
	2	1.161
	3	0.697
	4 (new)	0.580
	5	1.351
Ø5	1	0.638
	2	0.712
	3	0.725
	4	0.648
	5 (new)	0.623

Next, graphically presented different diameters (Ø5, Ø10, Ø16) cutting milling acceleration dependence on the speed. Graphs shows two different curves, which refer to the cutting direction. X - Vibration measuring point in the longitudinal (x-direction); Y - vibrations of the measuring point in the transverse (y-direction).

During the experiment were assessed three parameters: vibration measuring point in the longitudinal direction, vibrations of the measuring point in the transverse direction and the overall CNC machine noise level.

Research was executed with aluminum, low carbon steel and stainless steel workpieces. Oscillogram of aluminium and stainless steel was presented in appendixes (3 appendixes).

Figure 3.23 – 3.29 value a – acceleration, m/s^2.

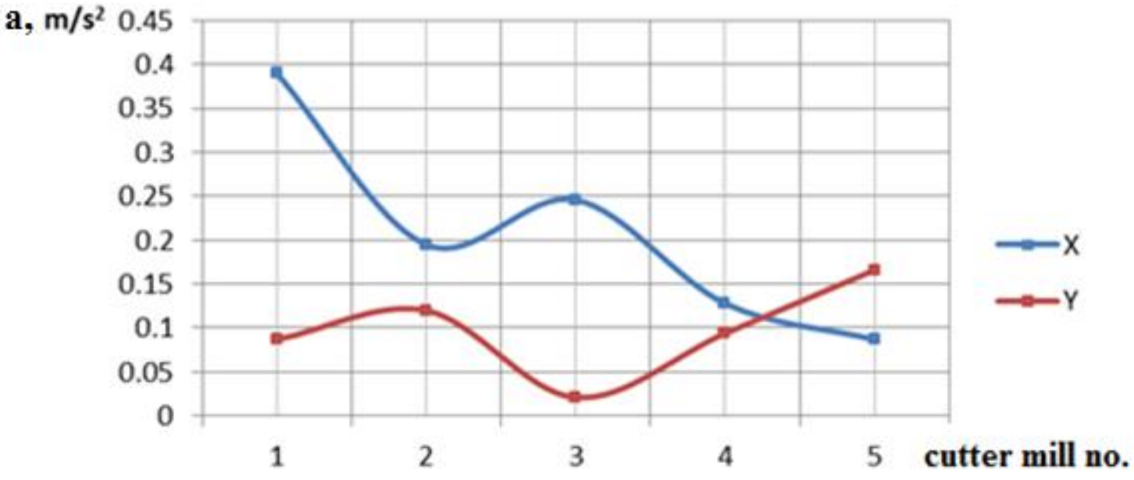


Fig. 3.23. Ø5 diameter milling cutting edges frequency range 112Hz

Figure 3.23 present the spindle rotation frequency component amplitude (112 Hz), y-axis direction does not reflect the quality of milling. No.5 is a new cutter and cutter mill No.4 is the worst of the five study Ø5 mm cutters. The change of these components presented in x curve.

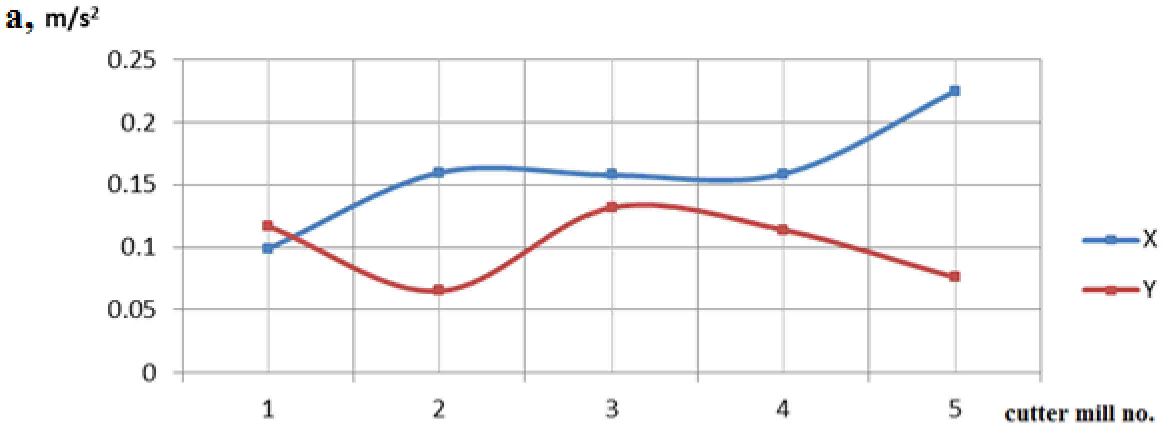


Fig. 3.24. Frequency range 337 Hz of the cutters cutting edge diameter Ø5

Figure 3.24 present the spindle rotation frequency component amplitude (337 Hz), y-axis direction does reflect the quality of milling. Cutter mill No.5 acceleration is low and differs from the cutter No.4, which is the worst. The change of these components did not present in x curve.

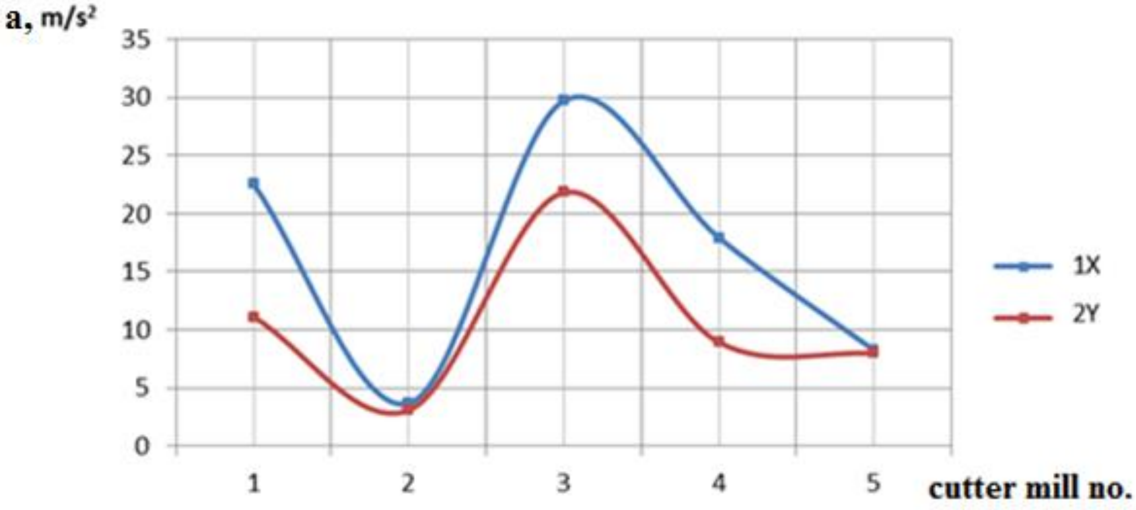


Fig. 3.25. Vibration amplitude of the frequency range from 0 to 6.4 kHz dependence from cutter condition (cutter Ø5)

Figure 3.25 present the vibration acceleration values fully meets with existing milling quality frequency range from 0 to 6.4 kHz. The data of presented schedule can rely on. You only have to specify dependencies in further experiments. Curves shows, that cutting with new cutter mill in both directions acceleration is the same.

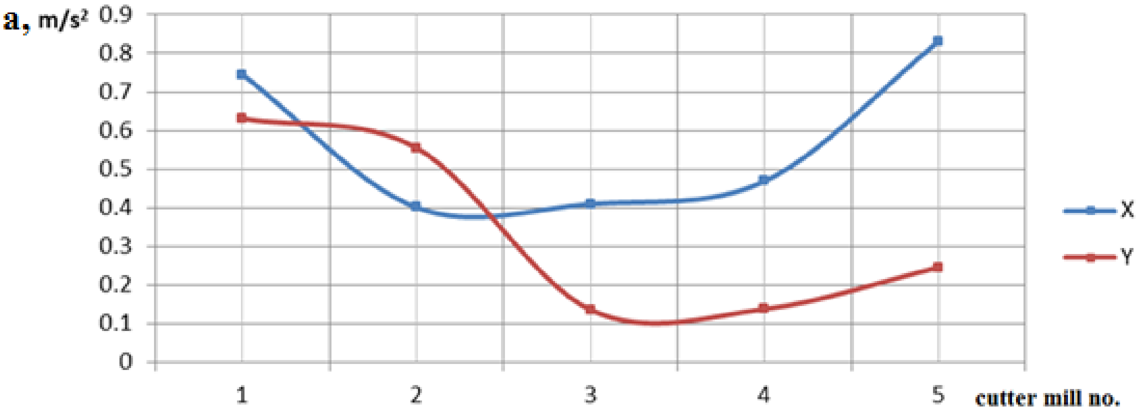


Fig. 3.26. Frequency range 337 Hz of the cutters cutting edge diameter Ø10

Figure 3.26 present that the spindle rotation frequency component amplitude (337 Hz), x-axis direction does reflect the quality of milling. No.4 is a new cutter and cutter mill No.5 is the worst of the five study Ø5 mm cutters. The change of these components showed in x and y curve.

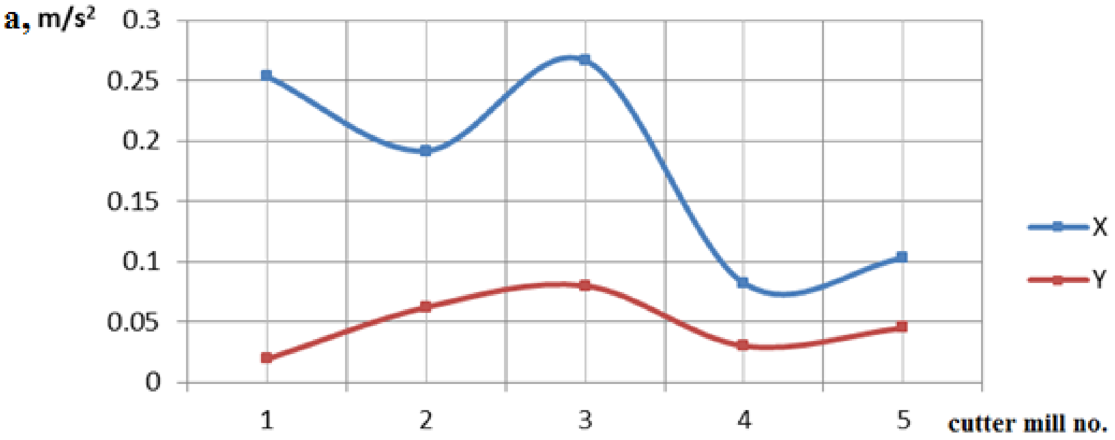


Fig. 3.27. Frequency range 46 Hz of the cutters cutting edge diameter Ø16

Figure 3.27 present that the spindle rotation frequency component amplitude (46 Hz), x-axis direction does reflect the quality of milling. Ø16 diameter cutter No.5 is a new cutter and cutter mill No.1 is the worst of the five study Ø16 mm cutters. The change of these components showed in x curve.

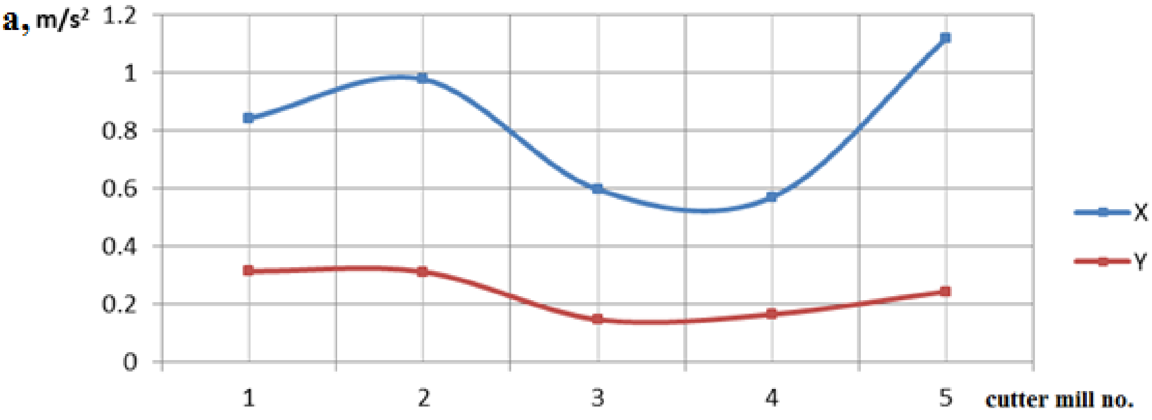


Fig. 3.28. Frequency range 138 Hz of the cutters cutting edge diameter Ø16

Figure 3.27 present that the spindle rotation frequency component amplitude (138 Hz), x-axis direction does reflect the quality of milling. Visible only a negligible change in acceleration and cannot rely on this graph. Need to do more experiments in this frequency range.

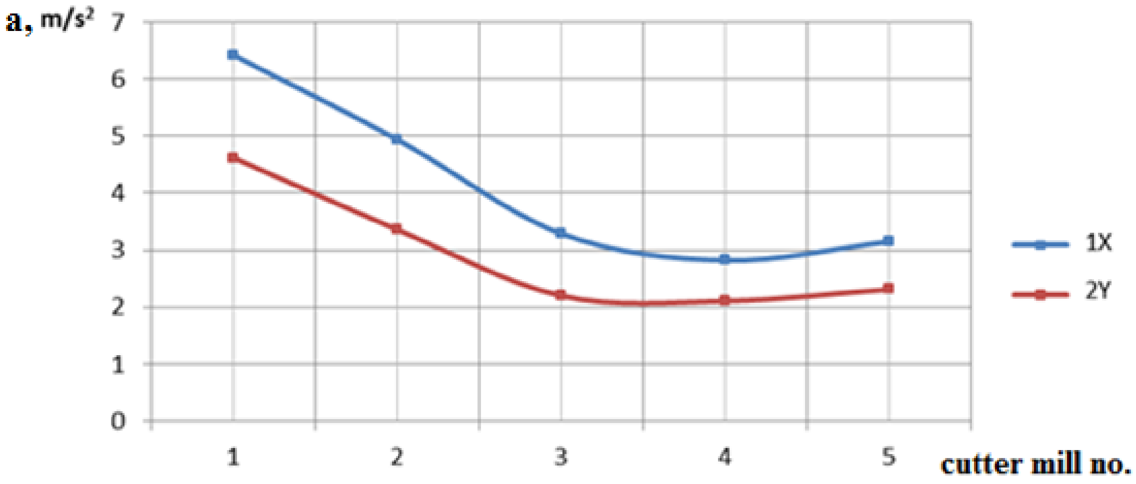


Fig. 3.29. Vibration amplitude of the frequency range from 0 to 6.4 kHz dependence from cutter condition (cutter Ø16)

Figure 3.29 present the vibration acceleration values fully meets with existing milling quality frequency range from 0 to 6.4 kHz. The data of presented schedule can rely on. The new cutter mills No.5 acceleration on both axes are similar and differ significantly from the change in acceleration cutter mill No.1, which is the worst of the experiment.

4. RESEARCH OF BEARING DIAGNOSTIC DATA AND RESULTS

The data analysis was accomplished using Pulse Multi-analyser system type 360C.

Non-contact displacement transducers measure the vibration (motion) of the object (in our case – spindle) in respect of transducer. The time history of the machine spindle vibrations are presented in Figure 4.1 (milling machine). By measuring spindle vibrations in two mutually orthogonal directions, present the orbit (motion) of spindle in space.

Fig. 4.1. Present oscillogram of spindle vibration in CNC milling machine. Machine works on free movement mode. Vibration amplitude is 66 µm

The measurements were made while the machines were operating in free movement mode and during work-piece processing. The spectral analysis of the vibrations was performed and the spectra determined. The characteristic spectra of the machine spindle vibrations are presented in Figure 4.2 (milling machine).

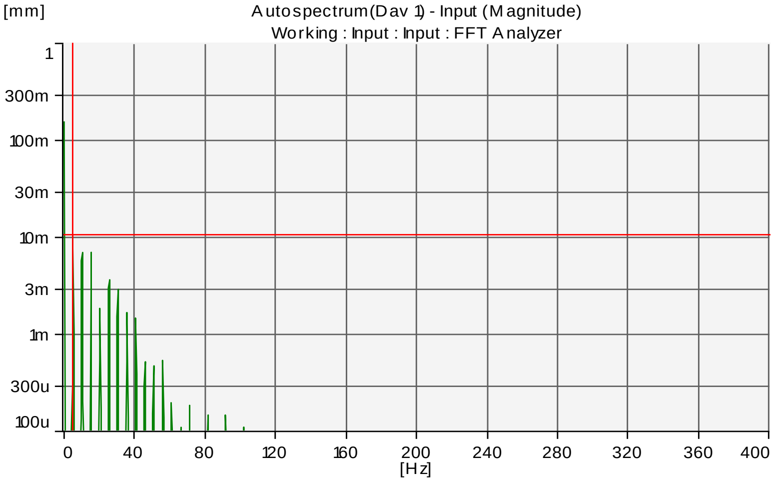


Fig. 4.2. Present spectrum of spindle vibration in CNC milling machine. The machine is operating in free movement mode making 300 rev/min.

Below presented the milling spindle orbits Figure 4.3 – 4.6.

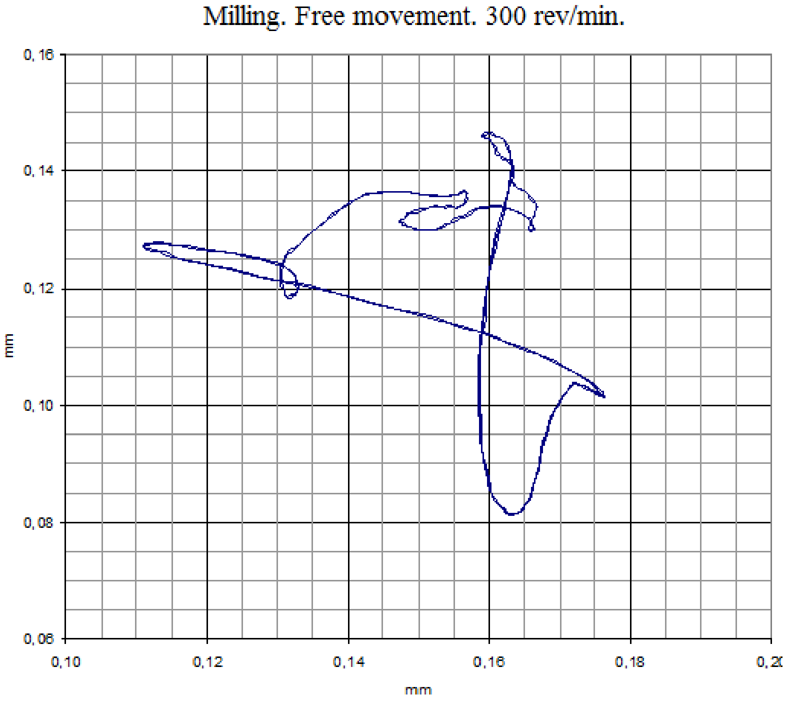


Fig. 4.3. Milling machine tool spindle orbit, free movement 300 rev/min.

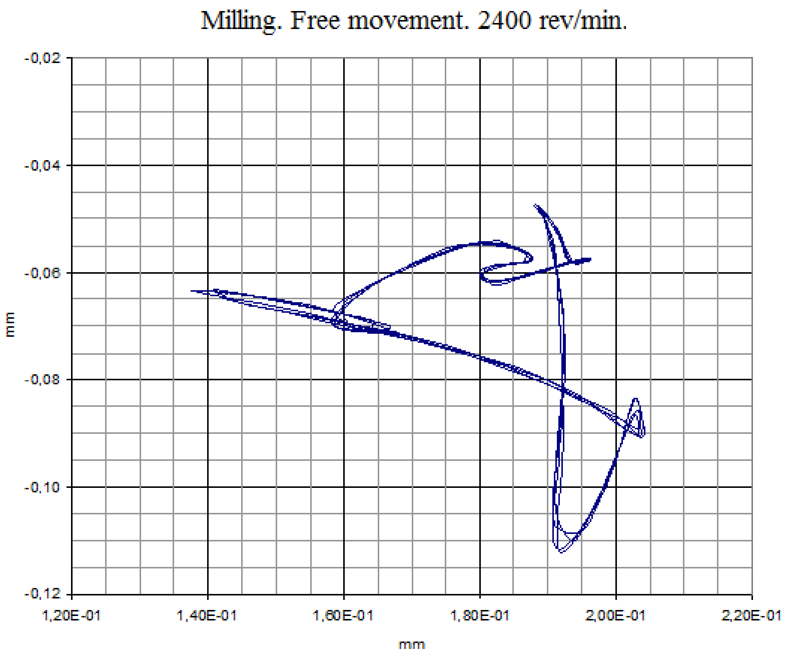


Fig. 4.4. Milling machine tool spindle orbit; free movement 2400 rev/min.

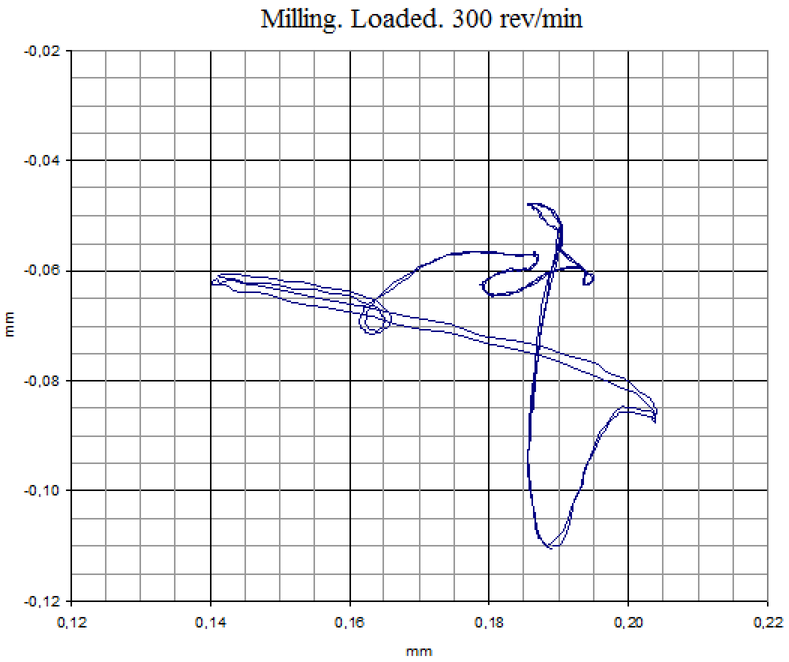


Fig. 4.5. Milling machine tool spindle orbit; working movement 300 rev/min.

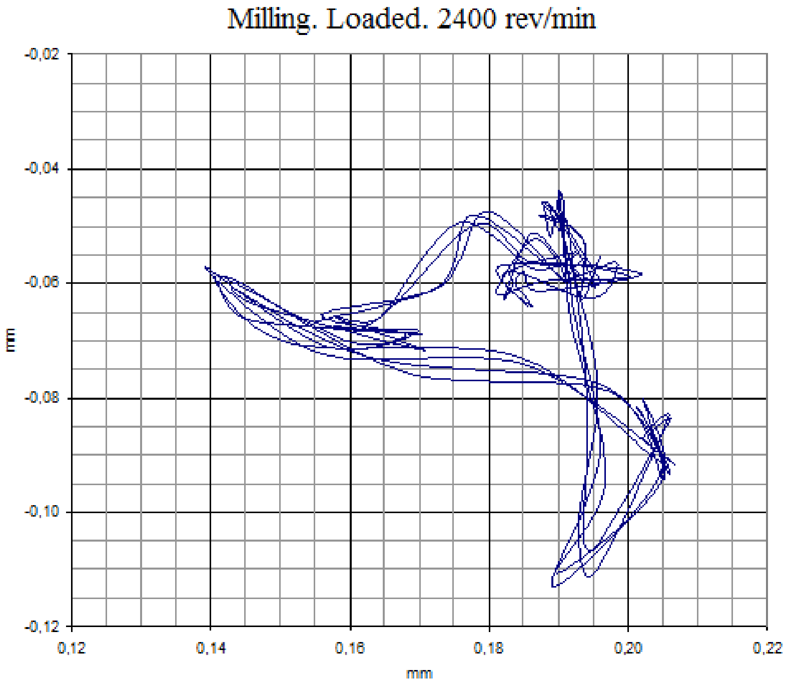


Fig. 4.6. Milling machine tool spindle orbit; working movement 2400 rev/min.

The purpose of the experimental research – to test possibilities of spectral and orbital vibration diagnostics methods for machine spindle diagnostics objective is reached. The applied methods provide specific information about the technical condition of the mentioned objects. The results allow:

1. Solving technical condition stability issues;
2. Seeing the correlation between the processed work piece peak to peak value spectrum components change;
3. Assuming that the increase or stability of the second harmonics value might prelate to the degradation process of the spindle bearings;
4. Claiming that graphical interpretation of the results (time history, spectra and orbits) are sufficiently informative in qualitative and quantitative point of view;
5. Noticing that although the vibration orbits of the milling machine were obtained without considering the profile of the surface and thus their form does not remind the circle, that orbits provide useful diagnostic information. The scattering of their curves represents the large random vibration of the gripping device with the fixed tool and its direction.

The further research could be associated with the confirmation of the results repeatability, consolidation of systematic attitude to the machine elements monitoring, investigation of the machine group, creation and approbation of the effective and cheap control instrument prototype.

CONCLUSIONS

1. During research the monitoring system was developed and analysed. This system allows observe and record CNC machine status, i.e cutting tool's wearing process, bearing state, working time and downtime duration during the shift. Analysis shows, that with the help of this system it is possible to ensure smooth cutting process. Also, the system gives possibility to evaluate the state of cutting tool and bearing, as it informs operator of necessity of changing tools, or fulfilling the maintenance of CNC machine. It helps to reduce downtime and spoilage volume of machining process and to increase labour productivity and efficiency.

2. Tool wear process in the CNC milling machine was investigated. For the experiment 4 different milling cutters with different diameters (5, 10, 12 and 16 mm) were selected for low carbon steel, aluminium and stainless steel manufacturing. The manufacturing modes for each milling cutter were calculated and adapted in the processing programme. Piezoelectric accelerometers and microphone were selected for vibrations and sound level measurements.

3. Vibrations change can be seen during milling of steel workpiece in every measured parameter (vibrations acceleration, frequencies of cutting edges, level of acoustic noise). The biggest change was recorded while measuring milling cutter edges under the 337 Hz frequency as a component of sound pressure level and vibration acceleration (diameter of the cutter Ø10). The change of sound pressure level is about 78.1 dB and vibration acceleration in X direction – 0.83 m/s^2.

4. The experimental results showed, that working with five millimetre diameter cutter mill, starting “run – in” time is noticeable (2 to 5 min), during which vibration amplitude decreases, later, gradually increases.

5. While milling stainless steel workpiece, the biggest change was recorded measuring cumulative vibrations acceleration in X and Y directions under the frequency band of 6 kHz. The changes of 121 Hz frequency component's sound pressure level and vibration acceleration of milling tool's cutting edges were negligible compared with carbon steel machining: in Y direction – 0.4 m/s^2 and in X direction – 0.7 m/s^2 . More significant change is observed while measuring sound pressure level. This change is about 6.3 dB.

6. During the experiments a relatively large scattering of measurement results was obtained. It was noticed working with all cutter mills. Probably such results can be affected by material structure of workpiece, operating mode, tool's quality and other factors. Whereas experiments were done with variety of metals and milling tools, it can be concluded, that vibration and acoustic parameters can characterise the quality of cutting tool. According to obtained results, limit values of vibration parameters can be determined.

7. The biggest change was obtained by measuring cutting edges frequency's components in X and Y directions. This frequency's component the most reflects tool wear rate, even if the change is not significant. The research shows that the graphic (oscillograms, spectrum and orbits) interpretation of the results are sufficiently informative to the qualitative and quantitative point of view.

8. Experiments showed, although cutting machine spindle vibration orbits were obtained by excluding surface profile and so their shape is distant from the circle, but the orbits provide useful diagnostic information. Their curves scattering testifies about large random vibration and its direction of the spindle and cutter mills.

REFERENCES

1. Shared and service-oriented CNC machining system for intelligent manufacturing process. Previewed 2017-01-23 Access through internet: http://link.springer.com/article/10.3901/CJME.2015.1010.119

2. Volkovas V. Neardomieji techninės diagnostikos metodai. Technologija. 2015, 407 p.

3. Noise, Vibration, and Harshness. Previewed 2017-02-14 Access through internet: http://www.globalspec.com/learnmore/test_measurement_equipment/electrical_electronic_test_equipment/noise_vibration_harshness_nvh_test_equipment

4. Schaffler group industrial. Rolling bearing damage. Recognision of damage and bearing inspection. Status 2001, p.76

5. Tatsubono M., Banda N. Sound and vibration in rolling bearings. NSK Basic Technology Reserch and development Center [article]. 2001, [previewed 2017-04-02]. Access through internet: http://www.nsk.com/

6. Volkovas V., Žiedelis S. Mechaninių sistemų techninė diagnostika ir monitoringas: Mokomoji knyga. Technologija, 2005, 73 p.

7. The different types of microphones and their Uses. Previewed 2017-01-25 Access through internet: https://www.gearank.com/articles/types-of-mics

8. Microphones specification. Previewed 2017-01-10 Access through internet: http://www.rode.com/microphones/

9. Types of Microphones. Previewed 2017-02-12 Access through internet: https://www.homebrewaudio.com/what-are-the-different-types-of-microphones/

10. Piezoelectric Sensors Information. Previewed 2017-02-12 Access through internet: http://www.globalspec.com/learnmore/electrical_electronic_components/passive_electronic_components/piezoelectric_devices/piezoelectric_sensors

11. Accelerometer Basics. Previewed 2017-02-12 Access through internet: https://learn.sparkfun.com/tutorials/accelerometer-basics

12. Automated Data Processing. Previewed 2017-02-14 Access through internet: http://learn.org/articles/What_is_Automated_Data_Processing.html

13. Noise, Vibration, and Harshness. Previewed 2017-02-14 Access through internet: http://www.globalspec.com/learnmore/test_measurement_equipment/electrical_electronic_test_equipment/noise_vibration_harshness_nvh_test_equipment

14. Types of Tool Wear. Previewed 2017-02-14 Access through internet: http://www.mecholic.com/2016/02/types-of-tool-wear-flank-crater-and-corner-wear.html

15. Šnurovas A., Volkovas V. Analythical Simulation of Machine Tool Spindle Vibrations Due to Bearing Faults. Proceedings of 19th International Conference Mechanika, Kaunas, 24-25 April, 2014, p.238-242.

16. Yuzong Cao. Modeling of high-speed machine-tool spindule systems. University of British Columbia: 2006, p.140

17. Brüel & Kjaer Sound and Vibration Measurement. Previewed 2017-02-23 Access through internet: https://www.bksv.com/en/products/transducers/acoustic/microphones/microphone-preamplifier-combinations/4189-A-021

18. Surface roughness tester TB-220. Previewed 2017-02-14 Access through internet: http://www.moris.lt/en/specialized-equipment/metal-testing-equipment/roughness-gauges/surface-roughness-tester-tb-220?showall=1

19. Šnurovas A., Volkovas V. Analythical Simulation of Machine Tool Spindle Vibrations Due to Bearing Faults. Proceedings of 19th International Conference Mechanika, Kaunas, 24-25 April, 2014, p.238-242.

20. Diesella RT-0162 roughness meter. Previewed 2017-03-22 Access through internet: http://www.building-supply.dk/supplement/view.html?id=3978

21. Measuring machine Precitool set 400 basic. Previewed 2017-03-22 Access through internet: https://www.precitool.de/#&panel1-1

22. Research equipment. Previewed 2017-03-22 Access through internet: https://apcis.ktu.edu/lt/

23. Vibration sensors. Previewed 2017-03-22 Access through internet: http://www.aimil.com/RESOURCES/RESOURCEFILE/373_Vibration_Sensor.pdf

24. Monitoring: Envelope Signal Processing. Using Envelope Signal Processing in Vibration Monitoring of Rolling Element Bearings. SKF Realiability Systems, 2009, 14p.

25. Kiral Z., Karagulle H. Simulation and analysis of vibration signals generated by rolling element bearing with defects. Tribology International Vol. 36, 2003, p.667-678

26. Tandon N., Choudhury A. An analytical model for the prediction of the vibration response of rolling element bearings due to a localized defect. Journal of sound and vibration Vol.205,1997, p.275-292

APPENDIXES

1 appendix. CNC machine processing program

```
%_N_10P_MPF
;$PATH=/_N_WKS_DIR/_N_RESEARCH_0321_WPD
;x FROM LEFT
;y FURTHER EDGE
;z UPPER PART
DEF REAL GIL, DELTA, GIL_N
MSG ("16MM CUTTER MILL")
;CUTTER
:2 T6
M06
G0 G17 G54 G90 G94 X10. Y10. S1800 F2000 D1
Z100 M3 M51
GIL=-1
DELTA=1
GIL_N=0
WHILE GIL_N<>GIL
GIL_N=GIL_N+DELTA
IF GIL_N>GIL
GIL_N=GIL
ENDIF
Z=-GIL_N+0.5
G1 Z=-GIL_N
G1Y-124
G0 z20
G0 X10. Y10.
ENDWHILE
G0 Z50.
MSG
G0 G53 D0 Z0 M5 M9
M30
```

2 appendix. CNC milling machine modes calculation

An engine speed is calculated:

$$n = \frac{V_c \cdot 1000}{\pi \cdot D} \text{ rev/min;} \qquad (2.1)$$

n − speed, rev/min; Vc −cutting speed m/min; π =3.14; D − tool diameter, mm.

Machine table feed rate is calculated:

$$f_v = n \cdot z \cdot f_z \text{ mm/min;} \qquad (2.2)$$

F_v – feed, mm/min; n – speed, rev/min; z – milling cutting surface number; f_z – the cutting feed per surface, mm/rev;

CNC machining parameter calculation example:

$$n = \frac{100 \cdot 1000}{3.14 \cdot 12} = 2654 \text{ rev/min;}$$

$$f_v = 2654 \cdot 3 \cdot 0.026 = 207 \text{ mm/min;}$$

3 appendix. Presented oscillograms of aluminum and stainless steel

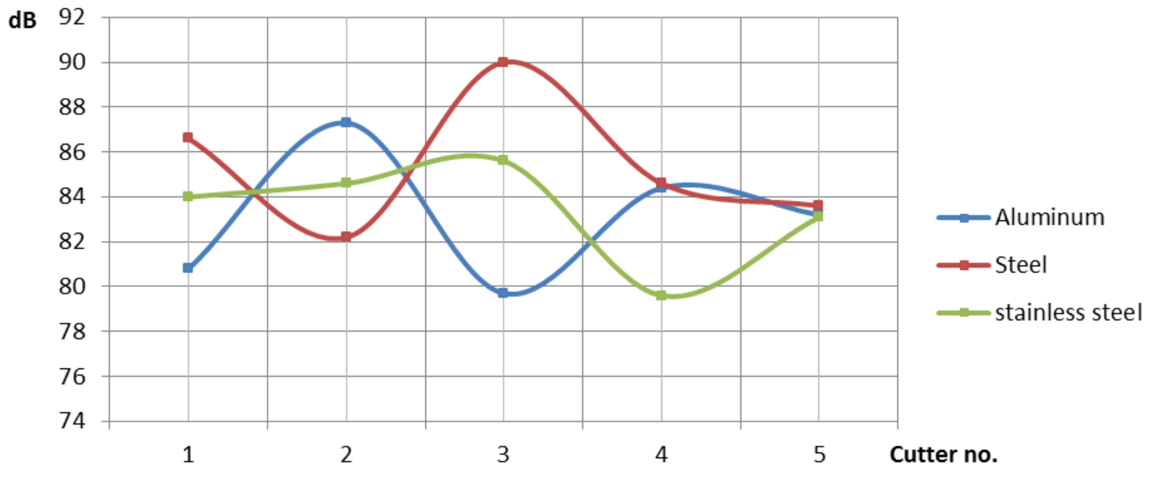


Fig. 1. Ø5 mm, frequency range 0…6.4 kHz

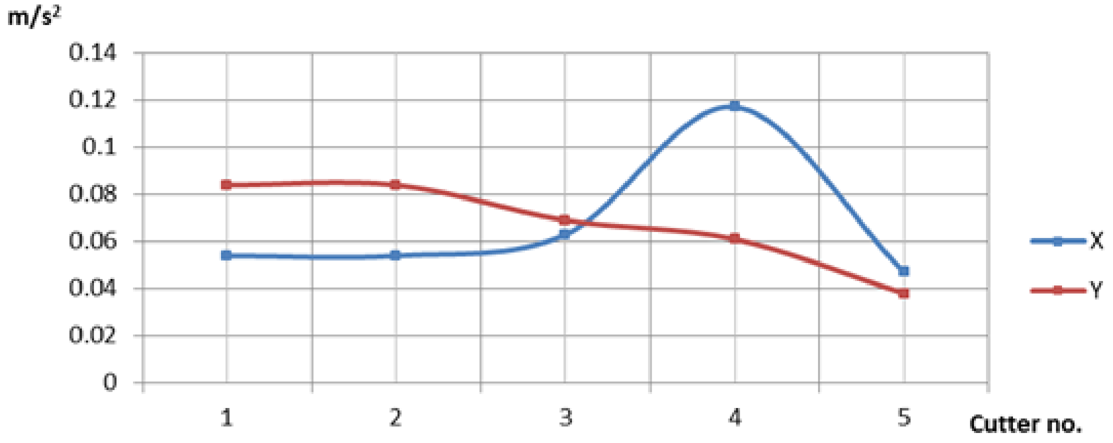


Fig. 2. Aluminum frequency range 337Hz of the cutters, cutting edge diameter Ø5

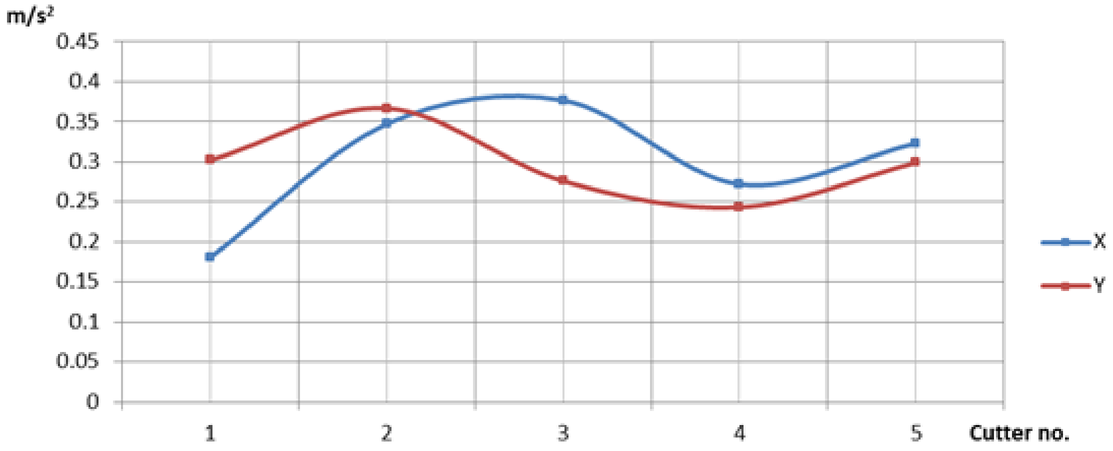


Fig. 3. Stainless steel frequency range 224 Hz of the cutters, cutting edge diameter Ø5

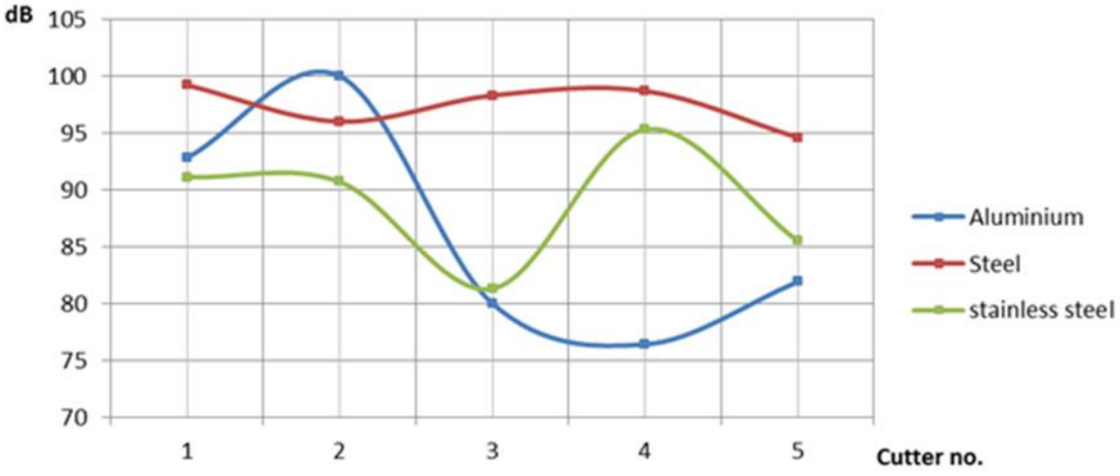


Fig. 4. Ø10 mm, frequency range 0…6.4 kHz

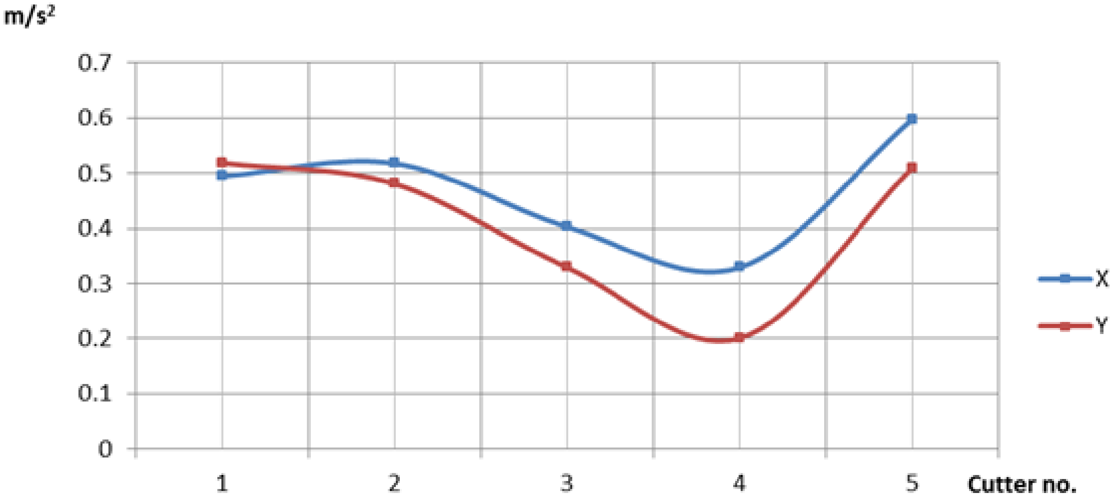


Fig. 5. Aluminum frequency range 202.5 Hz of the cutters, cutting edge diameter Ø10

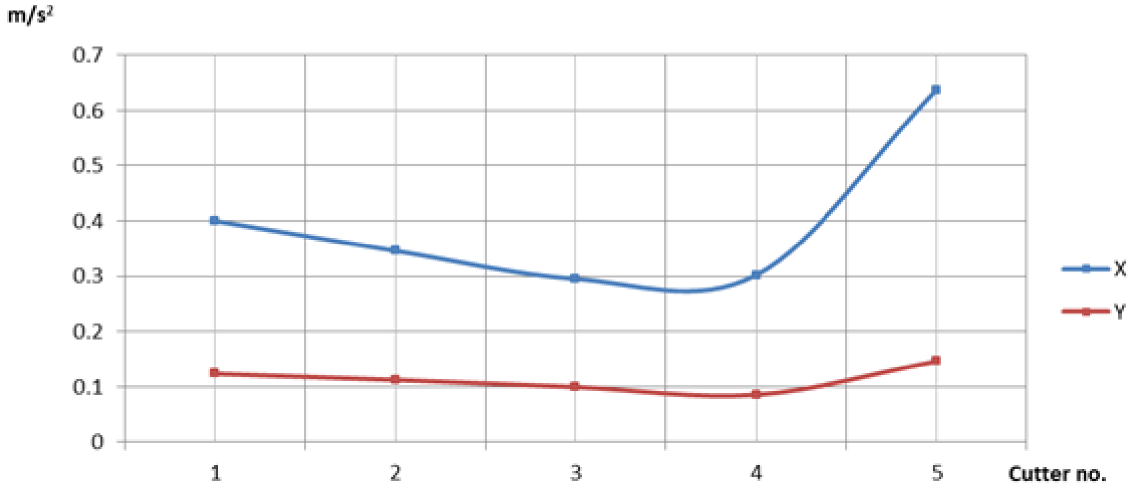


Fig. 6. Stainless steel frequency range 134 Hz of the cutters, cutting edge diameter Ø10

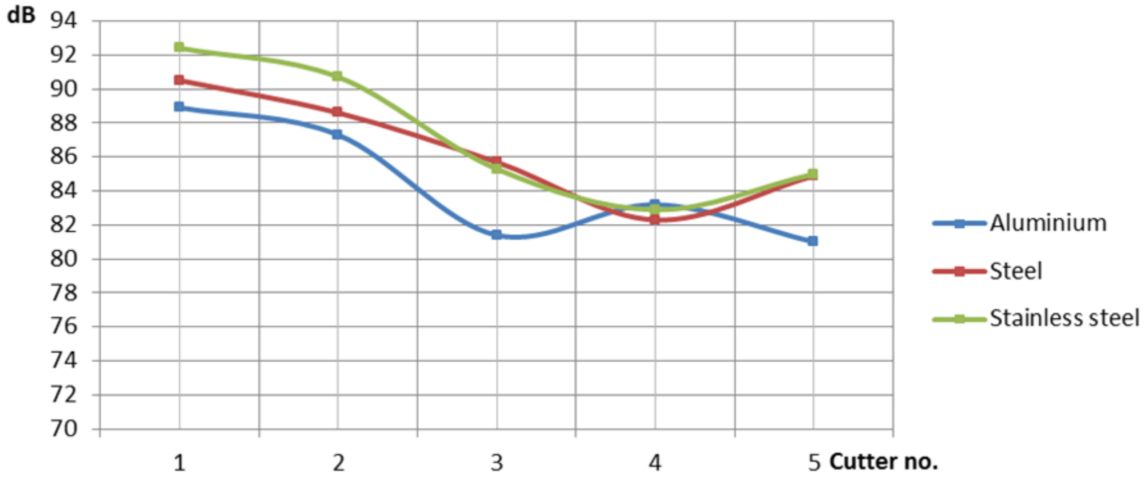


Fig. 7. Ø16 mm, frequency range 0…6.4 kHz

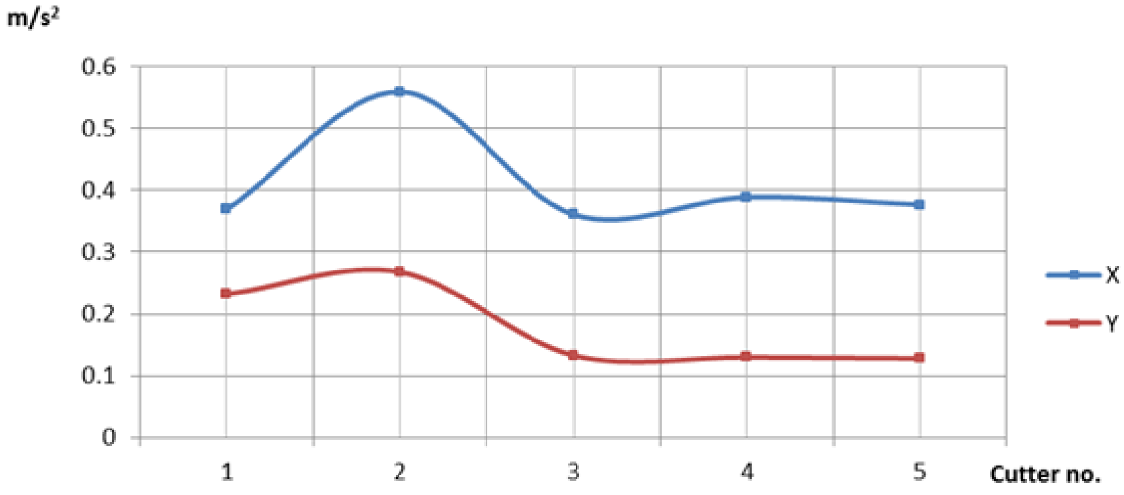


Fig. 8. Aluminium frequency range 138 Hz of the cutters, cutting edge diameter Ø16

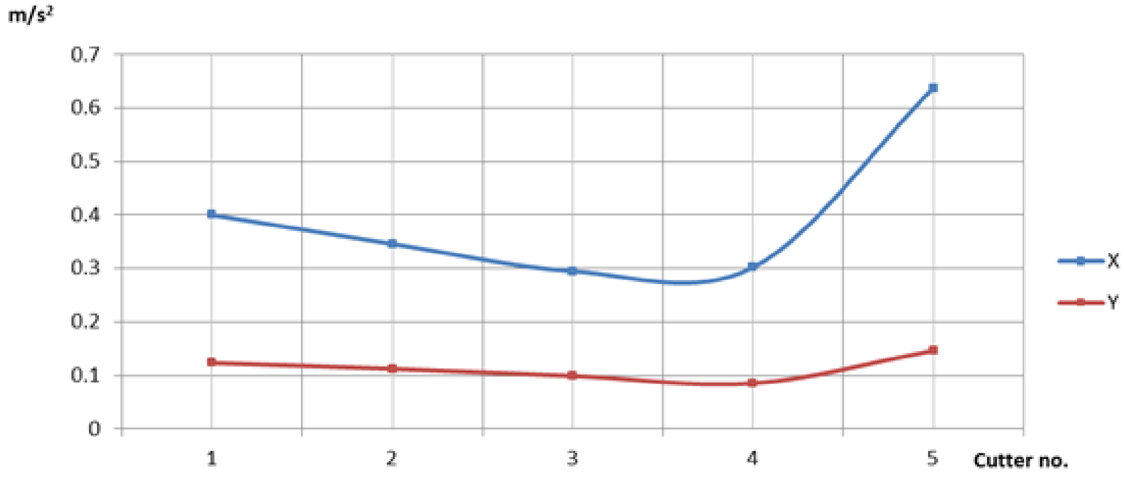


Fig. 9. Stainless steel frequency range 91.75 Hz of the cutters, cutting edge diameter Ø16