Adaptive Control of the Metalworking Process With Using Sound Generated During Cutting

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ADAPTIVE CONTROL OF THE METALWORKING PROCESS WITH USING SOUND GENERATED DURING CUTTING

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Abstract The presented paper proposes a method of adaptive control of the metal cutting process based on the analysis and interpretation of recorded sound for the identification of the cutting process. The presented research results clearly demonstrated the efficiency of using the sound generated during cutting by CNC lathe 16 K20T1 for the adaptive metalworking control. The sound makes it possible to control the accuracy of the workpiece part geometry and the surface quality in the online mode. The online mode also makes it possible to make an informed decision about a timely interruption of the cutting process or the continuation of the process in the altered modes for its successful completion. As the research results presented in the paper show, there is a close correlation between the sound generated by cutting and the roughness of the surface being machined or the degree of wear of the cutting tool. The correlation between the sound and roughness of the machined surface is 0.94, whereas between the sound and wear of the cutting tool is 0.93. The paper aims to use the generated sound as operational information needed for adaptive control of the metal processing process and timely monitoring and diagnostics of the condition of processed materials using the precision index, newly introduced as the machining quality index.

Keywords turning, rotary tool, cutting force, actively driven tool

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1 Introduction

High demands are placed on machine tools not only in terms of required technological parameters and efficiency but also in terms of their reliability. The key to ensuring reliable production is timely and correct operational diagnostics and self-diagnostics of modern machine tools. Machine tools are currently the most demanding application in an unattended mode with continuous operation, in which the diagnostic system must quickly detect a dangerous trend of a monitored parameter or even a sudden failure. In principle, the diagnostic system communicates with the machine tool system at such a level that it is possible to start the prepared program sequence in time, minimizing or averting the fault on the basis of the current diagnostic results. An external diagnostic system can be used for the specific diagnostic needs of the machining system. The design of the additional system is the content of the presented publication.

In particular, its implementation presupposes the connection of a computer with a diagnostic monitoring system, with measuring modules and signal processing modules. Analysis of an acoustic signal can identify common machine damage, such as imbalance, misalignment, bearing problems, gearing problems, loosening, electric motor problems, general drives, and more. The noise emitted by the machine provides partial information about its state. Vibration in machines can cause failure. With the help of vibrations and sound, it is possible to predict the condition of the surface and solve practical problems that most engineers and users face in the process of various technologies, especially when implementing control automation to maximize production performance and determine the values of process parameters that are placed on the required product quality [1-2]. Diagnostic and prediction methods for periodic measurement of vibration (noise) use vibration and noise as a diagnostic parameter [3-5]. The quality of machining products by cutting must be monitored throughout the technological chain because it is the result of the complex action of many technological influences. As a result of the cutting process, both the machined surface and the surface of the machining tool change interactively. In particular, the wear of the cutting tool has a decisive influence on the quality of the checked parameters. This fact requires the implementation of adaptive control with different purposes of cutting modes, which allow extending the failure time of a predetermined operation of machining materials by cutting.

The adaptive control system of the cutting process is based on the measurement of information signals of different nature representing a variety of external factors: mechanical stress, vibration, the processing system elastic deformations, the electric current, chemical exposure, and the like, which have a decisive influence on the degree of the tool wear and, consequently, on quality of the manufactured product [6]. So, in the course of the process of tool wear, such parameters as cutting force [7-8], the torque [9-10] and cutting power [11] are changing. These parameters are measured by dynamometers. Applying the vibration sensor, for example, when turning on the tool holder, the tool vibrations inevitably accompanying the cutting process are measured [12]. During the interaction of the wearing tool with a workpiece, acoustic emission waves are generated; they are recorded by acoustic emission sensors. Elastic waves are more sensitive to tool wear than force factors and vibration [13]. However, at the same time, it makes acoustic emission more sensitive to noise interference caused by the environmental influence and the work of the structural machine units. For this reason, registration of the "integrated settings" is referred to, as they are more resistant to noise disturbance. For example, thermocouples monitor the temperature in the cutting zone [14], they measure the thermo-EDS [15] and the electrical conductivity [16] of the tool-workpiece contact pair. The disadvantage of the "integral" methods is their considerable inertia and the need to incorporate a thermocouple and electrical connections into the instrument. Adaptive control also uses acoustic emission signals [17] and measurements of vibrations [18-20]. The vibrations and acoustic data signals turn out to be the simplest for the registration and subsequent processing [12, 18]. However, in practice, the use of these signals is related to a significant problem that is difficult to solve. These information signals are recorded by the contact method. The method requires an implementation of a mechanical communication of the sensor with the information signal source (the object surface).

In order to meet this requirement, it is necessary to solve two difficult tasks: to choose an informative point on the controlled objects where the sensor is supposed to be installed, and to avoid interference, always related to the method of measurement. When monitoring the cutting process, the informative point is considered to be the tool contact point with the workpiece. At this point, the useful signal carrying information about the course of the cutting process is generated. Placing the sensor at this point is impossible. Selection of other possible closest control points, for example, when the turned workpiece is placed on the cutting tool holder, makes it necessary to exclude the most significant interference from the measurement results. Noise disturbance, in this case, is the vibration generated by the machine operating nodes. To select the useful signal without significant distortion on the intensive level background and with the parasitic vibrations complex in frequency is almost impossible. The solution to this problem is achieved by eliminating the sensor contact with the machine tool vibrating surface that is implemented by a non-contact measurement method. In this case, it is of interest to control the sound accompanying the cutting process [21-27]. The close relationship between the parasitic vibrations of the machine tool and the roughness of the machined surface is clearly shown in [28]. The need for non-contact control of the cutting process is illustrated by examples of the ineffectiveness of cutting processing control by other methods. In this regard, in [29], it is proposed to use an additional vibrator, which dampens parasitic vibrations of the cutting tool at the point of contact with the workpiece surface. This significantly complicates the process of part manufacturing, which is unacceptable for mass production. In [30], the authors consider an even more complex system for suppressing parasitic vibrations by directly controlling the cutting force, which is also not acceptable in the practice of actual production.

The acoustic emission considered in [31] is very sensitive to the parasitic signals generated by a running machine and, therefore, is not acceptable for adaptive control of the cutting process. In the paper [32], it is noted that the complexity of adaptive control depends on the uncertainty of tool wear and fluctuations in the material properties of the part, which cannot be resolved at present. In the papers [33] and [29], it is proposed to use a vibrator to damp parasitic vibrations, which is very difficult for implementation in industrial conditions. In the paper [34], a digital control system for the longitudinal spindle stiffness is considered, which is designed to damp its parasitic vibrations, but significantly complicates the machining process. The authors in the paper [35] propose a sliding mode of adaptive control, demonstrating the complexity of the problem of adaptive control of the cutting process. In the paper [36], it is proposed to counteract parasitic vibrations using two piezo vibrators programmatically controlled by a neural system, which clearly indicates the complexity of the observed cutting process. In the paper [37], an example of a neural network is considered, which makes it possible to calculate the cutting force based on the cutting mode, and on the basis of this, in turn, to estimate the tool service life and the roughness of the machined surface. The Wavelet-Extreme-Machine software package is proposed [38], which allows controlling the cutting process based on the results of measuring the cutting force. A complex computerized system of adaptive control is considered in the paper [39], which allows using a computer cloud to store information that makes it possible to control the processed surface quality, which is the nearest opportunity for material processing cutting. As shown in the papers [40-41], the quality of adaptive control depends on the successful control of cutting modes, which is, in turn, ensured by the automation of the control process itself. The currently used relationships between the information signal and tool wear are phenomenological, often having no quantitative substantiation [42–46]. Therefore, at the present level of development of material processing by cutting, it is necessary to determine the degree of correlation between one of the promising information signals - the sound generated during the cutting process, the wear of the cutter and the surface roughness of the workpiece [47-49].

Modern adaptive control systems are particularly suitable in the case of insufficient information about the continuous change in the technical status of the processing system and represent the possibility of online control, i.e., without interrupting the processing process. They are based on an indirect method of controlling the processing process, i.e., they use information signals produced by many different physical phenomena that organically accompany the processing process. For example, the components of cutting forces [53-56], torque [57], drive motor power [58-60], acoustic emission signals [61, 62], vibration [63-65], sound [66-70], temperature [71-74], electrical conductivity of tool-material contact [75], and infrared radiation of shavings [76-77] are directly and continuously monitored during cutting. The above methods of monitoring the machining process have a significant predictive value, which can be finally reflected in a reduced form into the monitoring of the ongoing condition of the cutting tool itself. However, the main task of the adaptive control of the dynamic behaviour of the machining system is to ensure the quality of the machined part desired by the drawing. Furthermore, one of the most important parameters that determine the quality of a part is the quality of its surface, quantitatively expressed by roughness parameters [78]. If the surface roughness values determined by product quality indicators [79-83] exceed the permissible limits, they are classified as a technological failure of the processing system. The processing process monitoring methods in question are mainly applicable in laboratory conditions intended for research purposes because the sensor sets of the measuring and control system cause disturbances within the cutting process. The level of disturbance depends, for example, on probe placement, tool stiffness, materials and operating modes. In addition to the specific operational problems, indirect control methods have the significant disadvantage of a lack of published “vibration activity standards”, especially in the case of methods developed for rotating machines. It is this circumstance that has necessitated the monitoring and use of information signals generated by the accompanying physical processes. The main objective of the research presented here is the indirect and continuous assessment of the technical condition of the machined and inspected component, namely in a reliable, accurate and disturbance-resistant manner. The presented results clearly demonstrate that the sound waves generated during the cutting of materials meet these demanding requirements.

The paper mainly aims to describe the correlation interconnection between the sound generated during the turning process, tool wear and the roughness of the machined surface quantitatively. The novelty of the research lies in the establishment of a close correlation between the trends of sound and instrument wear, the resistance of sound to multiplicative, additive and impulsive interferences, the coincidence of the roughness profile and the shape of the sound wave. The advantage of the non-contact method of measuring the sound during adaptive cutting control lies in the almost complete elimination of rejects in the resulting machined part, thanks to the method of timely identification of the condition of the processed material using the precision index, i.e., the machining quality index.

2 Theoretical part

2.1 Process diagram

Process diagram (Fig. 1) schematically depicts a comprehensive view of how sound and surface parameters are theoretically identified as source signals, then measured in practice and evaluated for correlation, and finally used for feedback quality control of the technological process through feedback [50-52].

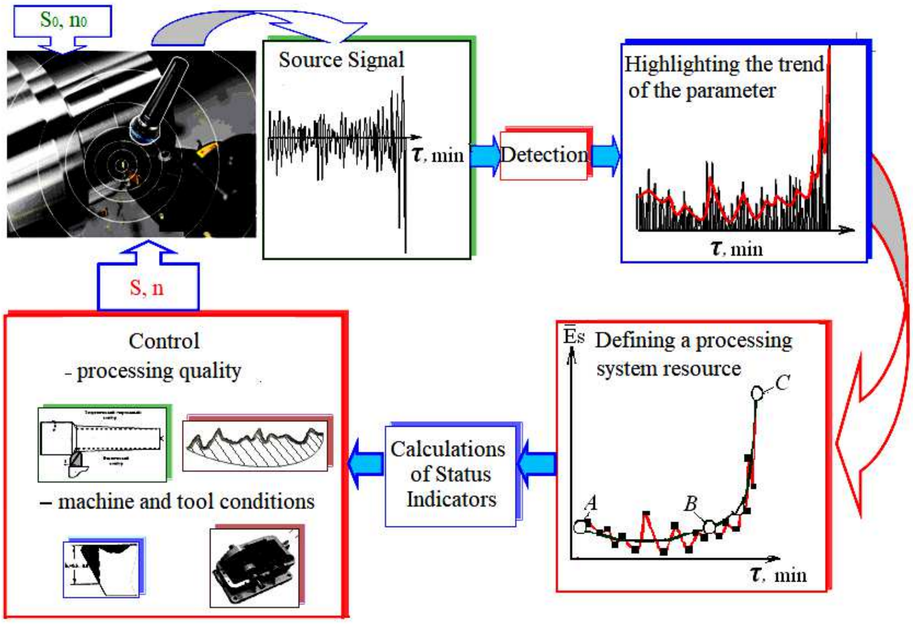

***Figure 1**. Process diagram, where S – adjustable feed rate, n – adjustable cutting speed, S_o – initial feed rate and n_o – initial cutting speed, $\bar{E}_s$ – relative sound signal.*

2.2 Sound resistance to noise interference

The sound generated during cutting is recorded by the microphone, i.e., the voltage of the electrical signal at the microphone output changes depending on the pressure of the measured sound. The most suitable type of microphone is an electret microphone, in principle, an electrostatic microphone-based capacitor, in which the electric field is generated by a non-conductive mass permanently electrically charged, i.e., by an electret. The simple design of this microphone allows for convenient miniaturization of its dimensions, while sensitivity at an acoustic frequency of 1kHz electric voltage 1-10 mV to a sound pressure of 1 Pa is well acceptable for the measurement.

It is necessary to estimate the noise resistance of the cutting sound to the influence of noise interference, which is additive and multiplicative by nature. The former interferes with the measuring circuit, which is not critical for measuring computer networks, where such interference is virtually absent.

In order to eliminate the multiplicative noise interference, it is necessary to present the measured microphone sound signal E_S in a dimensionless form. The dimensionless parameter is the ratio of the measured values of the sound signal E_{Si} to its value E_{So} recorded during the first measurement (1):

$$\bar{E}_S = \frac{E_{Si}}{E_{S0}} \qquad (1)$$

The extended relation (2) allows the elimination of the multiplicative noise fraction (1):

$$\bar{E}_S = \frac{E_{Si} \cdot \varepsilon(\tau)}{E_{S0} \cdot \varepsilon(\tau)} = \frac{E_{Si}}{E_{S0}} \qquad (2)$$

The cause of the additive noise is the background sound produced by the equipment surrounding this processing system. In the presence of additive noise fraction, the relation (1) takes the following form (3):

$$\bar{E}_S = \frac{\sqrt{\hat{E}_{Si}^2 + \hat{\varepsilon}^2(\tau)}}{\sqrt{\hat{E}_{S0}^2 + \hat{\varepsilon}^2(\tau)}} = \frac{\hat{E}_{Si}}{\hat{E}_{S0}} \frac{\sqrt{1 + \frac{\hat{\varepsilon}^2(\tau)}{\hat{E}_{Si}^2}}}{\sqrt{1 + \frac{\hat{\varepsilon}^2(\tau)}{\hat{E}_{S0}^2}}} \qquad (3)$$

where the values $\hat{E}_{Si}, \varepsilon(\tau)$ - or their respective RMS (Root Mean Square) values are the values of the useful effective signal and noise (4)

$$\hat{E}_S = \frac{E_S}{\sqrt{2}}; \quad \hat{\varepsilon}(\tau)_S = \frac{\varepsilon(\tau)}{\sqrt{2}} \qquad (4)$$

Strict requirements for accuracy of fit can be met by the use of clampoing screws whose head has a negative shape of the cutting insert hole. With tapered shapes, partial concentricity of fit can be achieved. Such a solution is costly because every single type of cutting insert must have a specially manufactured clamping screw.

The relations (3) and (4) show that the expressions under the square root in the numerator and the denominator in the general case are not equal and that they are not subject to reduction. This means that in the practice of cutting, there may be a danger of distorting the influence of the noise interference on the measurement results.

The extent of the impact from the nearby equipment interference was evaluated following the “Rule of 6 dB” known in acoustics, according to which the change in the sound (sound pressure) is directly proportional to the distance from the sound source to its point of control.

In the considered case, the distance to the cutting zone of this machine from neighbouring machines (sources of interference) was 4 meters. The total effective value of the sound pressure $\hat{E}_S^{SUM}$ (measured in pascals) at the checkpoint is determined analytically by the vector sum according to (5):

$$\hat{E}_S^{SUM} = \sqrt{\hat{E}_S^2 + \left(\frac{\hat{E}_S}{4}\right)^2 + \left(\frac{\hat{E}_S}{4}\right)^2} = \hat{E}_S \sqrt{\frac{18}{16}} = 1.06\hat{E}_S \qquad (5)$$

In the calculation of relation (5), it was assumed that in the process of work, three processing systems generated the sound of the same amplitude E_S, Pa. Noise interference from the surrounding equipment leads to an overestimation of the measurement results concerning the true value of the controlled sound magnitude only by 6 %.

According to (5), in the calculation, it is assumed that three process systems for sound pressure processing of the same amplitude ES (measured in Pa) were generated during the cutting process. It can be observed that noise disturbance due to the environment leads to an overestimation of the measurement results (for the actual value of the regulated acoustic value) by a maximum of 6 %.

Therefore, a microphone located at an immediate distance (measured in the order of centimetres) of the controlled working cutting zone virtually eliminates the distortion effect of the additional noise. This is because noise interference undergoes significant attenuation at a distance (measured in meters) from the source of its origin to the control point of the workspace.

The interferences with the pulse (shock) character appearing due to irregular mechanical shocks occurring in the surrounding machining equipment environment were classified into the additive noise category. Pulse load in the time domain of its submission is characterized by two parameters: the level E_{Sh} and duration τ_{Sh}.

The parameters E_{Sh} and τ_{Sh} are parameters characterizing the course of the response of the cutting process in real time. The aim is to obtain a parameter that will characterize the relationship between the obtained analogue signal and the real cutting process (6). Equation (6) declares the desired binding for further processing with an emphasis on the identification and interpretation of the cutting process. When the analogue signal, including pulse, enters the computer, it is subjected to "digitization", i.e., discrete reading with a particular time step $\Delta\tau$. The time step $\Delta\tau$ is 1/11025 s, where the number 11025 is the standard sample rate of discretization f_{dis}, used in the digital processing of analogue signals. The number of the read values of the signal n_{PCS} coincides with the number of time steps, which is determined from the following expression (6):

$$n_{PCS} = \frac{\tau_{Sh}}{\Delta\tau} = 11025 \cdot \tau_{Sh} \tag{6}$$

The number of steps, as follows from the relation (5), depends on the impulse frequency and duration pulse τ_{Sh}, which is determined by the following formula (7) as in [8]:

$$\tau_{Sh} = \frac{2L}{C} \tag{7}$$

where L is the length of the sound pulse of the dynamic characteristic of the metal object under investigation and C is the speed of propagation of the longitudinal vibrations in the metal.

As a result of sophisticated acoustic signal processing (on average 3,000 signal values for each measurement event), the noise resistance was gradually increased up to 100 % as the results of previous measurements were being stored. Table 1 shows the pulse width measurement results and the corresponding number of readings according to (5)-(6) for a length ranging from 0.1 to 1.0 m.

Table 1*. Change of the pulse duration τ_{Sh} and the number of the read values of the sound impulse n_{PCS}, depending on the rod length L*

L, m	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
τ_{Sh} 10^{-4}, s	0.77	1.16	1.55	1.93	2.32	2.71	3.10	3.48	3.67
n_{PCS}	0.85 ≈ 1	1.27 ≈ 2	1.7 ≈ 2	2.13 ≈ 2	2.55 ≈ 3	2.98 ≈ 3	3.4 ≈ 4	3.8 ≈ 4	4

The contribution of the sound pulse to the value recorded during the overall measurement of the generated sound can be reasonably estimated, provided that in the absence of pulse interference, the amplitude of the useful sound signal is E_S. If the total amplitude value is disturbed, E_S^{SUM} is the vector sum of the interference level E_{Sh} and the useful signal level E_S. Furthermore, it can be assumed that the noise level exceeds the useful signal level ($E_{Sh} = 10E_S$) ten times and allows a considerable margin, i.e. the pulse duration τ_{Sh} corresponds up to 100 times (less by almost two orders of magnitude).

A total of 3072 signal values are determined in the sound management process to improve measurement reliability and noise interference control (reading is performed three times for a total of 1024 samples). Read values are summed and averaged to 3072 units. In order to determine the unit of the useful signal and the amount of noise, the amplitude values of the pressures at their effective value can be assumed to determine the overall useful signal level and interference (8):

$$\hat{E}_S^{SUM} = \sqrt{\left(\hat{E}_S \cdot \frac{2972}{3072}\right)^2 + \left(10 \cdot \hat{E}_S \cdot \frac{100}{3072}\right)^2} = 1.02\hat{E}_S \tag{8}$$

It can be clearly seen that even if the noise level is exceeded ten times above the useful signal level, its contribution to the total signal does not exceed 2 %. Thus, the results of the above-mentioned studies have revealed that the noise generated during cutting has noise resistance properties and can, therefore, be considered as an initial information signal useful in adaptive control of the cutting process. At the same time, the cutting sound should provide a solution to the basic problem of adaptive control - maintaining the quality required for manufacturing parts in the documents, the desired degree of alignment of the part geometry, and the surface cleanliness in accordance with the drawings. The geometric accuracy of the desired workpiece shape is determined by tool wear and surface finish.

2.3. Control – processing quality

On the surface of the examined part of the workpiece, increased roughness is observed in the form of formed protrusions and depressions (Fig. 2). Tool traces left on the machined surface were caused interactively, i.e. by tool vibration and workpiece vibration. This phenomenon was first recorded 135 years ago as a phonogram, recording the effect of the milling cutter on the lateral surface of the wax roll. Figure 2 was created with the REM-100U scanning electron microscope.

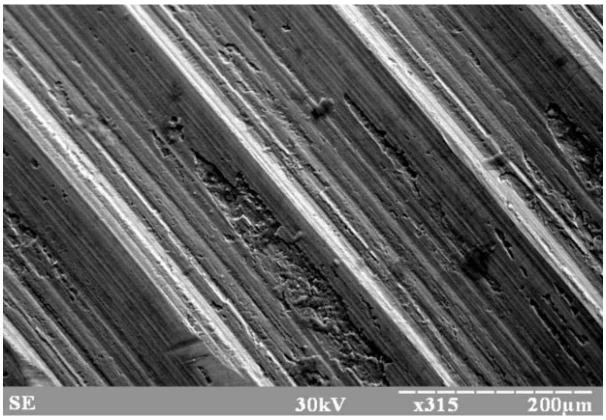

Figure 2. *The surface of part of the workpiece after the cutting process and magnified by microscope.*

The altered surface roughness, similar to the phonogram acoustic recording, is inextricably linked to the destructive wear of the tool; therefore, it contains necessary information about the extent of this wear and the quality of the processed workpiece surface. The study of the possibility of using the acoustic signal in machining as an information signal about this process relates mainly to determining the noise resistance of the acoustic signal. It is one of the main requirements for this kind of signal in adaptive control of cutting machining.

2.4. The indicator of the accuracy of measurement results processing

One of the main reasons for deviating the resulting geometrical shape of a part of the workpiece from its desired geometrical shape is the change in the cutting tooltip curvature radius h_r corresponding to the machined surface curvature radius.

The purpose of the presented experiments was to determine the possible correlation between the generated sound and tooltip wear during machining of the workpiece on the lathe. The sound measurements were made using a microphone installed near the cutting area with signal transmission to the computer; the acoustic signal was measured continuously. Simultaneously, the value of the wear by canting the main rear surface of the tool (measured in mm) was recorded in two tool passes using a digital measuring microscope. The experiment was stopped when the maximum permissible wear value was reached. Thus, the degree of correlation between the generated sound and the subject parameters was studied experimentally.

2.5. Quality indicator for adaptive control

The method of similarity and dimension was used to obtain the analytical term “member function” describing the quality indicator for adaptive control a_{qp}.

According to this theory, the desired indicator can be expressed using a set of determining parameters: initial wear $h_r(\tau_0)$, current wear $h_r(\tau)$, current tool life τ, the numerical value of tool life $\bar{T}_{exp}$.

These parameters have two dimensions – length L ($[h_r(\tau_0)] = L,\ [h_r(\tau)] = L$) and time T ($[\tau] = T,\ [\bar{T}_{exp}] = T$). The required exponent a_{qp} can be presented as a function of the product of these determining parameters, each of which is increased to its own degree (9):

$$a_{qp} = f(h_r(\tau_0), h_r(\tau), \tau, \bar{T}_{exp}) = h_r^{\alpha}(\tau_0) \cdot h_r^{\beta}(\tau) \cdot \tau^{\gamma} \cdot \bar{T}_{exp}^{\lambda} \tag{9}$$

Determining the rate indicator values is also necessary, i.e., replacing the quantities in the expression by their dimensions according to (10):

$$1 = L^{\alpha} \cdot L^{\beta} \cdot T^{\gamma} \cdot T^{\lambda} = L^{\alpha+\beta} \cdot T^{\gamma+\lambda}. \tag{10}$$

Since the desired indicator is a dimensionless quantity, its dimension according to the dimension theory is equal to one, whereas, for exponents in the relation (9), the following conditions (10) must be met:

$$\alpha + \beta = 0, \gamma + \lambda = 0. \tag{11}$$

The above-mentioned set of 2 equations is further supplemented by four unknown conditions $\beta = 1, \gamma = 1.$, whereby the common solution of 4 equations ($\alpha = -1, \beta = 1, \gamma = 1, \lambda = -1$) leads to the relation for the precision index, introduced here as the machining quality index a_{qp} (12):

$$a_{qp} = \frac{h_r(\tau)}{h_r(\tau_0)} \cdot \frac{\tau}{\bar{T}_{exp}}. \tag{12}$$

According to (1)-(2) definition relations for a close correlation between the tool wear curve and the generated sound trend, the relation (11) can be reformulated to the form (13):

$$a_{qp} = \frac{E_{Si}(\tau)}{E_{S0}(\tau_0)} \cdot \frac{\tau}{\bar{T}_{exp}} = \bar{E}_S(\tau) \cdot \frac{\tau}{\bar{T}_{exp}}. \tag{13}$$

The relation (12) is then a sought-after “member function” that varies according to the theory of “fuzzy sets” from zero to one [30]. The degree of change in the geometry of a workpiece component due to tooltip wear can be estimated by the relation (14):

$$\delta = \frac{D_{ф} - D_{н}}{D_{н}^{+\Delta B} - D_{н}}, \tag{14}$$

where D_H is the nominal size of the workpiece component; $D_{ф}$ actual size of the component ($D_{ф} = D_{н} + 2 \cdot h_r$); h_r is the radial wear of the tooltip; ΔB is the change in radial wear of the tool. The relation (14) can be rewritten into the relation (15):

$$\delta = \frac{D_{н} + 2 \cdot h_r - D_{н}}{D_{н} + \Delta B - D_{н}} = \frac{2 \cdot h_r}{\Delta B}. \tag{15}$$

The expression (15) varies from the 0 value when the tool is fully sharpened to 1 when the radial wear of the tool h_r reaches the maximum allowable value. Thus, the machining quality index a_{qp} (13) varying from zero to unit adequately describes the degree of change in the geometry of the part.

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3. Experimental part

The efficiency of adaptive control of the intensity of the generated sound by cutting was experimentally tested on a CNC lathe 16 K20T1 (Figure 3). The adaptive control algorithm is shown in Figure 1. According to the algorithm, adaptive control begins by continuously registering the audio signal, selecting its envelope, approximating with this envelope prediction model, determining the source of the cutting tool as one of the parameters of the model. Based on the results of the operative comparison of the actual tool life and the required workpiece processing time, which are ensuring the quality required by the drawing, the originally selected cutting modes are set.

Figure 3. *Automated monitoring of the technical conditions of the lathe.*

In accordance with the adaptive control algorithm, the sound level generated by the cutting process was monitored in the experiment (Fig. 3), and based on this, the value of the indicator a_{qp} was calculated. Based on the value of this indicator, the quality of the adaptive section control was assessed. The experimental conditions are shown in Table 2.

Table 2. *Experimental conditions implemented during turning*.

Cutting insert	Cutting conditions			*D*, mm workpiece diameter	Steel
	n, r/min spindle speed	*S*, mm/rev feed rate	*a*, mm cutting depth		
P 25	125	0,15	1	98,0	12X18H10T
T15K6	315	0,20	1		

Verification measurements were performed continuously for a period of 4 years, specifically in each mode with 10 repetitions, for a total of 280 measurements with an accuracy of 1 to 5%. From these measurements, 2 representative sets were created, the mean values of which were created the graphical dependencies.

3.1. Sound measurement

The sound parameter E_S was recorded using a program on the tablet (Fig. 4). The program implementing the derived algorithm is shown in Fig 1. The program is designed for the Android operating system. The first measurement of the generated sound (Fig. 4) was made at the beginning of the cutting process (theoretically at t = 0 s).

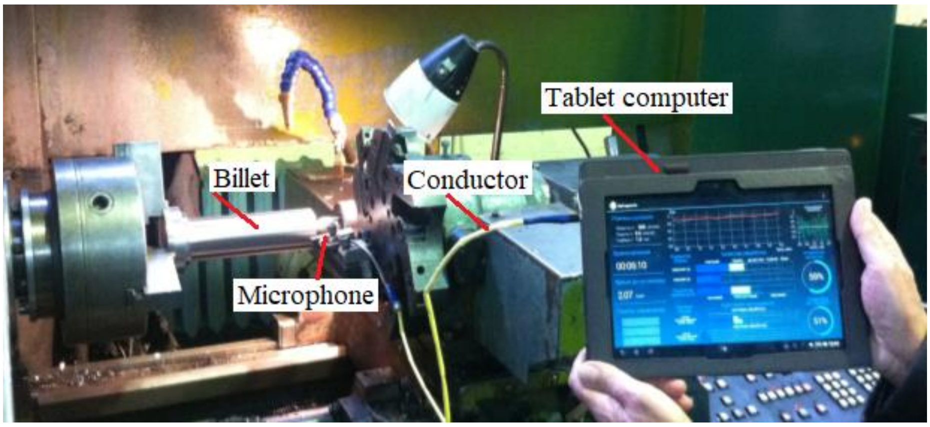

Figure 4. *Sound control with a tablet.*

During the experiment, the microphone was mounted on the cutter holder (Fig. 5) at a distance of 10 mm from the cutting zone.

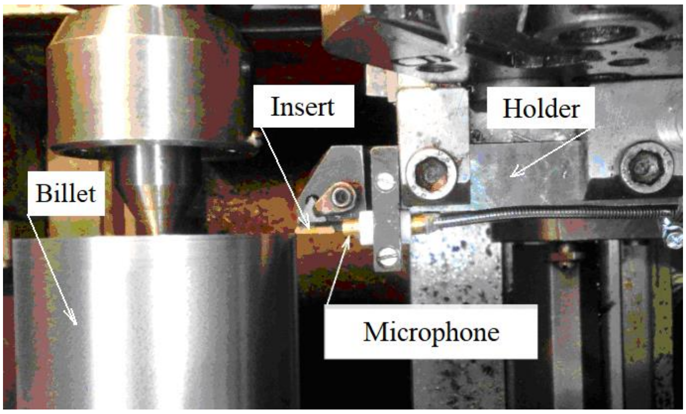

Figure 5. *Installing the microphone in the immediate vicinity of the cut area.*

The sound was measured by a microphone installed 1 cm from the cut area. The microphone is part of a newly developed cutting process control system because the generated sound is the only information signal that does not respond to the noise surrounding the cut area.

3.2. Measurement of surface roughness

The presented experiment aimed to determine the correlation relationship between the dimensionless sound parameter $\bar{R}a$ and the height parameter Ra characterizing roughness. The roughness was measured during longitudinal turning of the steel billet with P25 insert made of 12X18H10T steel and cutting insert T15K6 made of titanium cobalt alloy and tungsten group. Measuring Ra parameters was performed periodically every five passes using a cutting profile using a profilometer 283. The measurement results were recorded using a dial indicator and subsequently recorded in a notebook. The signal recorded in the notebook was subjected to further processing to determine the correlation between:

- sound trends and roughness parameters;

- the frequency spectrum of the roughness profile and sound;
- the temporal unfolding of the audio signal and roughness profile.

4. Results

4.1. Correlation between sound and tool wear - Experiment with the cutting insert R 25

The relationship between the tool wear curve and the development trend of the generated sound during cutting was determined using a P25 insert/plate made of 12X18H10T steel for the following modes: (330 m·min^{-1}, 0.15 mm·rev^{-1}, 1.0 mm (Fig. 6); i.e. a sample diagram of the cutting sound change (trend of parameters) and the wear curve VB (Fig. 7), information on the correlation dependence between them (Fig. 11), at a determined value of the correlation coefficient R = 0.93 [50, 52].

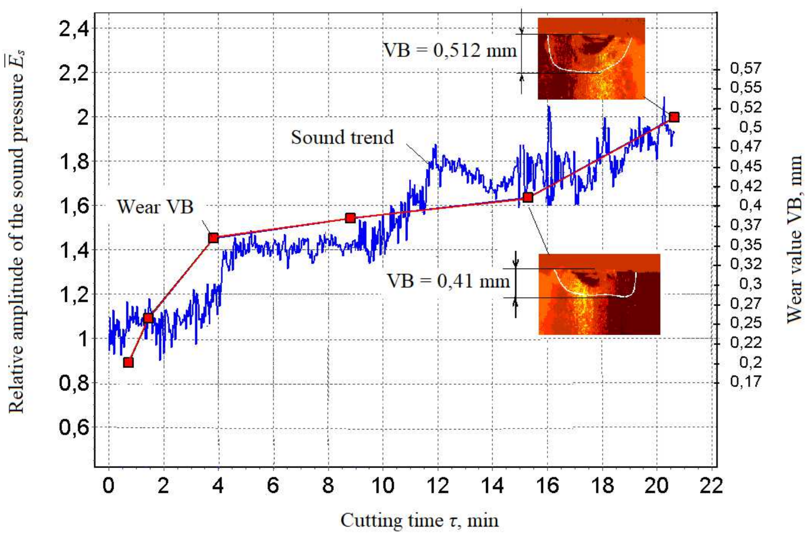

***Figure 6**. Trend of parameters and curve corresponding to the degree of wear VB.*

From the dependence (Fig. 10), it is possible to identify a clear relationship between sound and wear in the measured time and thus determine that at about the 15th minute, the wear curve moves from the area of normal wear to the area of catastrophic wear. Achieving the limit wear requires stopping the processing process. In order to illustrate, there are two states at the 15th minute when the process should stop. For research reasons, the cutting process was continued in order to find out how the dependence between sound and wear develops in an extreme situation. Based on the obtained measurement results, it was then possible to search for the connections in question, especially between sound and wear (Fig. 11) and then to examine the connection of the created surface quality.

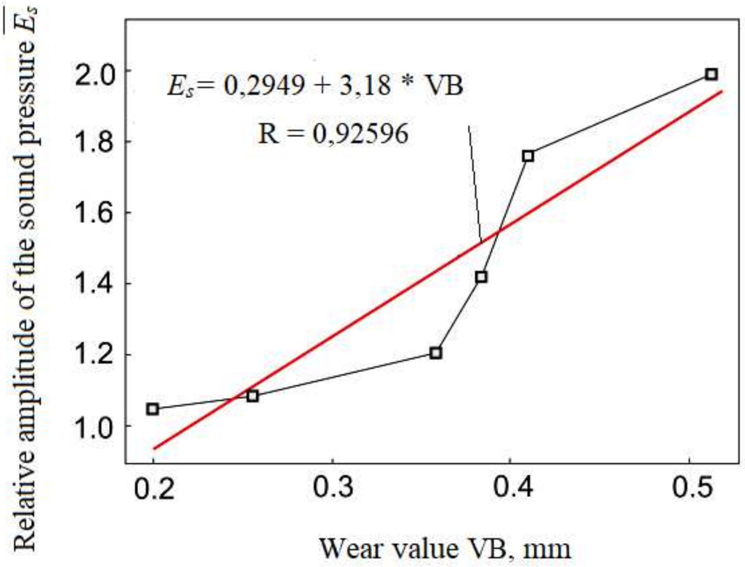

Figure 7*. Correlation dependence between parameter* $\overline{E}_{3B}$ *and size of flank wear VB.*

The correlation of the generated sound in cutting and wearing the cutting tool tip demonstrates a high degree of correlation between the change in sound development trend and the wear curve that follows from the previously presented material. Figure 8 clearly shows that at the 15th minute, the wear curve changes from the area of normal wear to the area of catastrophic wear, which requires stopping the metalworking process. This method of early diagnosis of the tool wear condition using the a_{qp} parameter is very important for the retrograde regulation of the generated surface quality during the timely measurement of sound. Thus, it is possible to achieve the highest quality process emphasizing the quality of the created surface represented by the surface roughness.

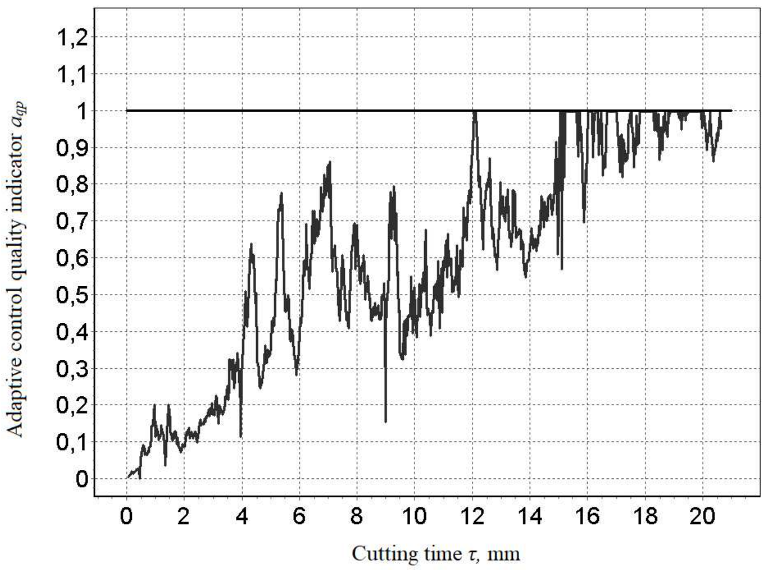

Figure 8*. A quality indicator for adaptive control* a_{qp}*.*

4.2. Correlation between sound and tool wear - Experiment with the cutting insert T15K6

The size trend and the wear curve of the cutting insert (flank width VB) are shown in Figure 9. Here, the link between sound and wear by another blade is identified. In order to search for and examine the relationships between the parameters in question, a symmetrical image of the sound trend (Fig. 9) is presented by a curve that changes at the same distance from the concerned significant change in the wear curve portion corresponding to the normal wear portion. The consistency of the change in the sound trend and the wear curve is clearly confirmed (Fig. 9) by the relationship between the amplitude of the sound wave and the wear rate.

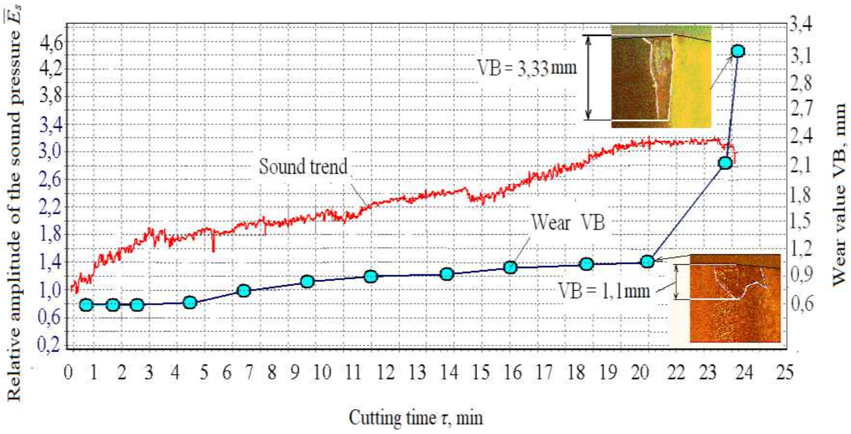

Figure 9. *Sound trend and wear curve.*

The analysis shows that at the 20th minute, the wear curve shifts from the area of normal wear to the area of catastrophic wear, which requires to finish the metalworking process, and this is also evidenced by the change in machining quality index a_{qp}, which has reached a critical value equal to one (Fig.10). The moment that corresponds to the transition from the faultless operation of the processing system to the defective state is specifically evident in the trend at 20.2nd minute when a failure occurs, i.e. at the time of the tool failure, the machining quality index aqp exceeded the maximum allowable level. In this way, it is possible to clearly predict when the process needs to be stopped and the blade replaced, which adequately corresponds to relations (12) and (13).

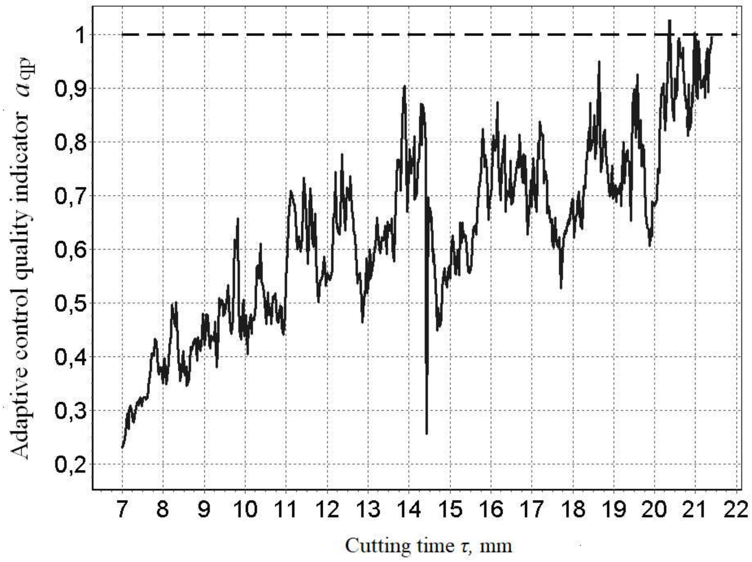

Figure 10. *Quality indicator for adaptive control* a_{qp}.

4.3. Correlation between sound and roughness

In order to compare the roughness *Ra* and the corresponding acoustic parameter $\bar{R}a$ in a dimensionless form, the definition relation (16) is used:

$$\bar{R}a = \frac{Ra(\tau)}{Ra(\tau_0)} \tag{16}$$

where $Ra\ (\tau_0)$ is the height roughness parameter defined at the beginning of the cutting process, and $Ra\ (\tau)$ is the height roughness parameter defined at the current cutting process time.

The experimental results also made it possible to define the relation (17) characterizing the coordinated evolution of the sound wave amplitude and height roughness parameter during processing:

$$\frac{Ra(\tau)}{Ra(\tau_0)} \approx \frac{E_{Si}(\tau)}{E_{S0}(\tau_0)}, \tag{17}$$

If the fraction on the left in relation (17) can be considered an analytical expression for the required “member function”, the relation for calculating the numerical value of the roughness quality index $a_R(\tau)$ (18) can be determined:

$$a_R(\tau) = \frac{E_{3B}(\tau)}{E_{3B}(\tau_0)}. \tag{18}$$

If the ratio (18) is solved relative to the current value of the height parameter, a roughness quality index having a length dimension of the order of μm (19) can be obtained:

$$a_R(\tau) = Ra(\tau_0) \cdot \frac{E_{Si}(\tau)}{E_{S0}(\tau_0)} = Ra(\tau_0) \cdot \bar{E}_S(\tau). \tag{19}$$

In controlling the dynamic behaviour of the processing system interactively, the roughness quality index is easier to evaluate by the relation (19) because it maintains the roughness dimension. Conversely, in automatic control, it is appropriate to select a dimensionless form of its representation (18), especially with respect to the corresponding software product that is part of the software environment of a specific automatic control system for the dynamic behaviour of the processing system.

Thus, the results of the experiments show a close correlation of the generated sound during cutting with the tooltip wear, as well as the correlation with machined surface quality (Fig. 11 to Fig 12), clearly demonstrating the efficiency of using the cutting sound as an information signal in the process of turning. This clearly shows the efficiency of using cutting sound as an information signal in turning materials.

Figure 16 compares time and length parallel changes in the sound signal and the roughness of the machined surface. During the machining process, the machining tool moves in the deformation contact with the material being machined, so a very intensive friction process takes place. Acoustic changes occur due to friction. These changes propagate both through the material and beyond the material through the material environment, i.e., air. The three-dimensional successive mechanical longitudinal sound wave propagates through space, while for its quantitative description, a relatively simple and precisely measurable time change of the air pressure is selected in technical practice. In the case of the machining process, this change is adequate to the cause, i.e. the change in the surface roughness. For the quantitative description of changes in the surface texture, a relatively simple and precisely measurable time change in surface roughness is chosen in technical practice. Figure 16 obtained from experimental results is also correlated with theoretical, analytical relations (17) to (19). The parameters of sound pressure and surface roughness change simultaneously with the change of the measured length of the sample of the machined material. The time delay between the two signals is negligible both in fractions of a second of the measured time and in fractions of a millimetre of the measured length.

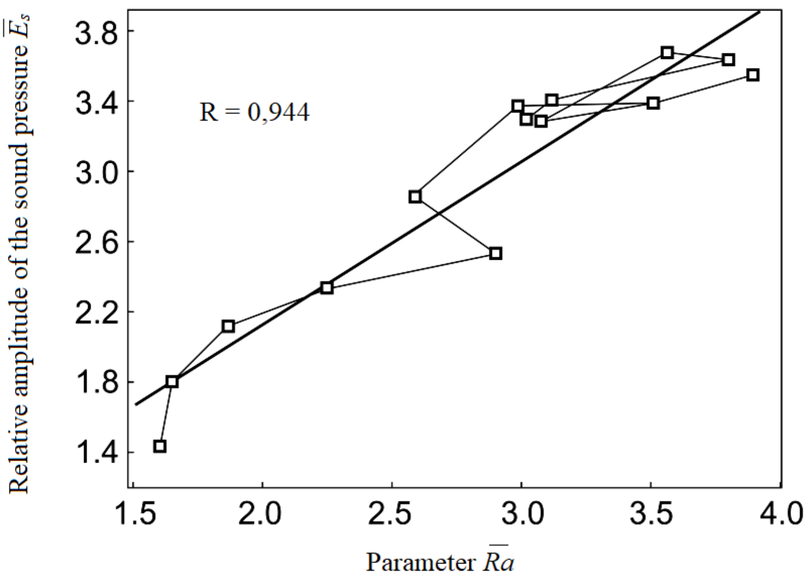

Figure 11. *Regression dependence between roughness* $\overline{R}a$ *and sound* $\overline{E}s$ *(parameters).*

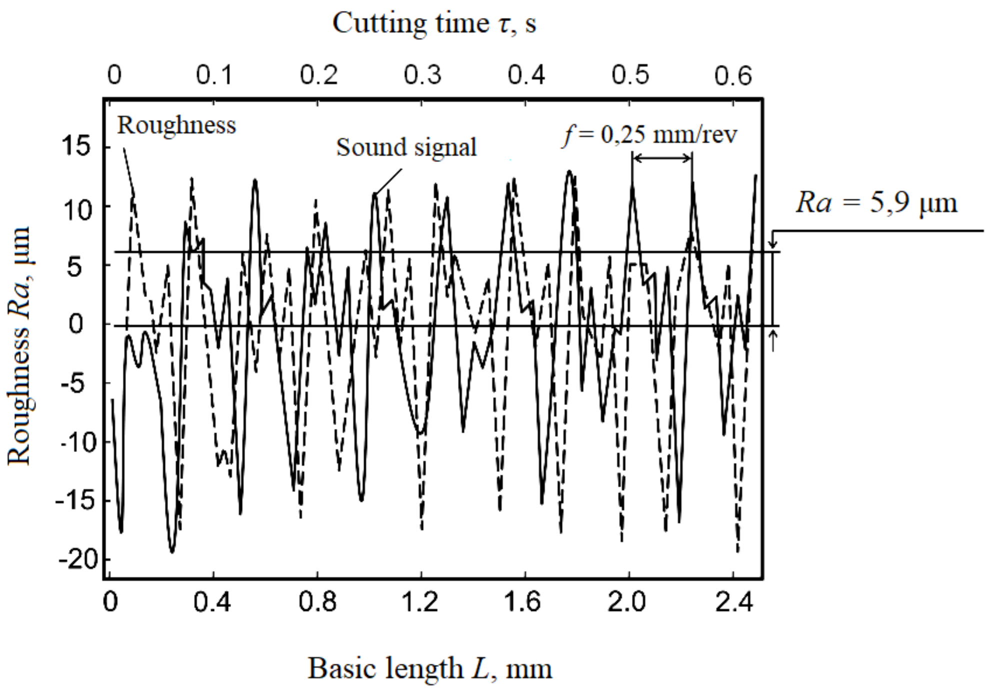

***Figure 12**. Roughness profile and form of the sound wave.*

It can be clearly stated that a smooth surface correlates with low wear of the tip of the instrument used and at the same time with a weaker intensity of sound, i.e., with its smaller amplitude. On the contrary, the roughened surface correlates with higher wear of the tip of the used tool, the blunt tool crushes the surface. This fact naturally manifests itself in the increased intensity and amplitude of the sound. Figure 12 thus declares a clear link between the sound and surface roughness, which can be used for retrograde control and regulation of the machining process, i.e., in terms of adaptive control for timely cutting-edge replacement.

5. Discussion

This article discusses an adaptive cutting control system that uses cutting sound as an interactive feedback signal for the first time. The sound is recorded in a non-contact manner, which makes it possible to eliminate disturbing effects on the recorded signal (e.g., due to machine vibrations) and thus to eliminate cutting process control errors in a timely manner. For this purpose, a computer program has been developed to complement the standard CNC machine tool software. The presented results were compared and verified [80-83], and a positive correlation between sound level, tool wear and surface roughness of the component were clearly demonstrated.

The paper [80] shows that optical inspection and sound analysis are techniques that can be used to effectively monitor the condition of a cutting tool (sharp, semi-blunt or blunt tool). These techniques provide different ways to determine the transition from a progressive tool wear state to an accelerated tool wear state (Figure 2-7). The sound produced during the machining process can be used to monitor tool condition by monitoring the power spectral density of the measured signal.

The article [81] clearly discusses that as the cutting parameters change, the sound pressure levels of the cutting process also change adequately; if the cutting process is not in progress, the overall sound pressure level is minimal;

if a negative event occurs in the cutting process, the sound pressure level suddenly increases or decreases; therefore, reducing the sound pressure level is an available method for developing an alarming system.

The work [82] shows that as the cutting parameters change, the sound pressure levels of the cutting process also change adequately. A comparison of the graphs in Figures 6 [82] and 7 shows the identity of the information provided and indicates a close correlation between sound trends and cutter wear. This information served as the basis for the use of sound as an information signal in the development of a system for adaptive control of the cutting process.

The results [83] showed that the emitted sound could be used to monitor the wear status of the tool flank during the turning process. It can be concluded that, under the circumstances, just monitoring the state of tool flank wear generated by sound is a feasible and relatively simple method. Another advantage of this method is that the time required to decide on the condition of the tool is very short, on the order of 1 second. Therefore, it is convenient and highly reliable to subject the signal part of a second to the presented method.

Based on the obtained results and comparison with other authors [80-83] (especially [82]), it can be concluded that in numerical control, the machining strategy is focused only on achieving the desired precise geometric shape, but in adaptive control, it is additionally focused on controlling the technological parameters of the machining process. The sound waves generated as noise due to mechanical vibrations of the machine are a verified information source. The method of non-contact sound measurement by means of a microphone placed close to the cutting area, and the definition of a dimensionless comparative indicator can provide accurate results of a multiplicative and additive nature, namely noise-proof results. It has been clearly demonstrated that the trends of changes in the sound levels (Figures 6, 9, 12) generated during cutting, the roughness of the machined surface and the wear of the cutting tool are highly correlated with each other. This fact also corresponds to sound efficiency as a physical quantity ideally suited for adaptive control of the metal cutting process.

In the future, it can be expected that there will be a sufficient number of applications in the practice of metal cutting and that the development of the investigated problem will move to the level of optimization adaptive control.

4 Conclusions

The paper presents a new method of effective use of the acoustic signal generated during the cutting process, in particular, to create the desired surface properties of the workpiece. The research aims to find and verify the correlation relationship between the sound generated during the turning process, tooltip wear and workpiece surface roughness.

The results of experimental studies offer the advantageous use of an audio signal as initial information for the adaptive control of materials machined by cutting with the following conclusions:

- unlike the data signals obtained by the contact method and thus subject to noise generated by the mechanical vibration of the machine, the non-contact sound measurement method using a microphone located close to the cutting area, and the definitions of comparative dimensionless indicator of the accuracy of measurement results processing provide noise-resistant results of multiplicative and additive character, as well as results resistant to pulse disturbance;

- the development trend of the generated sound and the trend of the tooltip wear change during the cutting process show a high degree of correlation, as evidenced by the high value of the correlation coefficient (R = 0.93);

- moreover, a strong correlation was found between the sound trend and surface roughness parameter *Ra* characterized by a relatively very close correlation coefficient (R = 0.94).

In conclusion, the data presented in this paper justify the recommendation of a non-contact method of measuring the sound generated during turning for the process of adaptive control of material processing.

The use of the cutting tool as a sound source and the adaptive control of the machining process in terms of the declared correlations consists in approximating the adopted trend model of the results of the sound pressure monitoring accompanying the cutting process by means of a graph. The quality of the approximation is evaluated by the degree of correlation between the calculated and measured trends in the amplitude of the sound wave. In addition, the correlation between the calculated and measured data in the area of the trend behaviour is crucial in the prediction. An acceptable level of correlation in a given area, in turn, determines the quality (reliability, accuracy) of the source prediction. It is, therefore, a predictive and diagnostic-experimental complex, which enables real-time monitoring of the technical condition and adaptive control of processing systems without interrupting the processing of materials by cutting. The predictive and diagnostic complex makes it possible to realize one of the important tasks of modern production, automation, in engineering practice.

The predictive-diagnostic complex of the machining process will enable:

- to expand the functionality and increase the productivity of processing systems;
- to improve the quality of operation of processing systems and eliminate their unplanned shutdown in order to replace defective elements;
- to improve working conditions, increase work safety and environmental friendliness of processing systems through the operational management of their work processes, which is the main goal of the modern metalworking industry.

The purpose of the work was not to create a regression equation that allows one to determine the value of the roughness and the amount of tool wear by the magnitude of the sound pressure. The aim of the work was to develop a technique for controlling the cutting process. This technique makes it possible to predict the timely replacement of a worn tool.

We have developed a technique for controlling the cutting process using the trend of sound generated during the metalworking process. Based on the results, the accuracy of the proposed method can be declared by the user up to 5%. Therefore, in this way, the instantaneous values of the measurements represent a sufficiently accurate real state and connections of individual parameters. This is a fundamental difference from current methods of adaptive control of the cutting process, which use the mean values and regression equations, but they change when the technological conditions change. This is a disadvantage of current methods of adaptive control.

Author contribution Volodymyr Nahornyi: conceptualization and methodology; Anton Panda: investigation and project administration; Jan Valíček: validation and writing – review and editing; Milena Kušnerová: validation and writing – review and editing; Marta Harničárová: validation and writing – review and editing; Iveta Pandová: data curation and investigation;

Stanislaw Legutko: formal analysis; Zuzana Palková: data curation; Ondrej Lukáč: investigation

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Consent to participate This research did not involve Human Participants; thus, consent to participate is not necessary.

Consent for publication This research did not involve Human Participants; thus, consent for publication is not necessary.

Competing interests The authors reported no potential conflict of interest.

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