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Investigation of the relationship between the cutting ability of the tool and the acoustic signal parameters during profile grinding

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ABSTRACT

Introduction. Modern mechanical engineering is closely connected with digital production management technologies, for which an important aspect is the collection of reliable information about the current state of the systems. Acoustic methods of current control of the tool cutting ability possess significant potential due to the possibility of continuously obtaining up-to-date data on the parameters of machining process. Profile grinding is one of the widespread methods of machining surfaces of complex configuration. The high importance of this method lies in the high degree of responsibility of shaped parts obtained with it. The wear parameter of profiled grinding wheels needs current control to the same extent as other types of cutting tools. At the same time, acoustic methods of research have not found wide application in relation to profile grinding. In view of this, the present work is aimed at studying the influence of the tool wear rate on the acoustic characteristics of grinding when using grinding wheels of different profiles. **Purpose of work** is to determine the acoustic parameters of profile grinding with application of planar grinding scheme as it wears out in comparison with analogical process with application of straight profile grinding wheel. As the basic **methods of research** an experiment is used to study the acoustic phenomena accompanying grinding with application of wheels of different profile. An analysis of the acoustic signal of grinding is carried out, as well as an analysis of the spectrum of its frequency composition. The frequencies of natural vibrations of grinding wheels of different profiles are investigated, its sound index is determined as a criterion for evaluating its characteristics. Acoustic characteristics of the grinding process with the use of grinding wheels of different profiles are compared. Regression analysis of acoustic data obtained as a result of the experiment is also used. **Results and discussion**. Spectrograms of frequencies of natural vibrations of the wheels under research, as well as a number of spectrograms of the acoustic signal accompanying the processing process for various technological conditions are received. As a result of comparing the obtained spectrograms, the informative frequencies of the grinding processes are determined. Mathematical models of sound level dependence on the value of periodic vertical feed S_t at depth t and processing time T are developed. It is established that the value of periodic vertical feed S_t at depth t has a greater influence on the acoustic index in comparison with the machining duration T. Practical significance and prospects of the results of the work lies in the possibility of increasing the efficiency of profile grinding processes due to the rational use of the tool availability.

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Introduction

Tool condition monitoring (*TCM*) is one of the most important elements in intelligent machining automation systems [1]. Inevitable tool wear accompanying such machining depends on process conditions and directly influences the properties of the final product. Therefore, wear parameter monitoring and precise determination of current tool performance are key to product quality assurance.

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As a widely used shaping method, grinding requires machining with a tool, the condition of which will ensure proper product quality. Dressing is used to return the original properties to the grinding wheel (*GW*). This also needs to be well timed for technological and economic reasons. *TCM* is the most effective tool to determine this moment. It is also performed at the end of the process chain, followed by finishing.

Methods which do not require suspension of the production process, in order to determine wear parameters, i.e. indirect methods, are of interest among many approaches to determine *GW* condition. Acoustic methods (acoustic emission and noise diagnostics as per *GOST 23829–85*) are both indirect and passive methods, meaning that there is no external source of energy affecting the object of study.

Many studies have focused on determining and predicting *GW* condition during processing through the use of acoustic emission signals [2]. It is shown that this method has a sufficiently high level of accuracy, information content [3], and sensitivity [4, 5] aimed at establishing current tool performance. However, this method is not common due to the high cost of equipment, and the need for specific signal transformations to filter it [6], etc. Furthermore, the method directly involving the acoustic wave generated by *GW* vibrations during processing (noise diagnostic) has been studied much less, despite its comparable practical potential [7].

Most of the main types of machining operations have been studied using acoustic methods (both acoustic emission and noise diagnostics): turning [8, 9]; milling [10]; micromilling [11]; drilling [12]; and grinding [13, 14]. All kinds of machined materials – brittle [15], ductile, composites [16], wood [17], have been considered. The studies have shown the applicability of the method for a wide range of process conditions of various machining operations aimed at determining the various parameters of the object to be studied. According to the majority of the authors of the works herein presented, the main aim of this method is to monitor cutting tool wear parameters. Researchers agree that acoustic monitoring methods are essential for practical application, in order to increase the process efficiency.

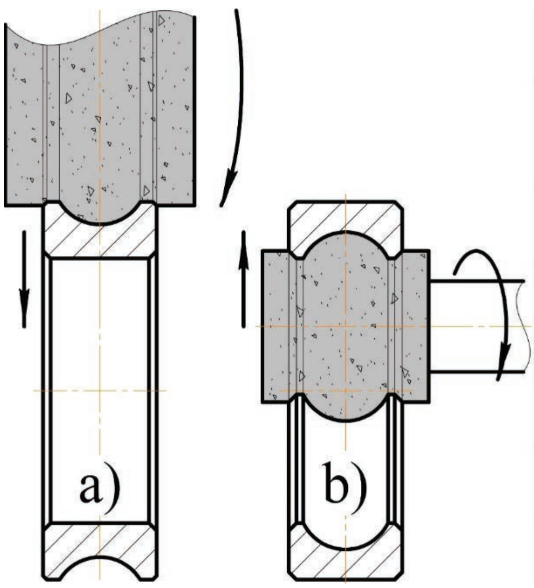


Fig. 1. Profile grinding of bearing rings:
a – external; *b* – internal

Despite all the advantages of acoustic monitoring methods and its wide use in various types of processing, determining *GW* condition by this method in profile grinding has not yet found extensive application. Profile grinding is used for finishing complex shape surfaces and involves the processing of a workpiece with a grinding wheel with a pre-shaped profile. The aim is to ensure the required dimensions, shape, and surface quality (Fig. 1). The significance of the method lies in the high degree of responsibility connected with the production of the profiled parts.

Surveys show that despite the high demand for profile grinding in mechanical engineering, the acoustic phenomena of this process have been poorly studied. Nevertheless, there is a demand for determination of the current cutting capacity of the profiled *GW* and predicting its durability period [18, 19, 20]. A deeper insight into this issue will allow rationalizing the consumption of cutting tools and increasing the efficiency of profile grinding in digital production.

An acoustic method for *TCM* in profile grinding needs to be developed. This is also connected with the need for expedient profile tool dressing in this type of processing, as well as in other types of grinding.

The **purpose** of this research is to establish the acoustic parameters of flat grinding with a profile wheel as it wears out, as opposed to a similar process using a straight profile wheel. The tasks to be solved to achieve this purpose are listed below.

Since the sound pressure generated by grinding results from the natural vibrations of the wheel [21], it is necessary to study the natural vibration frequencies (*NVF*) of grinding wheels of various profiles.

Task 1 – to determine experimentally the *NVF* of the grinding wheels studied here, in order to perform an analytical comparison of the *NVFs* of grinding wheels of various profiles.

Task 2 – to assess the contribution of the idle operation of the main systems in the experimental setup (in idle mode) to the overall spectrum of acoustic vibrations.

Task 3 – to establish experimentally the acoustic parameters of flat grinding with wheels of various profiles (spectral composition, sound level amplitudes).

Task 4 – to perform a qualitative comparison of the data acquired, in order to identify the distinctive features of the acoustic signal during profile grinding.

Research methodology

The experimental study consists of two stages. The first stage studies the natural vibration frequencies of grinding wheels. The second stage is focused on acoustic signal during processing. Each stage uses a *GW* of a straight profile and a profiled wheel. *GW* 1 is a standard straight profile grinding wheel, *GW* 2 is a grinding wheel profiled for grooving (Fig. 2).

Stage 1. A prerequisite for studying the natural vibrations of the *GIW*s is the existing relationship between the parameters of natural vibrations: physical and mechanical properties; and the geometric characteristics of a solid body [22].

$$f = F(a, \mu)C_L, \tag{1}$$

where $F(a, \mu)$ is the shape factor dependent on the geometric dimensions of the body, its shape, and Poisson's ratio; $C_L = \sqrt{\frac{E}{\rho}}$ is the parameter which represents the propagation speed of elastic vibrations in an infinitely long rod, the material of which is similar to the material of the body under consideration; E is the elastic modulus; ρ is the material density.

The shape factor $F{\cdot}(a, \mu)$ in this study is based on recommendations from the reference documentation (*GOST R 52710–2007 Abrasive tool. Acoustic method for determining the hardness and sound indices by the acoustic wave propagation speed*). The use of the method for determining the natural vibration frequency of the wheels and the sound indices as proposed in this standard is consistent with the aim of the study.

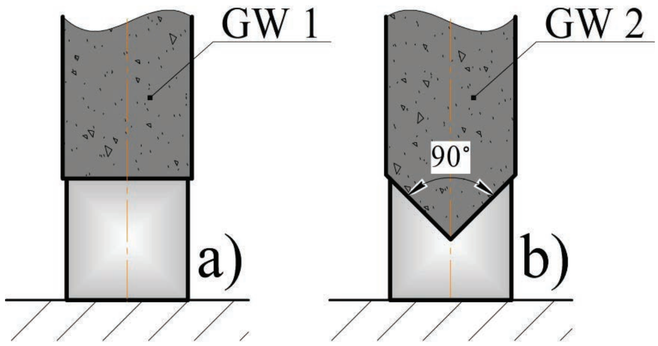


Fig. 2. Profile of the tool used:
a – *GW* 1; *b* – *GW* 2

The purpose of this stage is to determine the spectral composition of the acoustic signal excited by the impact force in the grinding wheels of various profiles. The variable factor of the experiment is the *GW* profile. The study parameter is the spectral composition of the natural vibrations of the *GW*.

Stage 2. The indirect (acoustic) characteristic of surface pendulum grinding depends on the tool profile during wear in different modes. The characteristics of the sound generated by similar processes using *GW* 1 and *GW* 2 are compared. In addition to geometric parameters, the tools used have no differences the wheel characteristics are identical.

Experimental study of the natural vibration frequencies of grinding wheels

Yuganov V.S. [23], in his study of low-frequency acoustic vibrations (*LAV*) during flat grinding, concludes that there is an almost complete coincidence of the informative frequencies characteristic of the grinding process and the natural frequencies of the wheel (Fig. 3). This conclusion was later confirmed by *Agafonov V.V.* [24]. As a result, the authors affirm that the direct source of vibrations at the informative frequency is the grinding wheel. Based on this assumption, the object of the study is the 2,700 rpm 1 250×32×76 *25A*

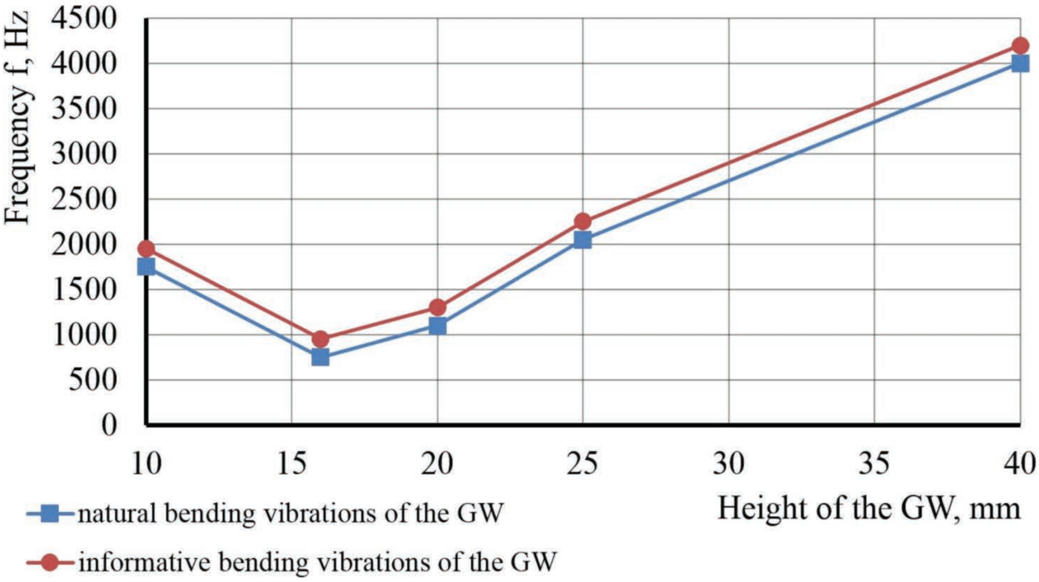


Fig. 3. Grinding wheels straight profile bending vibrations 250×H×76: Informative frequencies and Natural frequencies obtained experimentally [23]

F46 K 6 V 35 grinding wheel, pursuant to *GOST R 52781–2007*. The subject is the spectral composition of the natural vibration frequencies of *GW* 1 and *GW* 2.

An *ICHSK-2* natural vibration frequency meter was used to register and process the acoustic signal, and determine the spectral composition of the natural vibration frequencies of the grinding wheels. This device is designed for acoustic monitoring of the physical and mechanical properties of objects and detecting product defects using the spectral analysis of the acoustic signal of the object's response. In particular, the *ICHSK-2* has a mode to study grinding wheels. This enables the sound index (*SI*) of the wheel to be established, and, based on this, to determine the hardness degree of the object pursuant to *GOST R 52710 – 2007*. The device determines the *SI* based on the physical and mechanical properties of the material of the grinding wheels, as well as its geometric parameters (Table 1). Four experiments were carried out on each test object (*GW* 1 and *GW* 2).

According to the data summarized in Table 1, the *SI*s of the grinding wheels were determined according to its physical, mechanical, and geometric parameters.

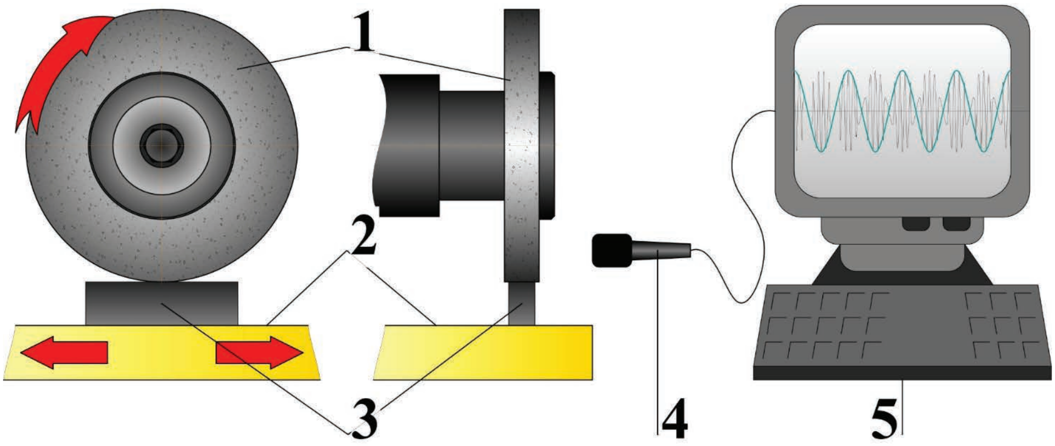
Experimental study of acoustic signals during flat grinding

The section describes a comparative experimental study of acoustic signals during flat grinding using wheels of varying profiles. The object of the study is flat pendulum grinding; the subject is an acoustic signal, accompanying this process.

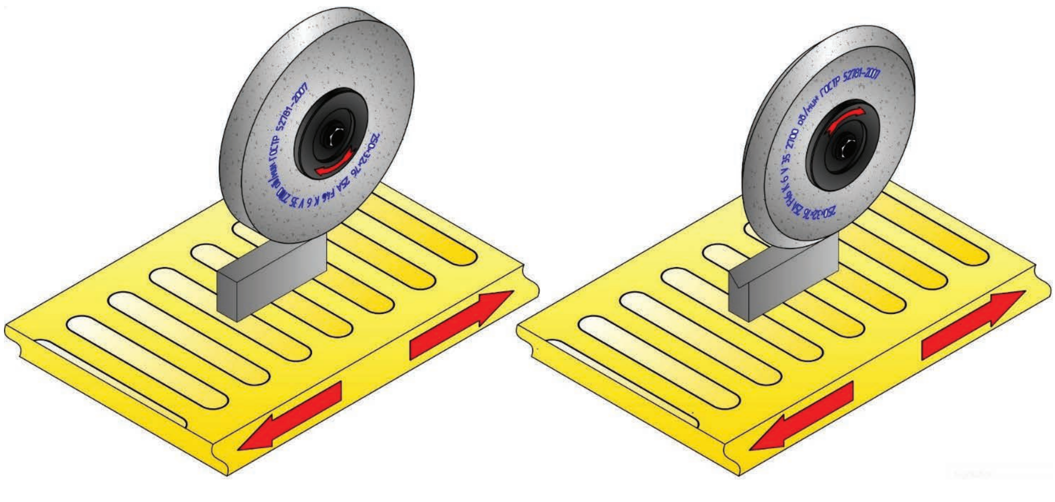
Table 1

Parameters of the grinding wheels required to determine the sound index

Parameter	GW 1	GW 2
GW designation	1 250×32×76 25A F46 K 6 V 35 2700 rpm GOST R 52781-2007	
Abrasive material type	white electrocorundum 25 A	
GW dimensions (D×H×d), mm	250×32×76	250×32×76
GW shape factor (F), m^{-1}	0.001175	0.001182
GW mass (m), kg	3.14	2.72
GW density (ρ), g/cm^3	2.02	



a



b *c*

Fig. 4. Experimental setup:

a – general view; *b* – using GW 1; *c* – using GW 2; *1* – tool; *2* – magnetic table; *3* – workpiece (sample); *4* – microphone; *5* – personal computer

Table 2

Processing modes

Mode	Value
Rotational speed of the GW V_k, rpm	2,700
Intermittent vertical feed S_t to a depth of t, mm/double stroke	0.01 / 0.015 / 0.02
Longitudinal feed of the table (workpiece) V_s, m/min	5
Grinding width l_g, mm	25 / 34
Processing time T, min	15

The experimental setup (Fig. 4) was mounted on a universal high-precision *3G71M* flat surface grinding machine with a horizontal spindle and a rectangular table. 140×25×30 mm samples of carbon structural *Steel 30* (30 % *C*) with a hardness of 37–41 HRC in the form of rectangular parallelepipeds were subjected to grinding. A 140×25 mm plane was processed with *GW* 1. A triangular groove with an angle of 90º and a length of 140 mm was processed with *GW* 2. The grinding modes are presented in Table 2.

Before processing, the grinding wheels are affixed in a statically balanced faceplate, mounted on the machine spindle, and dressed.

The aim of each individual experiment is to establish (record) acoustic signals for the established technological conditions.

The acoustic signal was recorded using a non-contact sensor. This was a compact directional microphone fixed on a tripod at a distance of 50 – 100 mm from the end surface of the tool. The analog acoustic signal received by the microphone was digitized by a *PC* sound card. A *WDM* sound card was used. *SOUNDFORGEPro 13.0* was used as the software to work with the acoustic data acquired.

The arithmetic mean deviation of the sample profile (*Ra*, μm) was measured, in order to assess the quality of the ground surface using a contact profilometer with accuracy degree 1, pursuant to *GOST 19300–86* (model 130). The processed surfaces were conditionally divided into five equal sections followed by five measurements of roughness inside each section in the direction of the longitudinal feed of the table V_S and perpendicular to V_S. The length of the baseline that was used to determine the microprofile of the sample surface was 4 mm.

The described methodology is a set of elements of the methodologies used in previous studies with a similar focus [23, 24]. The methodology was finalized and adapted taking into account the purpose of the study. The applied equipment, hardware, and software correspond to the purpose and objectives of this work and allow the required parameters to be established with sufficient accuracy.

Study of the acoustic signal of idle operation of the experimental setup

In the framework of this work, it is necessary to reflect separately the influence degree of “noise” that accompanies the operation of machine units and “noise” that does not carry information useful for research. Even in laboratory conditions, it is impossible to separate the acoustic signal of one particular source. Many elements of the machine system make its own contribution to the overall acoustic picture during processing. A preliminary study of the acoustic signals accompanying the idle operation of the machine is required, in order to achieve an insight into this contribution. When implementing this method in real production, the contribution of other sources of noise signals should be studies.

In this study, the various acoustic signals which do not carry information on the properties and condition of the tool will be called noise interference or *noise*. The signal, generated by the elastic vibrations of the *GW* during processing and changes depending on the degree of its wear, will be called an *informative* (*useful*) *acoustic signal* [23]. We analyzed the spectrum of acoustic vibrations of the basic elements in the process system, the operation of which is accompanied by noise background. We also considered the spectral composition during the series connection of the systems of (1) power supply, (2) hydraulic power plant, (3) spindle rotation, and (4) longitudinal feed of the table V_s.

Results and discussion

The section describes the results obtained during the experiment and its interpretation.

Natural vibration frequencies and the sound index of the grinding wheels of various profiles

Natural vibration frequencies. Figures 5 and 6 show the spectrograms of natural vibration frequencies for *GW* 1 and *GW* 2, respectively. Although the material of the grinding wheels and its physical and mechanical properties are identical, the *NVF* distribution spectra are different. This allows us to assert that the shape of the wheel strongly influences the nature of elastic vibrations.

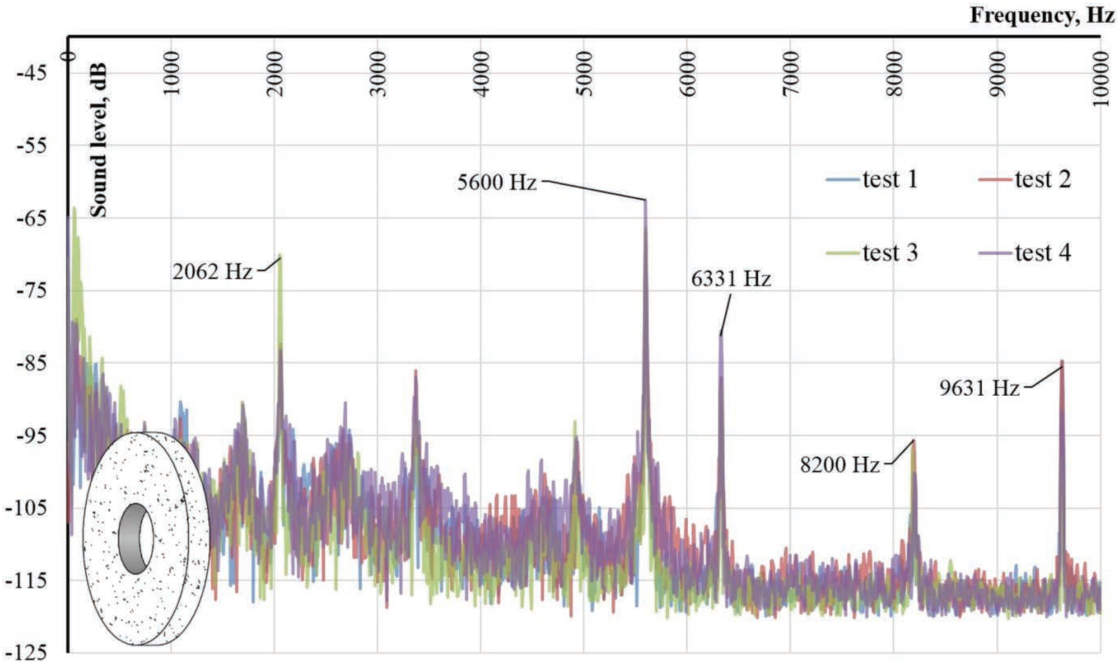


Fig. 5. Spectral composition of *GW* 1 natural vibration frequencies

A grinding wheel is considered to be a solid elastic isotropic body in the form of a disk with a central hole (sometimes as an annular plate) [22, 23, 24]. The proposed disk is a round plate, the thickness of which (wheel height *H*, mm) is small in relation to the diameter (wheel diameter *D*, mm), which has a central axial hole (bore diameter *d*, mm).

Each excess kurtosis on the spectrograms (Fig. 5, 6) indicates the physical frequency, at which vibrations appear with a certain *mode:* the spatial configuration of the vibrations of the grinding wheel points under the impact force (*GOST R ISO 2041–2012*). The graphs show that each wheel is characterized by the simultaneous appearance of several vibration modes. Each of the modes has its own shape – i.e. spatial configuration. This is when the points on its surfaces are at the maximum distance from the equilibrium (resting) position. Dominant modes are manifested at high sound levels. Due to significant deviations of body microvolumes from the equilibrium state, dominant modes are characterized by a more powerful acoustic signal recorded by the device at a certain frequency. Modes with the lowest natural vibration frequency are called fundamental natural modes. With regard to *GW* 1, the fundamental natural vibration mode f_{fun1} = 2.062 Hz; for *GW* 2, f_{fun2} = 2.337 Hz.

Sound index. An elastic acoustic wave propagating in the material of the grinding wheel and excited by the impact force has several specific characteristics. In our study, the illustrative characteristics are the normalized speed of its propagation C_L and the *sound index*. The sound index is a normalized integrated index, i.e. the value of C_L averaged in a certain range, provided for by GOST R 52710–2007 and used in acoustic monitoring [25, 26]. The connection of the *SI* with the shape factor of the object, Young's modulus (*E*-modulus), and the material density makes it a highly informative parameter enabling certain physical and mechanical properties of abrasive materials to be established, in particular the hardness degree.

The tests results enabled us to establish *SI* for each of the objects under study according to its parameters (Table 1). The sound indices for *GW* 1 and *GW* 2 took identical values and amounted to 47 units. This corresponds to the hardness degree *K*, pursuant to *GOST R 52587–2006* (or *CM1* as per *GOST 2424–83*). The values of the degree of hardness coincide with the marking as set by the manufacturer. The normalized acoustic wave propagation speed C_L recorded by the *ICHSK-2* device falls within the range of 4,600–4,800 m/s.

Based on the measurement results, the properties of the materials of *GW* 1 and *GW* 2 do not differ, which is factually correct. In this case, the change in the shape of the tested *GW* did not affect the *SI* value, i.e. the acoustic wave propagation speed C_L did not change, since this indicator depends on the physical

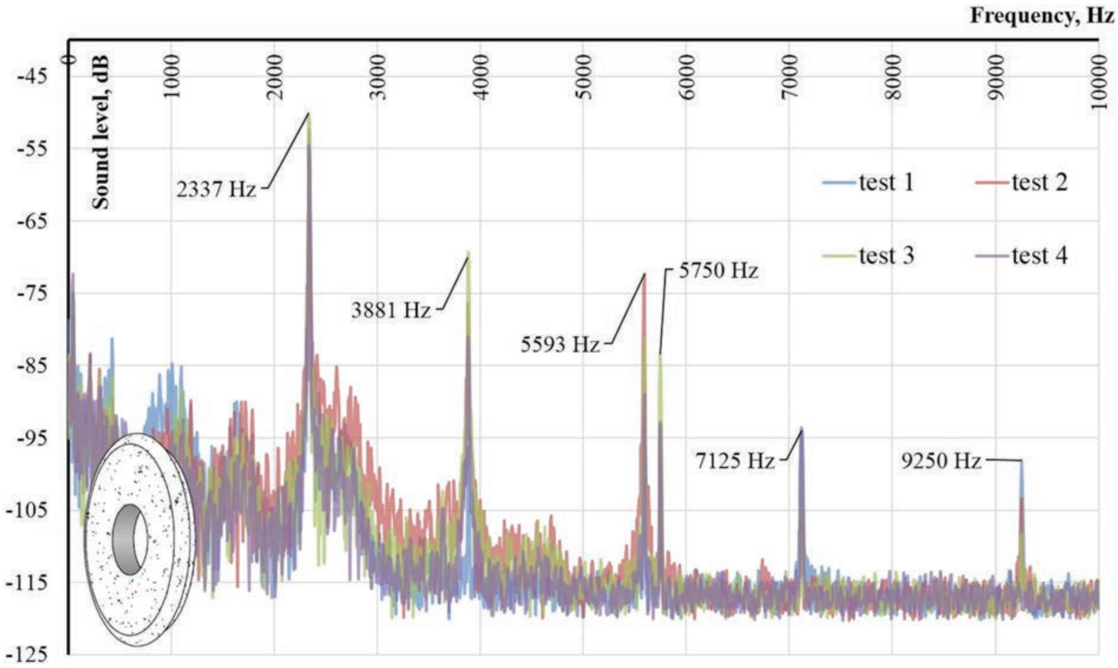


Fig. 6. Spectral composition of *GW* 2 natural vibration frequencies

and mechanical properties of the material, which remained unchanged. At the same time, we recorded significant changes in the spectral pattern of the *NVF* distribution, indicating the independence of the *SI* and *NVF* parameters.

We thus established that wheels of various geometric shapes studied herein are characterized by the different spectral composition of natural frequencies. At this stage of study, these differences do not show any regularity.

Acoustic signals accompanying the idle operation of the 3G71M flat surface grinding machine

We studied the acoustic signal accompanying the operation of the *3G71M* machine systems. Using a microphone, we recorded acoustic signals accompanying the series connection of the systems: (1) power supply; (2) hydraulic power plant; (3) spindle rotation; and (4) longitudinal pendulum feed of the table (V_s). Table 3 shows spectrograms which reflect the acoustic vibration frequency distribution for the recorded signals. At the first stage, we recorded a signal from the operation of the power supply system only, while at the last stage, – from all the above systems. Since dry grinding is used during the experiment, we did not need to take into account the operation of the coolant supply system.

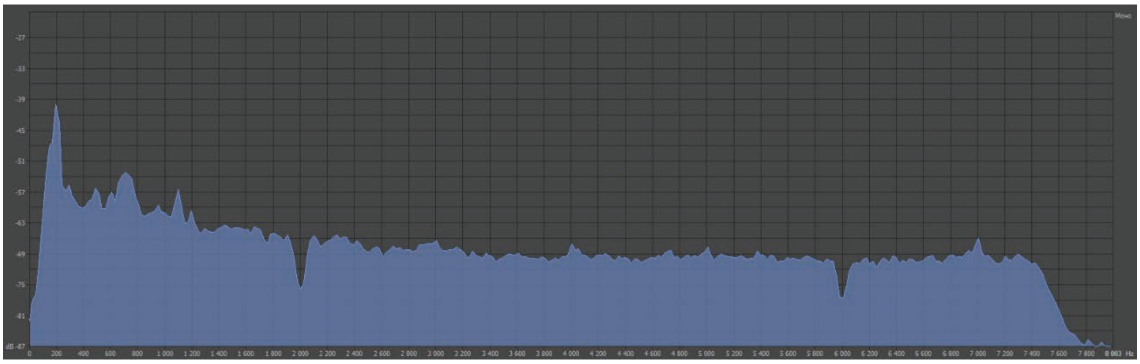
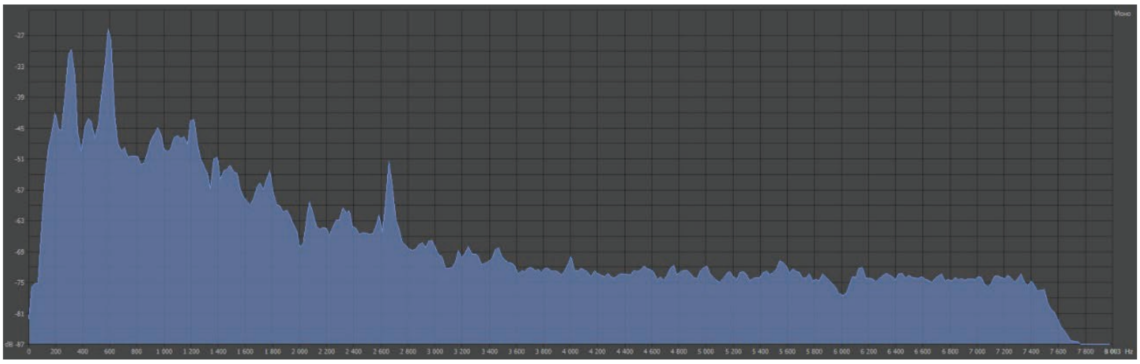
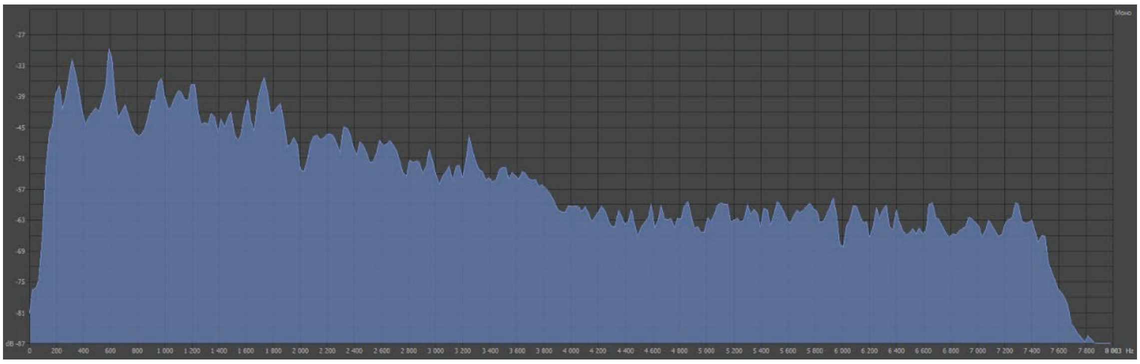
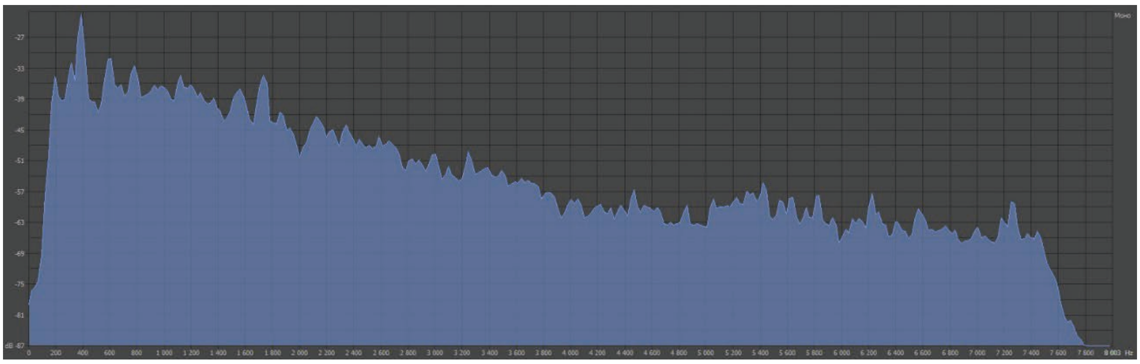
Analysis of the spectrum of acoustic vibrations of the process system (*PS*) elements showed that the grinding wheel spindle rotation made the maximum contribution to the acoustic picture of the idle machine operation (Table 3, (3)). A significant increase in the sound level in a wide frequency range (from 2 to 7.5 kHz) reached about 26% (Fig. 7) relative to the stage involving the power supply and hydraulic systems. This is caused by the combined action of the individual units of the grinding head: *M3* electric motor of the grinding wheel (2.2 kW, 2,860 rpm, 50 Hz, version *M101* with *KZ MRTU16 – 510.002–65 AOL2 – 22 – 2 – CI* terminal box); flat belt pulleys; three-point bearings; spindle; grinding wheel.

The acoustic signal corresponding to the operation of the hydraulic power plant was reflected in the frequency range of 250 – 650Hz as a stable excess kurtosis recorded on each of the presented spectrograms (except the first one). The sound level is pulsating in time, corresponding to the operating features of the oil pump. The sound level is from –17 dB to –50 dB.

The systems of power supply and longitudinal feed of the table (Table 3 (1), (4)) do not generate significant acoustic disturbances of the process system elements, do not introduce significant changes in the overall acoustic picture of the idle operation of the experimental setup.

Table 3

Acoustic signal spectrograms of *3G71M* machine systems

Active system	Spectrogram
(1) power supply	
+ (2) hydraulic power plant	
+ (3) spindle rotation	
+ (4) longitudinal feed	

An important fact to be considered in the further research is the stable “dip” in the idle operation spectrograms in the range of 1,900–2,100 Hz. When new overtones appear in the indicated range, we can affirm that it was caused by something not related to the sound of the idle machine operation.

Thus, the spectral composition presented in Table 3 (4) is the relatively constant background “noise” accompanying the processes under study. This acoustic component should not be taken into account when

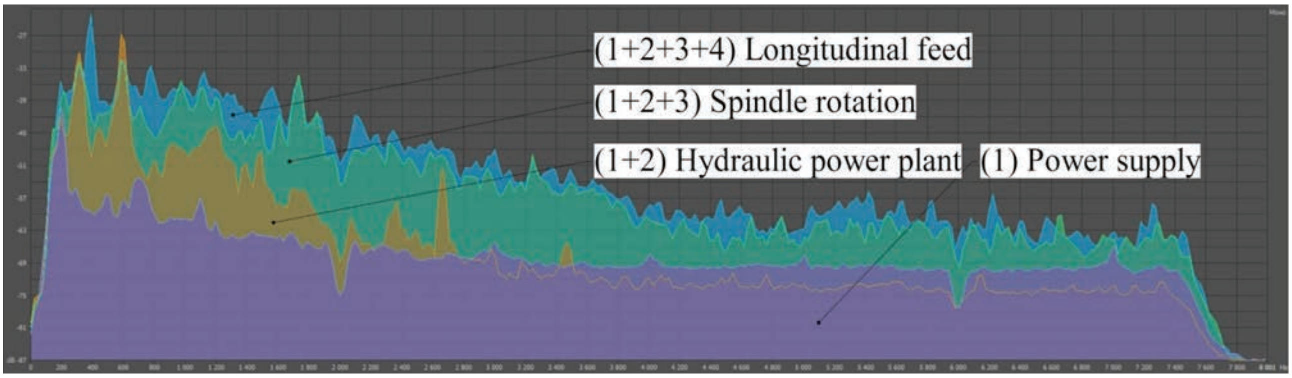


Fig. 7. Idle operation acoustic signal spectrogram of the experimental setup main systems

considering the change in the tool condition during grinding. In particular, the constant excess kurtoses present in the spectrograms (Fig. 7–11) in the ranges of 550–650 and 2,650–2,700 Hz are definitely related to the operation of the hydraulic system pumps. At the same time, it should be understood that the sound level cannot increase significantly within the indicated frequency limits during the normal operation of the hydraulic system.

Acoustic signals accompanying processing with the grinding wheels of various profiles

The test samples were ground for 15 minutes (900 seconds). The influence of the shape of the *GW* profile, the value of the periodic vertical feed S_t to the depth *t*, and the duration of grinding *T* on the acoustic phenomena accompanying the machining process were studied. The main results of studying the acoustic

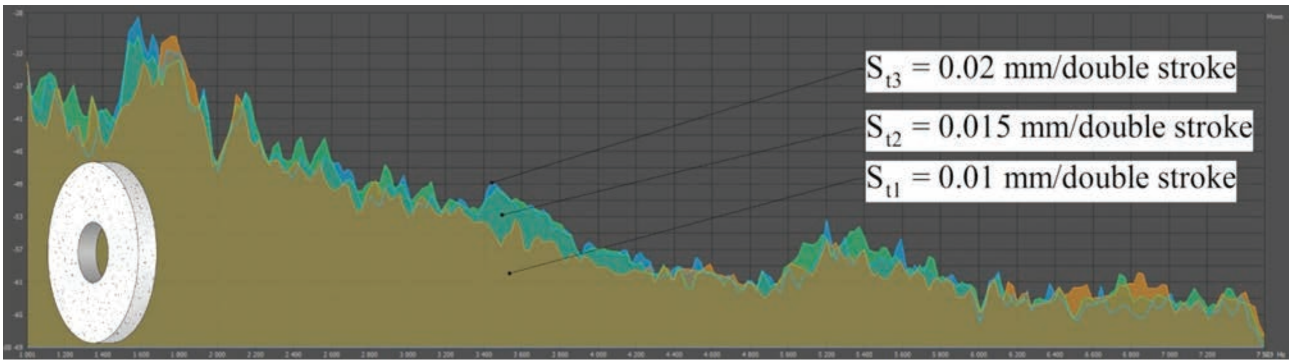


Fig. 8. Spectrograms of initial processing stage with use GW 1 and S_{t1} = 0.01; S_{t2} = 0.015; S_{t3} = 0.02 mm/double stroke feeds

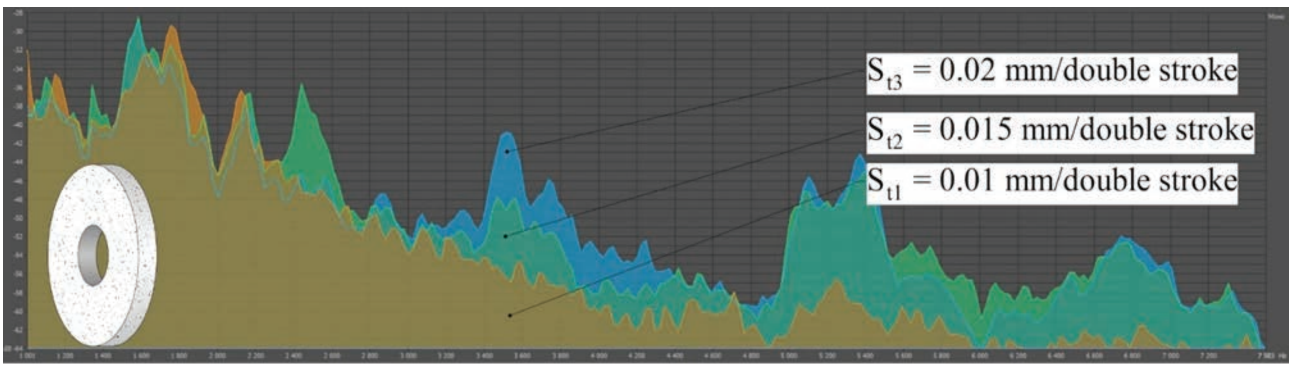


Fig. 9. Spectrograms of final processing stage with use GW 1 and S_{t1} = 0.01; S_{t2} = 0.015; S_{t3} = 0.02 mm/double stroke

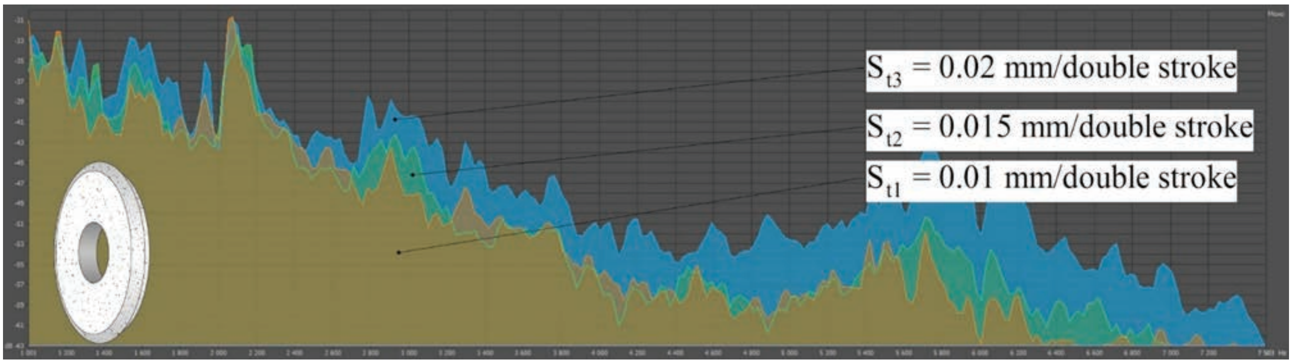


Fig. 10. Spectrograms of initial processing stage with use *GW* 2 and S_{t1} = 0.01; S_{t2} = 0.015; S_{t3} = 0.02 mm/double stroke

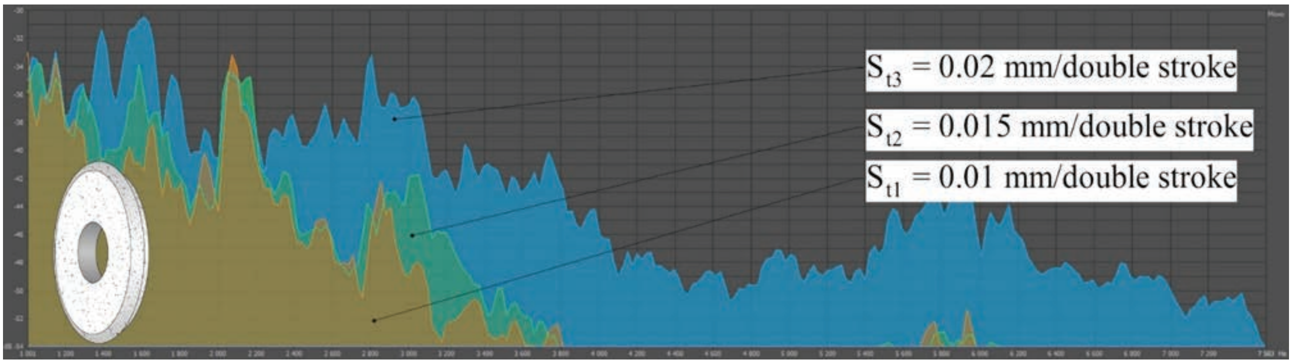


Fig. 11. Spectrograms of final processing stage with use *GW* 2 and S_{t1} = 0.01; S_{t2} = 0.015; S_{t3} = 0.02 mm/double stroke

signals are presented in the form of spectrograms of acoustic vibration frequency distribution for various process conditions and subject to comparison.

No significant and stable acoustic excess kurtoses are observed in the high-frequency range (>8 kHz). Furthermore, analysis of the spectrograms of the idle operation of the setup showed that significant excess kurtoses appear in the low-frequency region of the spectrum (<1,000 Hz). To this end, we considered the spectrograms in the range of 1–8 kHz.

The spectrograms of the initial processing stage (Fig. 8, 10) differ from the idle operation spectrogram in terms of new excess kurtoses. An additional source of acoustic vibrations here is only grinding (removal of surplus) with a dressed wheel. This process can be observed in the spectrograms in the form of increases in the amplitude of the sound level in the range of 1,400–2,000 Hz for processing with *GW* 1, and in the range of 1,400–2,400Hz for processing with *GW* 2. It can be concluded that the applied acoustic method is sensitive to the process under study.

The initial stage is also characterized by weak differences in the spectral compositions for different values of the periodic vertical feed. This applies in particular to the process using *GW* 1. Wheel surface diamond dressing involves a running-in stage. This stage can vary in duration depending on the periodic vertical feed, but the same mechanism for transforming the tool surface due to the removal of unfavorably oriented abrasive grains.

At the final stage, processing is performed with a tool, which has lost its original characteristics and has reduced cutting capacity. While the normal operation stage [27] corresponds mainly to the wearing of the peaks of abrasive grains and surface chipping, in the moment under consideration (emergency stage) it is already characterized by bulk failure of the grains and shearing from the bond. Intensively increasing tool wear and a decrease in its cutting capacity have the following manifestations in the spectrograms of the final processing stage (Fig. 9, 11). We can see a significant increase in the amplitude of the sound level in a wide frequency range. This is strongly manifested during grinding in harder modes (S_{t2}, S_{t3}). The amplitude of the sound level also increases for small values of S_t (S_{t1}), albeit to a lesser extent.

For the final processing stage with *GW* 1, the most characteristic frequency ranges containing significant increases in the amplitude of the sound level are: 2,150 ± 150 Hz; 3,500 ± 300 Hz; 4,900–5500 Hz; and 6,750 ± 200 Hz. We can similarly list the frequency ranges inherent in the final processing stage with *GW* 2: 2,070 ± 200 Hz; 2,750 ± 250 Hz; and 5,500–6,150 Hz.

Thus, due to the differences in the spectral composition of acoustic vibrations and the absence of other factors able to change it significantly, we can affirm that the shape of the grinding wheel significantly affects the spectral composition of acoustic vibrations during processing. Moreover, changes in the cutting capacity during grinding are also reflected in the spectrograms of the process acoustics.

We then compare the frequency distributions of acoustic signals obtained when studying the *NVF* of wheels and the grinding process. To this end, we place the graphs of the *NVF* (Fig. 5, 6) and the spectrograms of the grinding process at the final processing stage (Fig. 9, 11) in a single coordinate system in a simplified form and make a visual comparison (Fig. 12).

Let us single out the main frequency intervals containing significant excess kurtoses which develop in the course of processing. In order to do this, we need to take into account the noise accompanying the operation of the experimental setup units. Figure 12 schematically shows a comparison of the *NVF* of the grinding wheels and the acoustic signal frequencies recorded during grinding.

The dominant natural vibration frequencies of the grinding wheels are 2,062 Hz and 2,337 Hz for *GW* 1 and *GW* 2, respectively. These vibration frequencies were used to calculate the propagation speed of the sound wave C_L, and to determine the sound index. The graph in Figure 12 shows that there is no complete coincidence of the natural vibration frequencies of the grinding wheel with the frequencies of acoustic signals during grinding, as stated by *V.S. Yuganov* [23]. However, there are fairly close values of

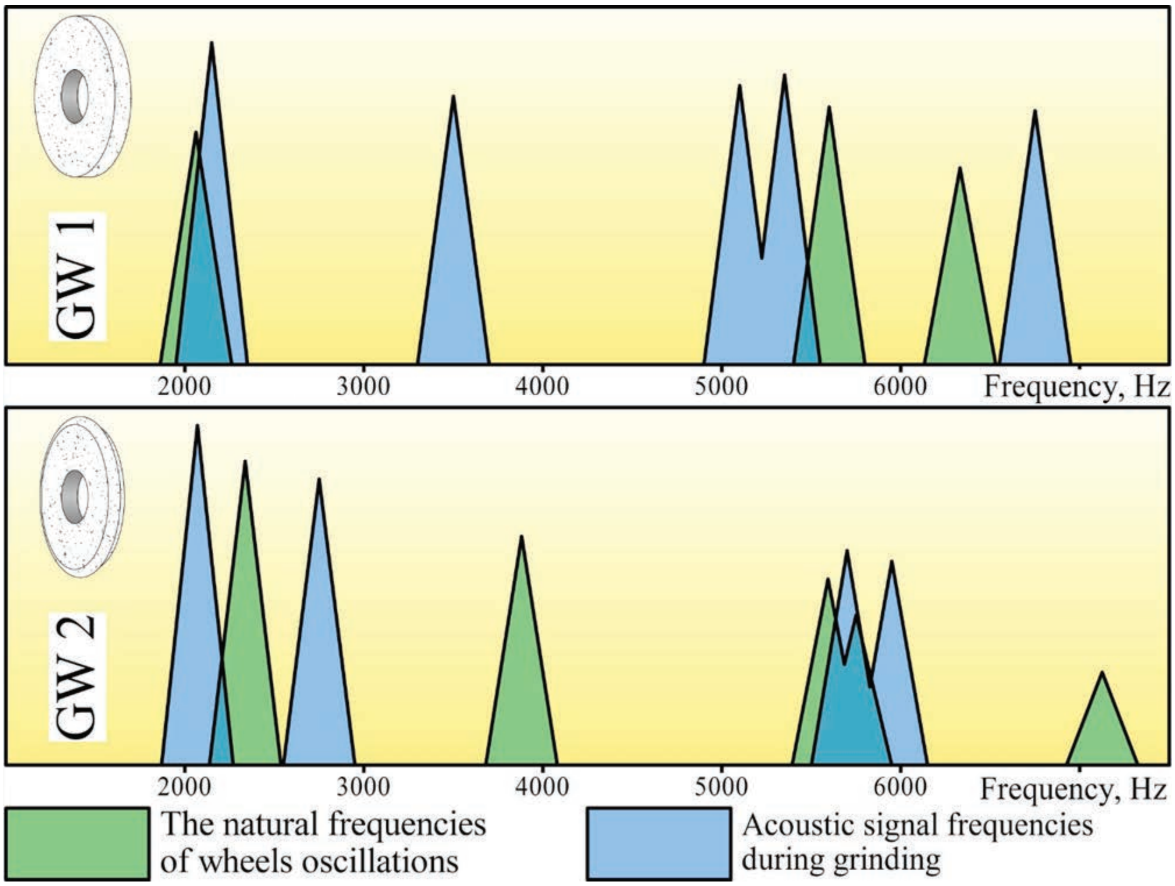


Fig. 12. Comparison scheme of grinding wheels natural vibrations frequencies and frequencies of acoustic grinding signal

these frequencies. The closest values are observed when considering the *NVF* of *GW* 1 and the frequencies during grinding with a straight profile wheel: 2,062 Hz and 2,150 Hz, respectively. In the event of a similar comparison of *GW* 2, the frequency difference is more significant: natural vibrations – 2,337 Hz: and grinding – 2,070 Hz. It can thus be confirmed that the source of the acoustic signal during grinding is the grinding wheel. Informative frequencies for the processes using *GW* 1 and *GW* 2 are, respectively: f_{GW1} = 2,050 – 2,250 Hz; (2,150 ± 100 Hz); and f_{GW2} = 1,970–2,170 Hz (2,070 ± 100 Hz).

As a result, we found that when studying the relationship between the acoustic characteristics of the grinding process and the tool cutting capacity for various process conditions (tool profile, the periodic vertical feed to the depth *t*, and the duration of processing), the dominant natural vibration frequencies of the grinding wheels need to be taken into account, since it can be used to determine the informative frequencies.

Mathematical modeling of the sound level parameter during grinding with the tools of various profiles

If we have data available on the dynamics of the acoustic signal during grinding, we can develop *regression models* (2, 3) which describe the dependence of the sound level (β, dB) on the processing time (*T*, min) and the periodic vertical feed to the depth *t* (S_t, mm/double stroke) for each of the wheels.

$$\beta_{GW1} = -38.6 + 128.7S_t + 0.096T; \tag{2}$$

$$\beta_{GW2} = -36.05 + 75.9S_t + 0.29T. \tag{3}$$

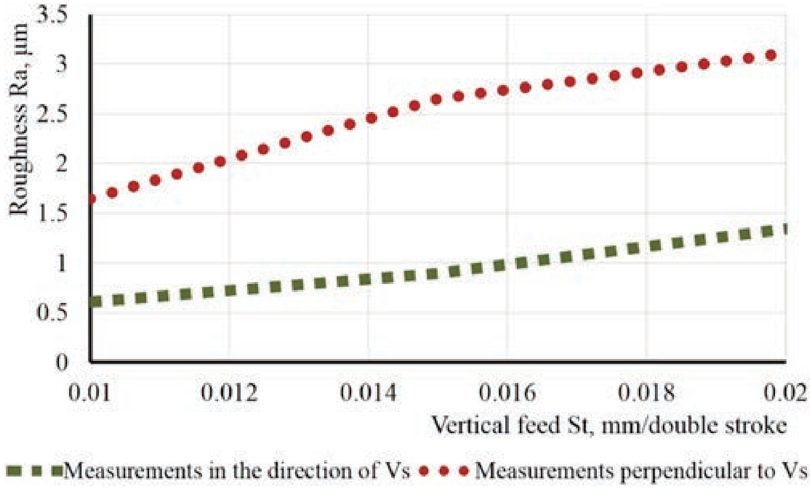
The statistical significance of the equations was verified using the determination coefficient and *Fisher's* criterion. With regard to equation (2), the determination coefficient is R^2 = 0.46, and for equation (3) R^2 = 0.63. The calculated value of *Fisher's* criterion for equation (2) F_{GW1} = 36.5, and for equation (3) F_{GW2} = 73.4. The table values of the criterion for the equations coincide, since during statistical processing it has an equal number of the degrees of freedom: F_{tabl} = 3.07. Since in both cases, the actual value of *Fisher's* criterion significantly exceeds the critical (tabulated) value, we can conclude that the determination coefficients are statistically significant and the regression equations are statistically reliable. In addition the coefficients at S_t and *t* are jointly significant.

Mathematical models (2) and (3) describe the dependence of the acoustic parameter – the sound level of a certain frequency on the periodic vertical feed to the depth *t* and the processing time. The models have both similarities and considerable differences. Analysis showed that the periodic vertical feed to the depth *t* (S_t, mm/double stroke) has a greater influence on the sound level (similar to [28]) as compared to the processing time (*T*, min). At the same time, the processing time factor is more important for equation (3) than for equation (2). Thus, *GW* 2 processing time has a greater influence on the sound level than *GW* 1 processing time.

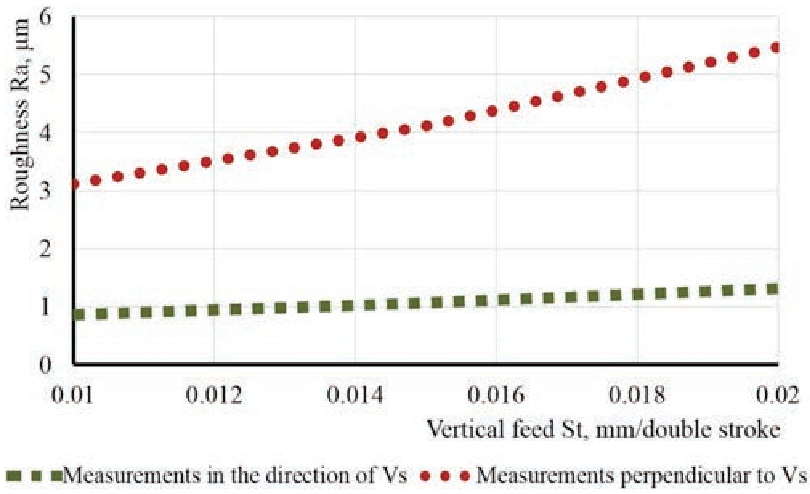
The applied significance of these models lies in the possible prediction of the sound level, in the aims of monitoring current cutting capacity in the ranges of S_t from 0.01 to 0.02 mm/double stroke, and the processing time from 0 to 15 minutes. The mathematical models thus obtained for determining the acoustic parameters (amplitude of the sound level) can be used correctly, only if the informative frequencies, for which these models were developed, match.

Roughness study. The roughness of the workpieces was studied at the end of the processing cycle which lasted for 15 minutes. The results of the measurements are presented in the graphs of Figure 13. We established the dependence of the arithmetic mean deviation of the sample profile (*Ra*, μm) on the periodic vertical feed to the depth *t* (S_t, mm/double stroke).

The graphs show that the surface roughness formed by profile wheel *GW* 2 is always much higher than when compared to the processing using *GW* 1. Thus, measurements in the direction of the longitudinal feed V_S differ by 20 %, and measurements taken perpendicular to the V_S direction – by 70 %. The roughness also increases with an increase in the periodic vertical feed to the depth *t*. Although the values for *GW* 2 exceed those for *GW* 1 for the measurements taken along the V_S direction, it increases more slowly (depend



a



b

Fig. 13. Dependence of roughness on the value of periodic vertical feed S_t at depth *t*:
a – for *GW* 1; *b* – for *GW* 2

less on S_t). The roughness obtained for S_{t1} = 0.01 mm/double stroke differs from the roughness obtained for S_{t3} = 0.02 mm/double stroke by 2.3 times for *GW* 1, and 1.6 times for *GW* 2.

Since the use of *GW* 2 increases the area of the contact spot of the tool with the workpiece (by 35 %), the processing requires more power consumption. This is consistent with the conclusions of *Ermolaev V.K.* [29]. Tougher processing conditions implemented on the same equipment worsened the quality of the processed surface.

Line of further research. The acoustic method, which has gained reputation in many types of processing, can provide high-quality information support, if sufficiently studied. Therefore, identifying the features of the acoustic characteristics inherent in profile grinding and establishing the relationship between it and the wear rate of the grinding wheel, allow the current condition of the tool to be established. It also opens the way for adjusting the grinding modes according to the product quality requirements.

The main line of further research in this area is the upgrading of the mathematical models and expanding the area of its practical applicability.

In order to establish a reliable relationship between the indirect acoustic parameters of profile grinding and the quality characteristics of the processed surface, the dynamics of changes in the *micro-* and *macrotopography* of the surface of the grinded workpieces over time need to be studied. The significance degree depends on the variety of experimental factors and, accordingly, the applicability of models in a wider range of process conditions. Such conditions, first of all, include: process flow diagrams and grinding modes; geometrical parameters of *GW* profiles and characteristics; and work piece material. When choosing factors, which influence the studied acoustic parameters and quality characteristics, we need to proceed from the current production needs.

An important stage in this work is to determine the informative frequencies using the analysis of the natural vibration frequencies of grinding wheels. Since the applied method showed close values of *NVF*, and informative frequencies of the acoustic signal during grinding, it would be expedient to continue research in this area and focus on grinding wheels of other geometry.

The outcome of the planned study will consist in the development of guidelines to choose efficient technology for the processing of a batch of workpieces. This will in turn depend on volume and quality requirements based on the characteristics of the acoustic signal.

Conclusions

Within the framework of this work, a study of profile grinding by the acoustic method was carried out. The informative acoustic range associated with the change in the state of the grinding wheel as the processing progresses is determined. From which it follows that the goal of the work has been achieved. The main conclusions of the study can be listed as follows:

1. The nature of the spectral composition of the natural vibration frequencies of the grinding wheel depends on its shape. There are significant differences in the *NVF* spectrograms for objects of different shapes. The empirically determined sound index showed no dependence on the shape of objects, since it is an indicator of physical and mechanical properties.

2. The study of the acoustic signal accompanying idle operation of the experimental setup showed that the spindle rotation with the grinding wheel made the most significant contribution to the acoustic picture. Furthermore, we established the influence of the hydraulic system on the acoustic signal in the low-frequency acoustic range (< 1,000 Hz). As a result, it will be further expedient to carry out a study of the spectrograms of the acoustic signal of grinding in the range from 1 to 8 kHz.

3. We identified the frequency ranges when the amplitude of the sound level increases during grinding with GW 1 and GW 2. These ranges are:

– for *GW* 1: 2,000 – 2,300 Hz, 3,200 – 3,800 Hz, 4,900 – 5,500 Hz, 6,550 – 6,950 Hz;

– for *GW* 2: 1,870 – 2,270 Hz; 2,500 – 3,000 Hz; 5,500 – 6,150 Hz.

We established informative frequency ranges: f_{GW1} = 2,050 – 2,250 Hz; (2,150 ± 100Hz); and f_{GW2} = 1,970 – 2,170 Hz (,2070 ± 100 Hz). We showed the dependence of *NVF* and acoustic signals during grinding. Preliminary assessment of *NVF* allows the informative frequencies of the acoustic signal of grinding to be determined when the wheels of various profiles are used.

4. Using the regression analysis of acoustic data, we developed mathematical models for the dependence of the sound level (β, dB) on the periodic vertical feed to the depth *t* (S_t, mm/double stroke), and the processing time (*T*, min) for the considered tools:

$$\beta_{GW1} = -38.6 + 128.7 S_t + 0.096T;$$

$$\beta_{GW2} = -36.05 + 75.9 S_t + 0.29T.$$

It has been established that the sound level can act as an indirect criterion for determining the current state of the grinding wheel during of processing, which makes it possible to maintain the specified quality requirements for the workpieces.

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Conflicts of Interest

The authors declare no conflict of interest.

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