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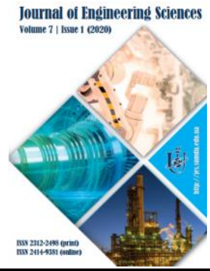

Vibrational Impact on Milled Surface Irregularities

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Abstract. The methodology and results of a simultaneous study of causally linked parameters of mechanical vibration (cause) and surface irregularities (consequence) in flat milling with an end mill are given. The features of measurement and analysis of surface quality parameters through the application of the separation frequency method of profilogram harmonic components on the surface roughness, waviness, and the deviation of the profile are reviewed. A new method of profilogram digital processing is developed, comprising the steps of its digitization, low-pass filtering, and the formation of the roughness profile. The initial theoretical positions on modeling mechanical (elastic) waves which are caused by vibration in the cutting zone and propagate in a solid, liquid, and gas (air) media are presented. The results of experimental studies of milled surface profilogram and the vibro-displacement signal in the milling are given.

Keywords: part performance, surface finish, surface integrity, vibro-acceleration, vibro-velocity, vibro-displacement, roughness, waviness, form deviation.

1 Introduction

Both the machined surface quality and physical-and-mechanical surface layer state as well as along with the machine part accuracy, are the most critical indicators that determine the machined part performance, i.e. its operational properties. The complexity of post-operative monitoring of micro- and macrogeometry of the surface machined makes the relevant task of technical diagnostics of the surface finish parameters (roughness, waviness, and contour) based on information signals through which it is possible to control the machining operation such as milling, turning, grinding, etc. The source of such signals is physical phenomena that accompany the metal cutting or abrasive machining, to wit: force, temperature, and vibro-acoustics. The knowledge of the connection of these phenomena with the indicated surface quality parameters will allow making it possible to predict this quality not only by controlling the result (control of roughness, waviness, and contour) but also by controlling the machining process state parameters, including vibrations and acoustic emission ones.

It should be noted that many problems from this direction still have no been solved scientifically, while others (solved tasks of the "know-how" type) are often inaccessible due to the commercial interest of the developers.

Surface irregularities on machine and instrument parts that characterize the quality of this surface have a significant impact both on the machine parts' operational characteristics and the machines themselves. The methodology for the design and assessment of both the surface quality and the part accuracy is used at various stages of the product life cycle: in the design and technological preparation of production, the production itself, and in control (testing) of products. It is generally accepted that the theory of surface irregularities roughness is part of a more general theory of dimensional parameters since all dimensional parameters of machine parts together affect the performance (operational properties) of the joints of these parts. For example, during friction and wear of machine parts, there is a joint effect of gaps, contour deviations (e. g., ovality, and conicity), waviness and surface roughness on the efficiency and durability of mechanical engineering products [1].

2 Literature Review

In recent years, the technological world has gained experience in using the relationship of surface quality with the machine parts' functional performance. Due to both the optimal standardization of the parameters of surface irregularities (roughness, waviness, and contour) and their technical support, a significant improvement in the quality of machines and mechanisms has been achieved, which positively affects their operational properties. At the same time, national standards for surface roughness have not been revised for a long time, their level (a lag of their level has been taken place) is lagged the corresponding German (DIN) American (ANSI) and Japanese (JIS) standards. Domestic designers do not have information about the roughness parameters, which reflect the functionality of the surfaces working on contact, as well as about the effect of waviness on the functional properties of the surface. There is insufficient information in the literature about a single concept of measuring and analyzing irregularities, regardless of the type of measured micro- or macro-irregularity (roughness, waviness, contour) [2, 3]. This information is of great importance and application in solving various applied problems. This concept, named the so-called Perthometer concept, is based on spectral analysis and transformation of the irregularity's spectrum, regardless of their metrological classification in the digital data processing. The concept is implemented on a modular computerized station (computer-controlled station) for measuring and analyzing the roughness, waviness, contour and even the all topography of the surface to be tested while documenting the results of the analysis under the officially applicable standard (DIN, ANSI, JIS) or considering customer requirements.

As an instrument for separating irregularities in the changing interval from "micro" to "macro" is filtering the digital signal of the profilogram obtained using computerized equipment. However, in the technical literature, there is no information about the methodology for conducting such digital data analysis. As a rule, some information is partially given in the manuals for portable measuring instruments with integrated microcontrollers (e. g., Mitutoyo, Japan), as well as for stationary and laboratory computerized stations of the type "Hommel-Etamic T8000" (JENOPTIC AG, Germany) and MarSurf LD 120 (Mahr GmbH, Germany).

The available information on the application of the frequency approach to the analysis of irregularities of the machined surface is segmental, based on different terminology and accepted notation, not related to the analysis of mechanical vibrations and waves in an elastic system during mechanical machining and the wave process of the propagation of mechanical waves in a solid elastic body (metal cutting machine) and sound in an elastic medium of air.

Thus, the development of a method for measuring and analyzing the quality parameters of the machined surface and vibroacoustic oscillations during its machining based on the frequency approach is an urgent task in mechanical engineering technology since this technique can be used in computer diagnostics of the cutting or grinding system on CNC machines. It is necessary to develop a methodology for surface profilogram digital processing after milling by applying a frequency approach to the analysis of surface roughness and vibration analysis during milling to establish the relationship between the obtained spectrograms of the surface profile and vibrations during its machining [4].

3 Research Methodology

Vibrations or mechanical oscillations in metal cutting and abrasive machining (grinding) characterize the current state of the cutting (grinding) system and, in this regard, are another important area in the technology of mechanical machining, called cutting (grinding) dynamics. The literature review has shown that new approaches are emerging to the study of both vibrations and surface irregularities that are formed during metalworking. In this regard the following main aim of the research is formulated: to develop a unified methodology for the analysis and assessment of both mechanical vibration in the elastic system of a metal cutting machine and surface irregularities that arise during machining. The mathematical apparatus that is convenient to use for the unified methodology is the well-known in mathematics direct and inverse Fourier transforms, including discrete and fast [10].

A disturbance or vibration causes mechanical (sound, elastic) waves in matter, whether solid, gas, liquid, or plasma. The matter that waves are traveling through is called a medium. For example, water waves are formed by vibrations in a liquid, and sound waves are formed by vibrations in a gas (air). These mechanical waves travel through a medium by causing the substance particles (i.e., molecules) to bump into each other, like falling dominoes transferring energy from one to the next. Sound waves cannot travel in the vacuum of space because there is no medium to transmit these mechanical waves (what can't be said about electromagnetic waves).

The displacement $y(x,\tau)$ of medium particles from the equilibrium position in a sine wave depends on the coordinate x on the OX axis along which the wave propagates, and on time according to the following law for the "plane progressive wave" [11]:

$$y(x,\tau) = A \sin \omega \left(\tau - \frac{x}{v}\right) = A \sin(\omega\tau - kx), \qquad (1)$$

where $k = \omega/v$ is the so-called wave number, rad/m; $\omega = 2\pi f$ the angular frequency, pad/s; $v = \omega/k$ is the phase (wave) velocity of the wave (the velocity with which any given phase is traveling).

Given that the angular frequency $\omega = \frac{2\pi}{T}$ and the wavelength $\lambda = Tv$, equation (1) can also be written in the following forms (Fig. 1):

$$y(x,\tau) = A\sin\frac{2\pi}{T v}(v\tau - x) = A\sin\frac{2\pi}{\lambda}(v\tau - x), \quad (2)$$

$$y(x,\tau) = A\sin\frac{2\pi}{\lambda}\left(\frac{\lambda}{T}\tau - x\right) = A\sin 2\pi\left(\frac{\tau}{T} - \frac{x}{\lambda}\right), \quad (3)$$

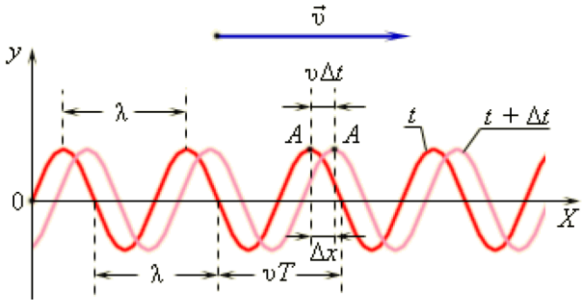


Figure 1 – A plane progressive simple harmonic elastic wave moved in a matter

Formulas (1)–(3) take place if the elastic wave is regular (monochromatic) in the sense that the different quantities describing the wave such as the wavelength, frequency and thus the wavenumber are constants.

Group velocity is the velocity of movement of a group of waves that form a wave packet localized in space at any given time. Its value is as follows:

$$u = \frac{dx}{d\tau} = \frac{d\omega}{dk}, \quad (4)$$

Relationship between group and phase velocities is the following

$$u = v - \lambda\frac{dv}{d\lambda}, \quad (5)$$

So, the group velocity is less than the phase one by the amount of the additive $\lambda\frac{dv}{d\lambda}$.

The group velocity of a wave is the velocity with which the overall (total) envelope shape of the wave's amplitudes – known as the modulation or envelope of the wave – propagates through space.

Sound or acoustic waves in the broad sense are all sorts of mechanical waves propagating in an elastic medium. In the narrow sense, the sound is called sound waves in the frequency range from 16 Hz to 20 kHz, which is perceived by the human ear. Below this range lies the region of infrasound, above – the region of ultrasound. The main characteristics of sound include a volume (loudness) and a pitch (tone).

Sound volume is determined by the amplitude of the pressure fluctuations in the sound wave and is measured in particular units – decibels (dB). For example, a volume of 0 dB is the threshold for audibility, 10 dB is the tick of the clock, 50 dB is the typical conversation, 80 dB is the scream, and 130 dB is the upper limit of audibility (the so-called pain threshold).

A pitch (tone) is a sound made by a body that performs harmonic vibrations (for example, a tuning fork or string). The frequency of these vibrations determines the pitch: the higher the frequency, the higher the sound seems to us. So, pulling the string, we increase the frequency of its vibrations and, accordingly, the pitch of the sound.

The sound speed in different media is different: the more elastic the medium, the faster the sound propagates in it. In liquids, the speed of sound is more significant than in gases, and in solids – more than in liquids. For example, the speed of sound in air at a temperature of 0 °C is approximately 340 m/s. It is convenient to remember it as “a third of a kilometer per second” or “one kilometer per three seconds”. In water, sound travels at a speed of about 1,500 m/s, and in steel – about 5,000 m/s. Note that the frequency of sound from a given source is the same in all media: medium particles make forced vibrations with the frequency of the sound source (vibration). According to formula (1), we conclude that, when passing from one medium to another, along with the speed of sound, the length of the sound wave changes because $\lambda = Tv$ (Fig. 1).

For oscillation parameters that change over time, the frequency approach (Hamming’s term), which represents the possibility of transferring information from the time-dependent form of its presentation to the frequency one, has been used for a long time. This is since the vibroacoustic parameters of vibrations (vibration acceleration, vibration velocity, vibration displacement, sound pressure) by their physical nature change as the processes of metal cutting and abrasive machining occur over time.

The signal characterizing surface irregularities is a function of the coordinates of this surface, but initially, during the formation of roughness, this signal also depended on time. Therefore, concerning already-formed irregularities (the result of cutting or grinding), the frequency approach mathematical apparatus is fully applicable, since the coordinate of the displacement (path) is directly proportional to time. The only formal difference in the frequency analysis of irregularities is in the use of the irregularities step (measured in units of length) instead of the frequency of their change. To do this, the abscissa axis is the ratio of the main step (equivalent of the first harmonic) to the subsequent current steps (equivalent of harmonics with frequencies higher than the first).

The studies were performed on CNC machining center 500V/5, where there was milling the individual samples (specimens). Besides, there were measuring the quality parameters of the milled surface with the aid of computer measuring station T8000. This station is a benchtop type, made in the form of a CNC coordinate measuring machine. It contains a motorized column of Wavelift type for vertical movement of the transverse crosshead by 400 mm, a rotary support of the drive, a drive of the feed mechanism of the Waveline type (to a length of 60 or 120 mm), a two-coordinate measuring table without an electric drive, a granite slab with a *T*-shaped groove. The GTR-4 type tool table has a niche with a printer and a passive vibration reduction system. There are two contact elements: an unsupported probe for measuring surface roughness and waviness (toolkit TKU 300/600) and the Wavecontour type sensor for measuring contour [12].

The software, including TURBO ROUGHNESS, TURBO WAVE, TURBO CONTOUR, and EVOVIS, is used to measure roughness, waviness, geometric parameters of the surface profile and topography, respectively, by DIN EN ISO 4287.

Prefix "Turbo" allows to package applications and their dependencies into a lightweight; isolated virtual environment called a "container". The "Turbo" simplifies development and eliminates bugs by deploying applications in a "known good" configuration with a fixed set of components and dependencies. Containers obviate the need for installers and prevent conflicts with the natively installed software. Thus, the TURBO software is isolated from the host environment. Turbo containers are built on top of the Turbo Virtual Machine, an application virtualization engine that provides lightweight namespace isolation of core operating system objects such as the file system, registry, process, networking, and threading subsystems.

The used digital filters make it possible to separate the long and short waves which are contained in the primary profile (Fig. 1). To distinguish between types of irregularities, the following filters are used: RC discretely calculating (mm) according to DIN 4768; Gaussian (M1) digital filter (mm) according to DIN EN ISO 11562, part 1, (50 % Gauss); double Gauss (M2) for determining the relative reference length and R_k parameters according to DIN EN ISO 13565-1.

The maximum wavelength (cutoff step) for all filters (RC, Gauss M1 and M2) is: 0.025; 0.08; 0.25; 0.8; 2.5; 8 mm. The maximum length λs for ultrashort waves is selected by the steps of the ratio λc/λs: 30; 100; 300. The sampling length (base length) lr for the roughness (or cutoff step λc): 0.08; 0.25; 0.8; 2.5; 8 mm. Tracing speed: 0.05; 0.15; 0.5 mm/s.

Tracing length *lt* can be 0.48; 1.5; 4.8; 15; 48 mm or it may be variable from 0.1 to 200 mm. Evaluation length *ln* (Fig. 2) may be: 0.40; 1.25; 4.0; 12.5; 40 mm or it may be variable with cut-off of the maximum wavelength. The curvature radius of the probe in the mode of measuring roughness (waviness) is 2 or 5 microns, while in the mode of measuring the contour (or profile): 22, 250, 500, 1000, 2000, and 3000 μm.

4 Results

The data processing algorithm for assessing roughness and waviness contains two stages: obtaining a digitized primary profile to be filtered and assessing the parameters of waviness and roughness depending on the purpose of the analysis (Fig. 2).

The following technique of measuring and analyzing the primary profilogram information signal has been developed.

Digitization of the primary profile diagram (Fig. 2 a) by extracting a discrete digital code from the computer format ".bmp". The primary profile digital code generation, for example, in the formats "Text document" or Excel.

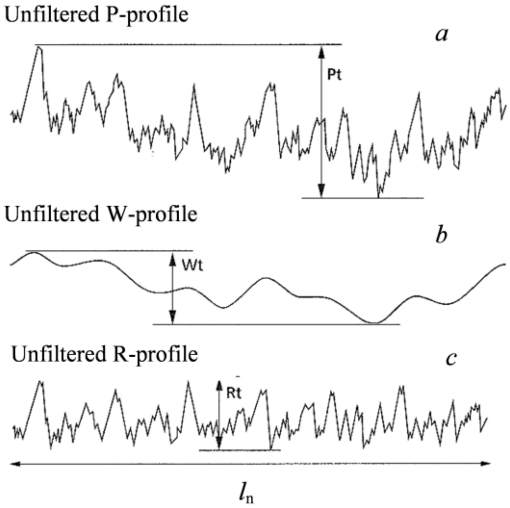


Figure 2 – How to divide the primary profile (a) to separate the waviness (b) and roughness (c) information signals from it [7]

The formation and analysis of the waveform signal (Fig. 2, b), for example, by constructing a moving average with variable weighting coefficients determined by the Gauss law. Subtracting the ordinate (for each discrete abscissa value) from the digital image of the primary profile of the waveform to obtain a digital roughness signal (Fig. 2, c). Analysis of the roughness signal to determine its standard parameters, for example, Ra and Rz. The fast Fourier transform for frequency analysis of the primary profile signal.

A certain difficulty in applying the frequency approach is the transition from the "time-dependent" domain to the "frequency" one. The fact is that the signal characterizing the profilogram does not belong to the time series of data $x(t)$ in contrast to the signal characterizing the vibration parameters. Therefore, this profilogram signal is represented by a sequence of numbers x_n or $x(n)$, which as a discrete change in n, where n is an integer, represents the results of equally spaced measurements. Thus, a one-dimensional array of numbers or a matrix-row is obtained with the length (or size) n. In this case, the profilogram signal is a series of discrete numbers that can be subjected to digital filtering. In this case, by the definition of Hamming digital filter is the conversion of the input matrix-row x_n to the output matrix-row of the following form [12]:

$$y_n = \sum_{k=-\infty}^{\infty} c_k x_{n-k} + \sum_{k=1}^{\infty} d_k y_{n-k}, \qquad (6)$$

where y_n is the output (n-th) discrete signal at the output of the digital filter (n = 1, 2, … n); c_k and d_k are the coefficients.

Thus, the so designed digital filter is both a linear combination of equally spaced samples x_{n-k} of some input function $x(t)$ and previously calculated output values y_{n-k}. In other words, for each successive n, formula (1) shifts the current calculated result point along the stream of input samples x_{n-k} [12].

Using the example of formula (1), we can show the difference between a non-recursive (without feedback) filter and a recursive (with feedback) filter. In the first case, all the coefficients d_k for all output samples y_{n-k} are equal to zero. In the second case, the coefficients d_k are not zero. It is known that both filters lead to a change in the phase of harmonic components passing through the filter [12]

When highlighting the surface waviness, this leads to a distortion of the amplitude and position of the wave formed during filtration. Therefore, following European (DIN) and American (ASNI) standards, an additional requirement for a digital filter is the absence of a phase shift for all harmonic components passing through the filter. The idea of phase correction of a signal during digital filtering was described and further developed in [12], which refers to a method for constructing a "zero-phase filter". A distinctive feature of this filter is the impossibility of its use in real-time systems because all input points must be taken into calculation, even those absent to the current moment.

The frequency approach to the description of digital filters following formula (6) allows us to consider the well-known mathematical operations for approximating and smoothing discrete digital series of numbers, as usual, low-frequency digital filtering procedures. Besides, it was shown in [12]

that the well-known mathematical operation of integrating a sequence of input samples of a physical quantity is also a low-frequency digital filtering procedure. This fully applies, for example, to the operation of integrating the input signal of acceleration (input of the low-pass filter-integrator) upon receipt of the output signal of the filter-integrator, which is the vibration velocity. Similar considerations can lead to the formation of a vibration displacement signal from a vibration velocity signal.

The complexity of constructing a "zero-phase filter" or a phase correcting filter makes the urgent task of smoothing profilogram data to highlight the waviness profile at the least distortion of the shape and position of the resulting wave. Conducted research studies have identified the most acceptable smoothing algorithm available in the Mathcad 14.0 application, to wit: Mathcad Help → Functions → Curve Fitting and Smoothing Functions → Smoothing Data → k-smooth (Gaussian Kernel Smoothing). The built-in function k-smooth (*vx*, *vy*, *b*) creates a vector of local weighted average elements in the *vy* array using a Gaussian kernel of width *b*. In this case, the smoothed elements from *vy* are formed under the expression

$$vy' = \frac{\sum_{j=1}^{n} K\left(\frac{vx_i - vx_j}{b}\right) \cdot vy_j}{\sum_{j=1}^{n} K\left(\frac{vx_i - vx_j}{b}\right)}, \qquad (7)$$

where $K(t) = \frac{1}{\sqrt{2\pi}\cdot(0{,}37)} exp\left(-\frac{t^2}{2\cdot 0{,}37^2}\right)$; *vx* is the vector of real numbers with elements in ascending order (it is an argument, i.e. filter input); *vy* is a vector of real numbers of the same length as *vx* (it is also the argument, i.e. filter input); *b* is the bandwidth of the smoothing window (it is also the argument, i.e. filter input).

From a comparison of expressions (6) and (7), it follows that the smoothing algorithm by formula (7) is similar to a recursive filter (i.e., a filter with feedback) since the output of this smoothing algorithm is a function of not only the input array *vx* but also previously received filter output signals *vy*. Bandwidth *b* is usually set to be equal to several distances between data points on the *x*-axis, depending on the smoothing degree desired. When determining the waviness, we take *b* = *lr* (or the cutoff λc of the step), i.e. the strip width *b* is equal to the base length *lr* of the roughness determination area.

The European standard DIN ISO 11562: 1996 defines the metrological characteristics of phase correcting filters for measuring surface profiles. This standard specifies, particularly, how to separate the composition of long waves from the composition of short waves. By this standard, the weight function of a phase correcting filter corresponds to the shape of a Gaussian probability density function. Its equation at a filter step cut-off wavelength which is equal to λc has the form [13]

$$S(x) = \frac{1}{0{,}4697\cdot\lambda c} exp\left(-\frac{x}{0{,}4697\cdot\lambda c}\right)^2, \qquad (8)$$

As follows from equation (8), there are components with a wavelength at the output of the low-pass filter $x \le 0{,}5\cdot\lambda c$. Therefore, this filter is called the "50% Gaussian filter". This low-pass filter passes spectral composition with wavelengths less than 50 % of the step cut-off wavelength.

Thus, $S(x)$ and $K(t)$ expressions are similar to each other. The filter transfer characteristic is determined considering expression (6) through the weight function (8) using the Fourier transformation (not given in this article). The short-wave set of profile components (spectrum of surface roughness) following the standard is found as the difference between the primary profile and the long-wave set of profile components (output of a phase correcting low-pass filter).

The criteria for selecting a phase correcting filter are as follows [14]:

1. Spatial (instead of the "time-dependent" term) and frequency characteristics have the same meaning.
2. The filtered profile, even in the region of the cutoff of the profile filter step, is not distorted due to a phase shift. The short-wave component of the profile after passing through the filter is similar to the short-wave component of the original profile.
3. The transfer characteristics of the short-wave and long-wave components of the profile have got the

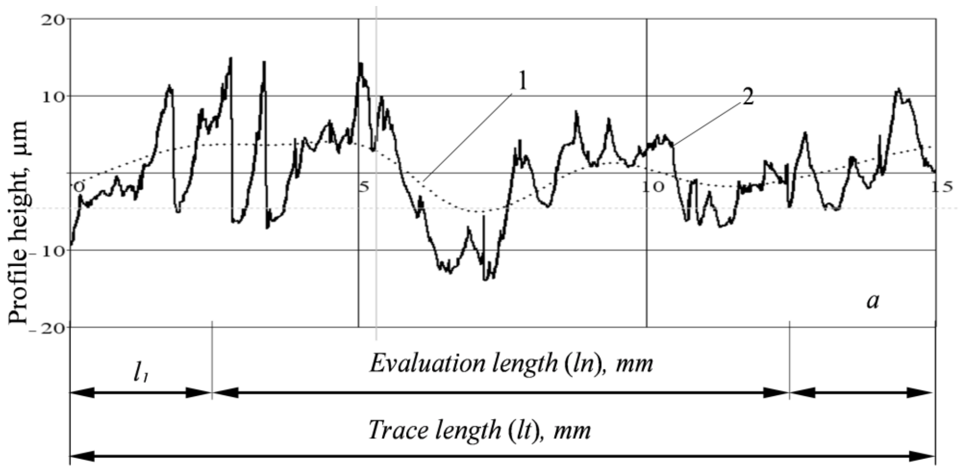
properties of phase correction and 50 % amplitude transfer at the filter step cutoff level.

4. For digital systems, a phase correcting filter is implemented using a Gaussian approximation.

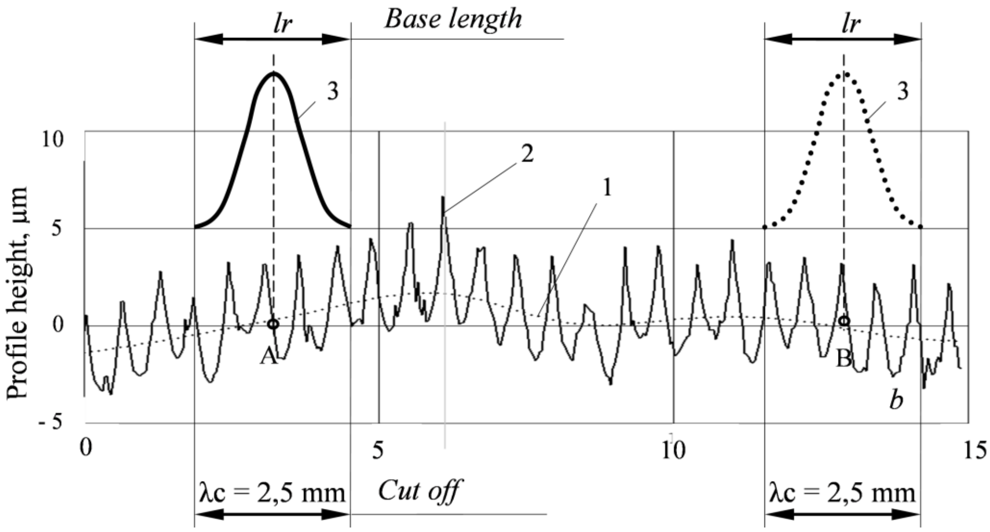
Experimental verification of the data processing technique based on the formula (7) was carried out when analyzing the profilogram of the surface of milled samples 2.1 and 5.1 (Fig. 3). Milling is performed on the CNC machining center 500V/5 with Siemens 840 D type CNC under the following machining parameters: cutting depth 0.5 mm, feed per tooth 0.15 mm, mill rotary speed 950 min^{-1} (sample 2.1) and 3800 min^{-1} (sample 5.1). Cutting tool: end mill with four teeth made of high-speed steel P6M5 with a diameter of 18 mm, which have a cylindrical shank for a collet clip. A prismatic sample made of steel grade Ст3 (RSt37-2 Germany analog) with overall dimensions of 65x50x30 mm [14].

Following international standards, the tracing length *lt* and the evaluation length *ln* are connected each other as follows: $lt = ln + l_1 + l_2$, where l_1 and l_2 are the intervals of the path of increasing and decreasing (transient process) of the probe speed along with the studied surface (Fig. 3 a).

The waviness is extracted using a smoothing algorithm that replaces the phase correcting "50 % Gaussian filter". For this purpose, the computer algebra system MathCAD implements the built-in function k-smooth (*vx*, *vy*, *b*), the core of which is the weight function described by the Gaussian curve (curve 3 in Fig. 3 b).



a



b

Figure 3 – Profilogram wave component (1) construction based on the digitization of the primary profilogram (2) using the Gaussian smoothing function (3) for samples 2.1 (a) and 5.1 (b)

The essence of the mathematical filtering procedure with variable weights is visible in Fig. 3, b. For example, to obtain the ordinate of point A (Fig. 3, b), it is necessary to multiply all the ordinates of curve 2 at the interval of the cutoff step λc = *lr* by the weight coefficients which is determined by curve 3. Next, perform the calculation according to the formula (7). The number of such calculations at the base length *lr* is equal to the number of discrete ordinates of curve 2 along the entire length. The ordinate of point B is similarly obtained (Fig. 3, b).

For the subsequent comparative analysis, we used the portion of the profilogram of sample 5.1 obtained with a trace length *lt* = 4.8 mm (Fig. 4). The decrease in the tracing length from *lt* = 15 mm (Fig. 3, b) to *lt* = 4.8 mm (Fig.4) is caused by the following methodological considerations: the time during which the profile section is formed during milling should be close to the measurement time of the vibration displacement signal (Fig. 5) when milling the same portion of the sample. In the NI-DAQmx data acquisition system with NI-LabVIEW software, the indicated time is 0.2 s [14]. This time predetermines the current spectrum of such signals as vibration acceleration, vibration velocity, and vibration displacement during the transition from the time interval to the corresponding frequency interval.

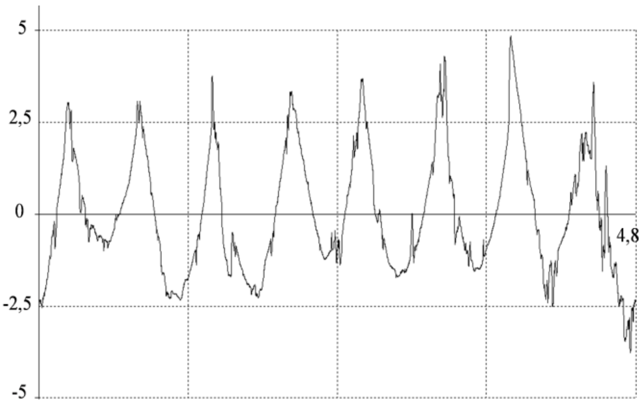


Figure 4 – Profilogram of the surface of sample 5.1 at lt = 4.8 mm measured in station T8000

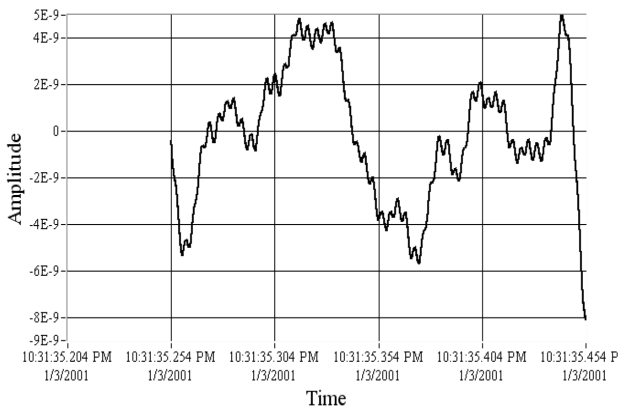


Figure 5 – Time-dependent vibration displacement signal for flat milling of sample № 5.1 (when the AP2019 vibration sensor is located on the workpiece in the X-axis direction of the CNC machine 500V/5)

Thus, to ensure the comparability of the data in Fig. 4 and Fig. 5 the corresponding dependencies of the profile height (Fig. 4) and vibration displacement value (Fig. 5) on the milling time were taken for the same section of the milled surface. Indeed, the transformation of the abscissa axis of the profilogram (length *lt*) into the time axis (i.e., $\Delta t(lt)$ in seconds) can be performed according to the well-known formula for determining the milling time, $\Delta t(lt) = (60\,lt)/(n S_z z)$ where *n* is the mill rotational speed, min^{-1}; *Sz* the feed to the mill cutter tooth, mm per tooth; *z* is the number of teeth of the mill. Therefore, with *n* = 3800 rpm, *Sz* = 0.15 mm/tooth and *z* = 4, we get $\Delta t(lt)$ = 0.1263 s, which is comparable to the value of the time interval of 0.2 s indicated above.

For a comparative analysis of the profilogram (Fig. 4) and the vibration displacement signal (Fig. 5), it is necessary to identify the frequency composition of these time-dependent signals. For this, in the NI-LabVIEW software environment, the output profilogram signal after its preliminary digitization is fed to the NI-LabVIEW system "spectral measurements block", which performs the fast Fourier transform procedure. The result obtained after this transform is displayed in the form of a spectrogram on the virtual instrument front panel in the NI-DAQmx system using the "waveform graph display units" (Fig. 6). Similarly, a spectrogram of a time-dependent vibration displacement signal was obtained (Fig. 7).

In the LabVIEW environment, it is possible to differentiate a signal that changes over time or by coordinate. The operation of differentiating the profilogram signal is performed using the LabVIEW program as follows: Functions → Mathematics → Integration & Differentiation → Time Domain Math → Derivative (d*X*/d*t*). Fig. 8 shows the spectrum of the speed characteristic of the profilogram, i.e. the spectrum from the derivative of the function plotted in Fig. 4.

To obtain the spectrum of the vibration velocity signal for mechanical elastic vibrations, the numerical integration of the initial vibration acceleration signal, which comes from the AP2019 accelerometer installed in the workpiece subsystem, is performed (Fig. 9).

Comparison of the spectrograms in Fig. 6–9 allows us to note a certain similarity that can be used in the development of a milling diagnostic system for recognizing surface quality parameters based on the analysis of vibration parameters during milling, to wit: vibration acceleration, vibration velocity, and vibration displacement. This is reflected detailer in the following conclusions.

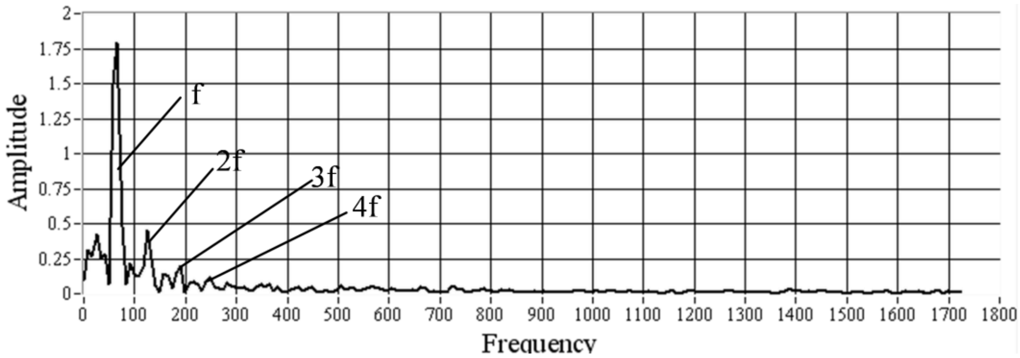


Figure 6 – Spectrogram obtained from the sample № 5.1 using the surface digitized profilogram

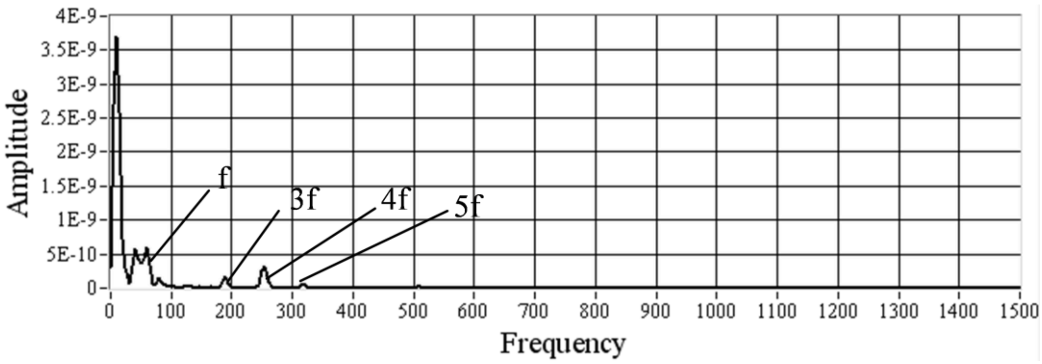


Figure 7 – Spectrum of the vibration displacement signal during milling the sample No. 5.1 test section

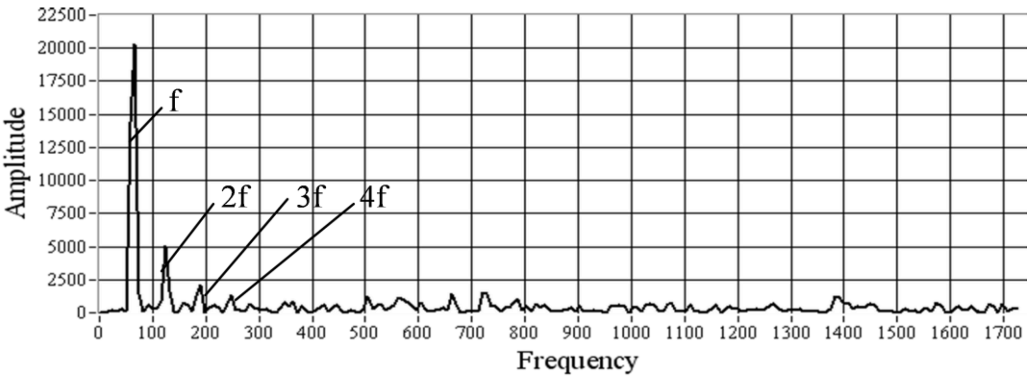


Figure 8 – Profilogram speed characteristic spectrum (spectrum of a function that is a derivative of the profilogram signal)

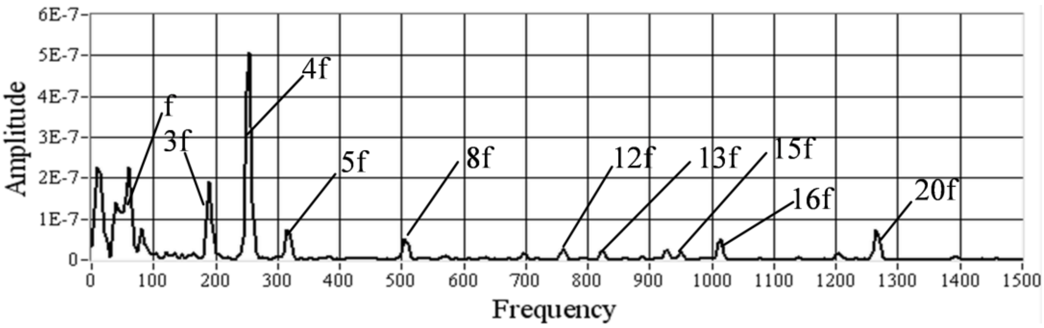


Figure 9 – Spectrum of the vibration velocity signal (vibration velocity of mechanical oscillations)

5 Conclusions

An evaluating procedure has been developed for the profilogram of the milled surface under modern international standards (DIN, ASNI, JIS), which consists of digitizing the profilogram and its spectral analysis, which allows separating the roughness and waviness parameters on the milled surface.

In the spectra obtained from Fig. 6 and Fig. 8, the harmonic corresponding to the main spindle rotation frequency has the largest amplitude; for sample 5.1, this frequency is $f = 3800/60 = 63$ Hz.

In the vibration velocity spectrum (Fig. 9), the harmonic corresponding to the frequency $4f = = 252$ Hz has the largest amplitude.

In the spectra showed in Fig. 6, 8 in addition to harmonics with the main spindle rotation frequency, there are harmonics observed at multiple frequencies $2f = 126$ Hz; $3f = 189$ Hz; $4f = 252$ Hz.

In the spectra in Fig. 7, and Fig. 9, in addition to harmonics with the main spindle rotation frequency, there occur the following harmonics with multiple frequencies: $3f = 189$ Hz; $4f = 252$ Hz; $5f = 315$ Hz and others.

The investigations performed made it possible to conduct spectral analysis of the milled surface profilogram and the vibration displacement signal during its formation in a milling machine closed system based on the same frequency approach. This allows establishing a correlation between dynamic phenomena in the milling zone and their consequence in the form of milled surface profilogram.

6 Acknowledgments

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