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RESEARCH ON A SURFACE TEXTURE ANALYSIS BY DIGITAL SIGNAL PROCESSING METHODS

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Original scientific paper
Surface quality has a crucial influence on exploitation properties and durability of machine parts. Hence, measurements and evaluation of surface texture is one of the most significant fields of metrology of geometrical quantities. Taking into account reliability and materials strength of mechanical elements particularly important components of a surface texture are such defects as scratches or cracks. Occurrence of such defects may result in serious damage or even break down of a whole mechanical device. Due to the local character of occurrence of such irregularities they may be easily overlooked during typical measurement and evaluation of surface texture. The paper describes an analysis of applicability of selected digital signal processing techniques, such as the Fourier and wavelet analysis to the detection of surface texture defects. Theoretical considerations are supported by a practical example.

Keywords: *analysis, surface, texture, transform, wavelet*

Analiza strukture površine metodama obrade digitalnog signala

Izvorni znanstveni članak
Kvaliteta površine bitno utječe na radna svojstva i trajnost strojnih dijelova. Stoga je mjerenje i procjena strukture površine jedno od najvažnijih područja metrologije geometrijskih veličina. Uzimajući u obzir pouzdanost i čvrstoću materijala mehaničkih elemenata, oštećenja kao što su ogrebotine i napukline posebno su važne komponente površinske strukture. Takva oštećenja mogu dovesti do velike štete ili čak kvara čitavog mehaničkog uređaja. Zbog lokalnog karaktera pojave takvih nepravilnosti može ih se lako previdjeti tijekom tipičnog mjerenja i procjene strukture površine. U radu je opisana analiza primjenjivosti odabranih metoda obrade digitalnog signala, kao što su Fourierova analiza i analiza valova u detekciji oštećenja strukture površine. Teoretska razmatranja popraćena su praktičnim primjerom.

Ključne riječi: *analiza, površina, struktura, transformirati, val*

1 Introduction

Due to such factors as vibrations, tool wear, etc. surfaces of machine parts are not ideally smooth. Surface texture of mechanical components is characterized by certain irregularities that are the reason for differences between the real and the nominal workpiece [1, 2].

The classification of surface texture components is shown in Fig. 1.

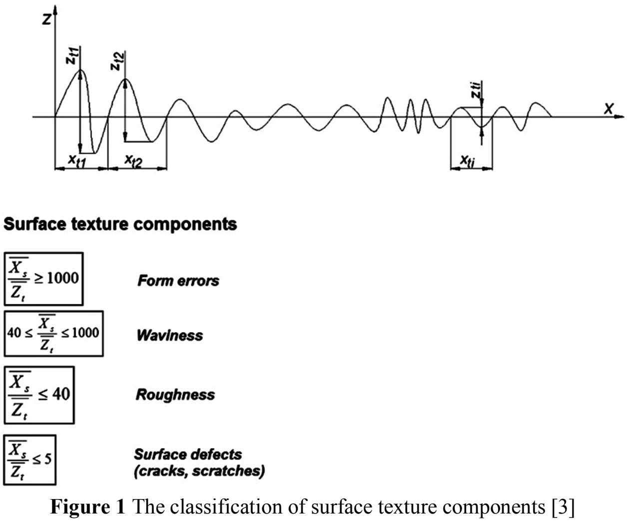

Figure 1 The classification of surface texture components [3]

Form errors are assumed to occur when the distance between irregularities is equal or more than 1000:1. Form deviations are caused, for example, by guideway errors, errors of rotary elements, or by thermal expansion of elements [4]. Waviness is observed when the distance between irregularities is from about 40 to 1000 times larger than their depth. Waviness is usually a result of a disturbed manufacturing process an example of which can be vibrations between the workpiece and the grinding wheel [5]. Surface roughness occurs when the distance between irregularities is from about 5 to 40 times larger than their depth [6 ÷ 8]. Surface roughness is usually related to tool paths, for example, turning, grinding or finishing cuts [9 ÷ 12]. Surface defects such as cracks and scratches occur when the ratio between the distance and the depth of the irregularity is less than or equal to 5 [13, 14].

Measurements of surface structure are subject of interest of many researchers, who investigate it from various points of view [15 ÷ 17]. Demircioglu et al. in [18] and Durakbasa et al in [19] investigate influence of stylus tip and other factors on measurement results. Grzesik in the work [20] analyses an influence of a tool wear on surface roughness during turning with the use of ceramic tools. Zawada-Tomkiewicz in [21] makes an attempt to evaluate surface roughness parameters by an image processing. Zhengkai Zhang et al in [22] propose a new approach to the analysis of surface topography that is based on empirical decomposition of the profile. Quinsat and Tournier in [23] describe a novel non-contact system allowing in-situ measurements of roughness of elements that due to their dimensions and mass cannot be measured in laboratory. Janecki in works [24 ÷ 26] investigated new methods of filtering of surface texture components. Generally, surface texture of machine parts is evaluated quantitatively with the use of parameters such as *Pa*, *Ra*, *Wa* and similar [27 ÷ 30]. Qualitative assessment of the surface texture is usually performed through a graphical representation of irregularities in different types of diagrams. Sometimes an additional analysis of the surface is useful, which is based on digital signal processing methods. Among methods of digital signal processing the

Fourier analysis is the most common method. It allows determining which harmonic components are dominant in an analysed signal. Unfortunately, the Fourier components are global in time and therefore some information about local defects of the surface cannot be found. This is why a research work on the application of other methods of analysis of the surface texture is carried out. Nowadays, more and more popular method of such analysis is a wavelet transform. It permits to detect local irregularities of the profile of the machine part [31]. This paper presents results of the analysis of surface textures with the use of a traditional method (the Fourier analysis) and with the use of the wavelet analysis. A special attention is paid to evaluate the applicability of these methods for detection of surface defects such as scratches of cracks. The research was divided into two parts. Firstly, the methodology was verified through computer simulations. Next, the concept was tested on real measurement data.

2 Mathematical fundamentals of Fourier and wavelet transform

2.1 Fourier analysis

Fourier analysis is a set of techniques that permit to decompose a signal into series of sinusoids. The time domain of the Fourier analysis is periodic and continuous. A synthesis equation of the Fourier series is given by the Eq. (1):

$$x(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(2\pi f t n) - \sum_{n=1}^{\infty} b_n \sin(2\pi f t n), \quad (1)$$

where $x(t)$ is the signal reconstructed from sine and cosine waves, f is the fundamental frequency, a_n and b_n are the amplitudes of cosine and sine waves, respectively, n are consecutive integer numbers [32].

The analysis equations of the Fourier series are usually written not in terms of the fundamental frequency f but in terms of the period T. The relation between the frequency and the period is the following:

$$f = \frac{1}{T}. \quad (2)$$

The analysis equations of the Fourier series can be formulated as follows:

$$a_0 = \frac{1}{T}\int_0^T x(t)\mathrm{d}t, \quad (3)$$

$$a_n = \frac{2}{T}\int_0^T x(t)\cos\left(\frac{2\pi t n}{T}\right)\mathrm{d}t, \quad (4)$$

$$b_n = -\frac{2}{T}\int_0^T x(t)\sin\left(\frac{2\pi t n}{T}\right)\mathrm{d}t. \quad (5)$$

In the Eqs. (3) ÷ (5) $x(t)$ is the time domain signal to be decomposed, a_0 is the mean value of the signal, a_n and b_n are the amplitudes of cosine and sine waves, respectively, and T is the period of the waveform.

The example of the Fourier transform of a non-periodic signal is shown in Fig. 2.

A value denoted in Fig. 2 by ω is a natural frequency and $\omega = 2\pi f$. Diagrams presented in Fig. 2 show that output signals of the Fourier transform are determined in the frequency domain and the input signal is a time-domain signal. It is the characteristic feature of the Fourier transform that permits to apply it to evaluate harmonic components of the input signal. However, this property makes the Fourier transform quite useless in an analysis of unexpected signal disturbances.

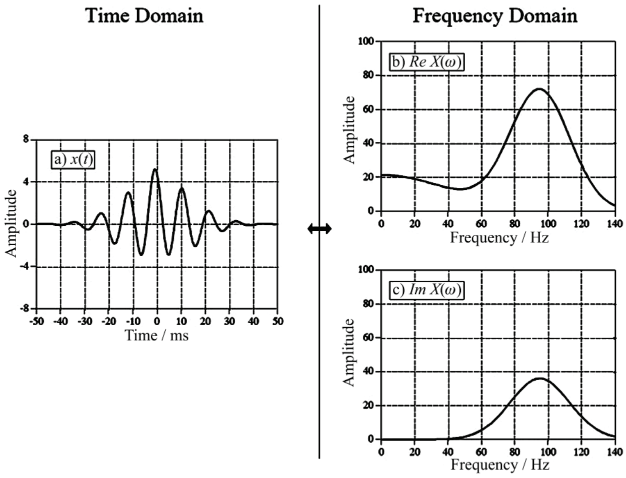

Figure 2 An example of the Fourier transform of a time-domain signal [32]

It is obvious that in practice signals to be processed are discrete, not continuous. Therefore, practical application of the Fourier series is based upon using a discrete Fourier transform (DFT). DFT changes an N point input signal into two $(N/2)+1$ output signals. The output signals consist of amplitudes of sine and cosine waves that are scaled in an appropriate way. The input signal is usually determined in a time domain while output signals are in the frequency domain. The most efficient algorithm to calculate the DFT is called the Fast Fourier Transform (FFT). The algorithm FFT is based upon the complex Discrete Fourier transform. It is relatively complicated but extremely efficient. This is the reason why the FFT is the one of the most significant techniques of digital signal processing.

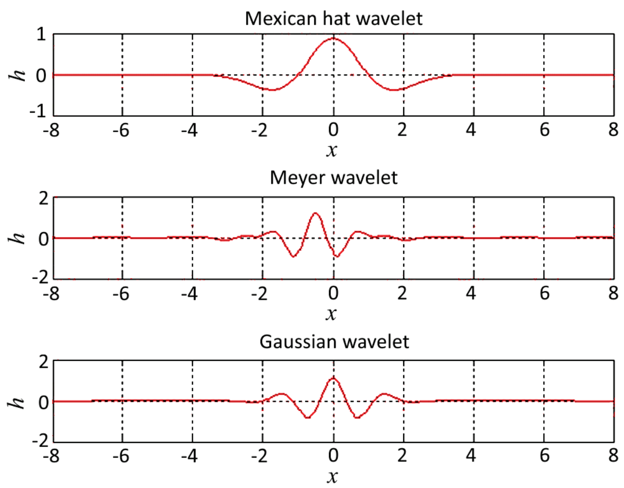

Figure 3 Selected examples of wavelets

2.2 Wavelet analysis

Wavelets are small waveform functions that are extremely useful in an analysis of non-stationary signals.

Wavelets are finite in duration and oscillatory (their amplitude starts at zero, increases to reach the maximum and then decreases back to zero). Because they are local in time, they can be used to detect local disturbances of 2D and 3D signals. This is the reason why they are applied in a very wide range of applications: for example in medicine, seismology, image and sound processing, etc. Wavelet transform is based upon scaling and translating of basic functions that are called mother wavelets. There are different types of mother wavelets, for example Mexican Hat, Meyer, Daubechie, Coiflet, biorthogonal, etc.

The examples of wavelets are shown in Fig. 3.

Different daughter wavelets $d_{a,b}$ can be calculated from mother wavelets $h(x)$ by scaling and shifting them from the following formula:

$$d_{a,b}(x) = \frac{1}{\sqrt{a}} h\left(\frac{x-b}{a}\right), \tag{6}$$

where a is the scale and b is the shift.

The one-dimensional wavelet transform of the continuous function $f(x)$ is given by the Eq. (7):

$$W(a,b) = \int_{-\infty}^{\infty} f(x) d_{a,b}(x) \mathrm{d}x. \tag{7}$$

The algorithm of the one-dimensional signal decomposition with the use of wavelet transform is shown in Fig. 4. The signal denoted as $f^{(0)}$ is an original signal, which is decomposed in the first stage of the decomposition into two other signals: an approximated signal, denoted as $a^{(1)}$ and the details of the signal denoted as $d^{(1)}$. In the second stage of the decomposition the approximation $a^{(1)}$ is divided into the next approximation $a^{(1)}$ and the next detail $d^{(1)}$. The procedure of the decomposition is then repeated to the desired level of the analysis of the signal.

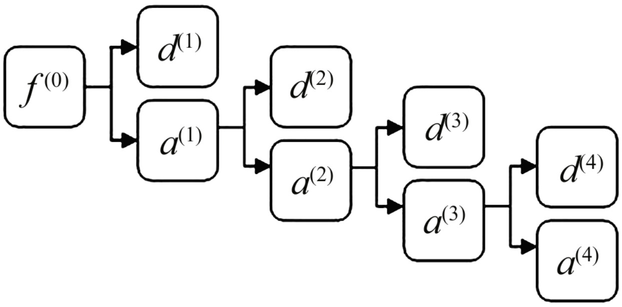

Figure 4 The tree of pyramidal wavelet decomposition: $f^{(0)}$- measured signal,$a^{(i)}$ – an approximation in the i - step, $d^{(i)}$ – addition (detail) in the i-step [14]

Note that sometimes another type of the decomposition is applied, so-called binary tree decomposition. In such type of the decomposition not only approximations are decomposed but also details.

Fig. 5 presents an application of the single-stage wavelet decomposition for a real signal s.

It is easy to notice that after the decomposition one obtains two signals: an approximation a_1 and a detail d_1. This way the information about the characteristic features of the signal s can be obtained.

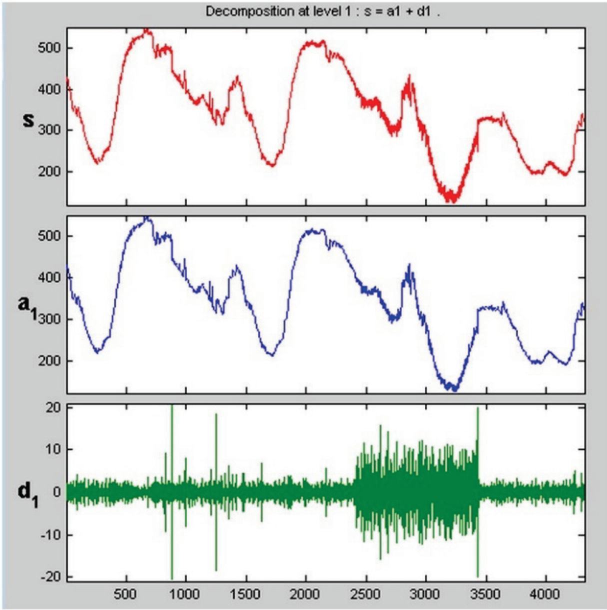

Figure 5 The single stage wavelet decomposition of the signal s

3 Simulations

In order to investigate applicability of the Fourier and wavelet transform to the analysis of surface structure of machine parts computer simulations were conducted. The first stage of the research was simulation of a real profile. It was assumed that it will be a periodical profile containing significant random irregularities and the noise. The equation of the periodical profile without irregularities and the noise was the following:

$$R(\alpha) = 5 + \cos\alpha + \cos 2\alpha + \sin 3\alpha + 0{,}5\cos 5\alpha + 0{,}2\sin 10\alpha + 0{,}1\cos 15\alpha + 0{,}05\sin 25\alpha. \tag{8}$$

Fig. 6 presents simulated profiles: the upper diagram shows the profile calculated according to the Eq. (8), the diagram in the middle shows this profile with added white noise, and the lower one the original profile containing the white noise and the surface defects.

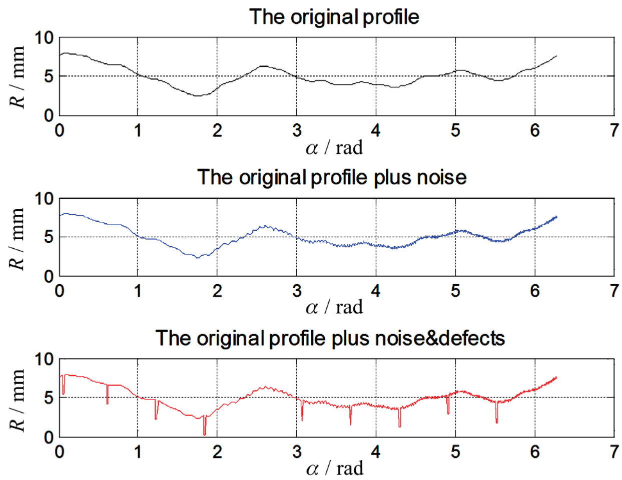

Figure 6 The profiles generated for the purpose of the simulations

3.1 Fourier analysis

The first stage of the simulations was the Fourier analysis of profiles shown in Figure 6. Firstly, the algorithm of Fast Fourier Transform was applied to the original profile. After conduction of the FFT algorithm a set of values of harmonic components of the profile that are shown in Fig. 7 was obtained. The harmonic components from the range 1 ÷ 50 were analysed.

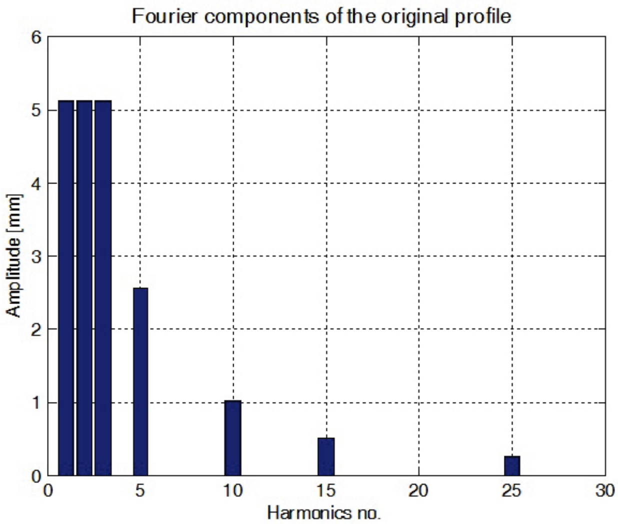

Figure 7 Amplitudes of harmonic components of the original profile (the range of the components: 1 to 25)

The diagram presented in Fig. 7 shows clearly that the Fourier analysis allowed obtaining accurate information on the original profile. The application of FFT algorithm provided the values of the harmonic components that constitute analysed signal given by the Eq. (8).

The next stage of the research was the Fourier analysis of the signal containing the noise and random local disturbances. Fig. 8 shows amplitudes of harmonic components of the original profile with added white noise.

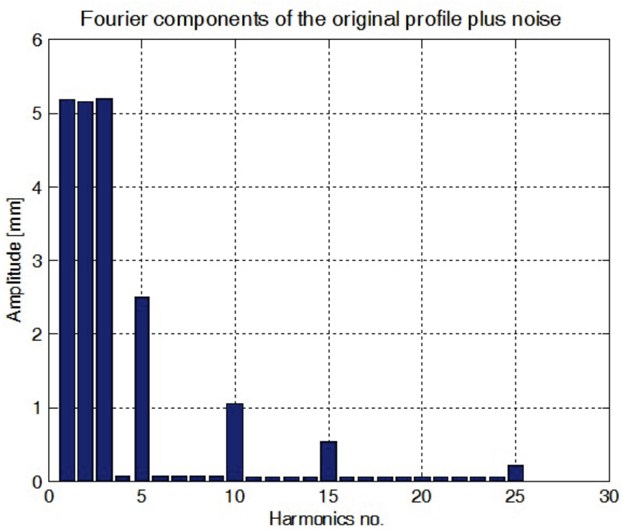

Figure 8 Amplitudes of harmonic components of the profile containing white noise (the range of the components: 1 to 25)

It is easy to notice that in this case the application of the Fourier transform does not allow obtaining so accurate information on the analysed signal. One can see that values of amplitudes of harmonic components of the profile are slightly changed in relation to the previous case. Moreover, Fourier components of other harmonics are observed on the diagram that does not appear in the Eq. (8).

Fig. 9 shows amplitudes of harmonic components of the original profile with added white noise and some local disturbances.

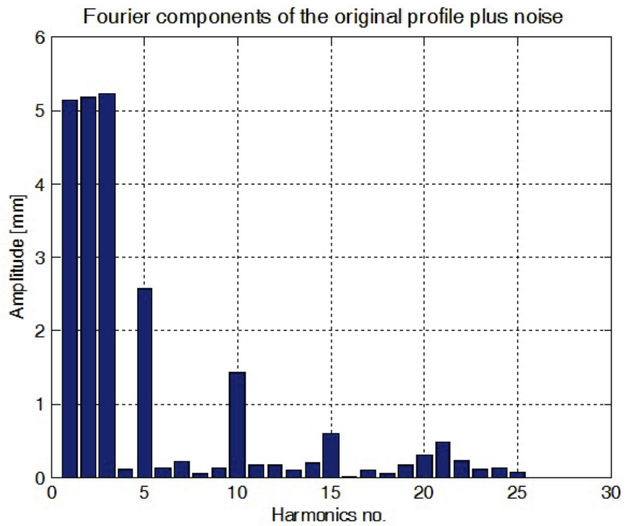

Figure 9 Amplitudes of harmonic components of the profile containing white noise and local disturbances (the range of the components: 1 to 25)

The diagram presented in Fig. 9 shows that adding local disturbances to the analysed ones results in further changes of amplitudes of harmonic components. Moreover, it is obvious that the Fourier analysis is completely useless in localization of the disturbances. This is why it cannot be used in detection of surface texture defects such as cracks or scratches of the surface.

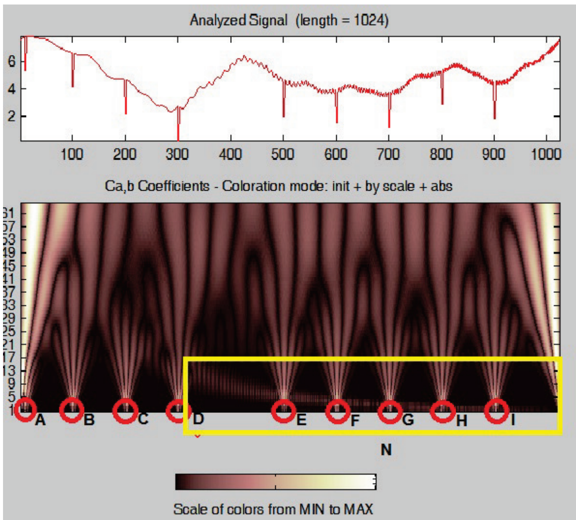

Figure 10 The one-dimensional continuous wavelet transform of the signal containing the noise and local disturbances

3.2 Wavelet analysis

The next stage of the research was to investigate the applicability of the wavelet transform to an analysis of surface texture simulated by the signals shown in Fig. 6.

The analysis was performed with the use of the Wavelet Toolbox, which is a part of MATLAB package. The analysed signal was the one containing the noise and defects. Firstly, the one-dimensional continuous wavelet transform was conducted with the use of a Gauss mother wavelet. The analysed signal and values of coefficients of the decomposition are shown in Fig. 10.

In the diagram shown in Fig. 10 it is easy to notice how useful the wavelet transform to identification of sudden changes of the signal can be. Areas denoted by capital letters A-I correspond to the local disturbances of the signal and in the area denoted by *N* there are coefficients that refer to the noise of the signal.

The signal containing the noise and local disturbances was investigated also by the discrete wavelet transform. Fig. 11 shows approximations of the analysed signals in five levels of decompositions. The mother wavelet Daubechies was applied to decompose the signal.

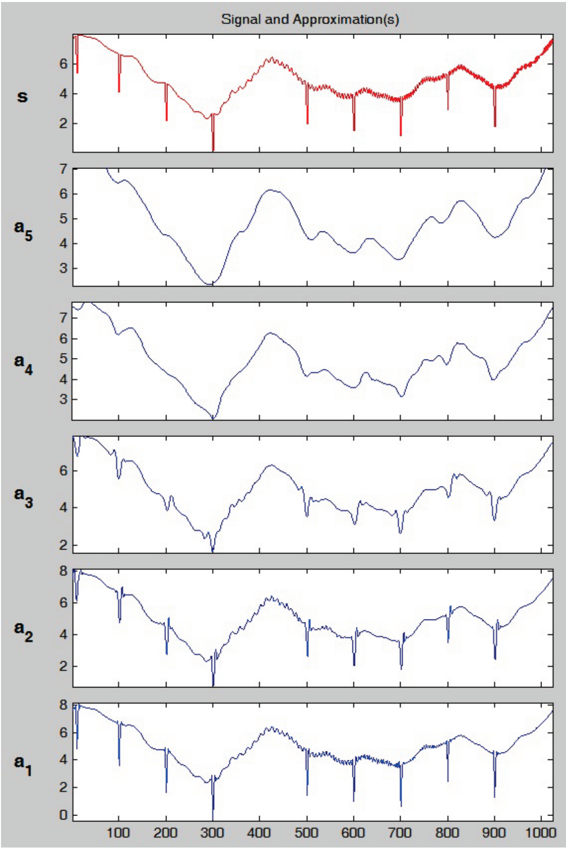

Figure 11 Approximations of the signal containing the noise and local disturbances

In Fig. 11 approximations in consecutive levels of decompositions are denoted by the letter *a* with appropriate numbers. For example a_1 is the approximation at the first level of decomposition, a_2 is the approximation at the second level of decomposition and so on. An analysis of diagrams shown in Fig. 11 proves that the wavelet transform is a very efficient method to approximate the signal. Approximations in the consecutive levels of decompositions are more and more smooth, which is clearly seen if one compares the approximation a_5 and a_2.

It is obvious that due to the approximation information on local changes of the signal is lost. But such information is easily available through the analysis of details of the decomposition, which is shown in Fig. 12.

In the upper diagram the coefficients of details of the decomposition are shown (the diagram is denoted as *cfs*). It is easy to notice that bright areas in this diagram correspond to location of the analysed signal disturbances. In the lower diagrams the analysed signal *s* is shown and details in the consecutive levels of decomposition, where d_1 corresponds to the details in the first level of decomposition, d_2 to the details in the second level of decomposition and so on. An analysis of diagrams of details shows that they can be used to detect the locations of local disturbances of the analysed signal. In the analysed case details in the lower decomposition levels are particularly useful (e.g. d_1 or d_2). It is noticeable that the sudden changes of details d_1 or d_2 correspond to the location of local changes of the analysed signal. One can also see that it is not so easy to notice in the case of details d_4 or d_5.

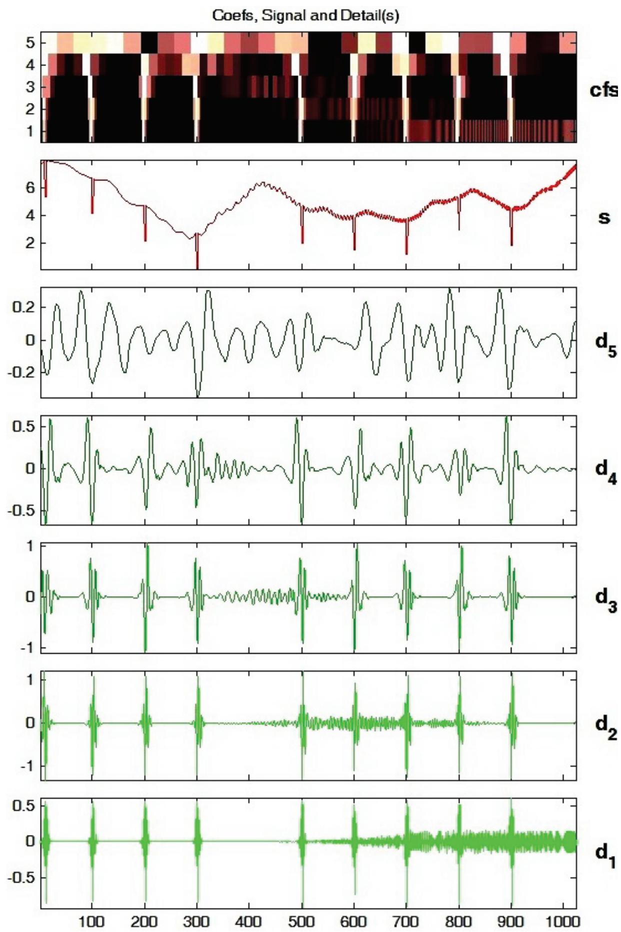

Figure 12 Approximations of the signal containing the noise and local disturbances

Another very interesting property of the wavelet transform is quite convenient removing of the noise from the signal. In order to illustrate this property a procedure of denoising with the use of the Wavelet toolbox was conducted that was applied to the signal containing the noise. The result of the removing the noise from the signal is shown in Fig. 13. The procedure was applied with the use of the Daubechies mother wavelet.

The procedure was applied with the use of the Daubechies mother wavelet. The diagrams presented in

Fig. 13 were obtained for the fourth level of decomposition. Additional analysis showed that at a higher level of decomposition the more local changes are removed from the signal. Thus, one should be careful not to lose important information on the signal in higher levels of the decomposition.

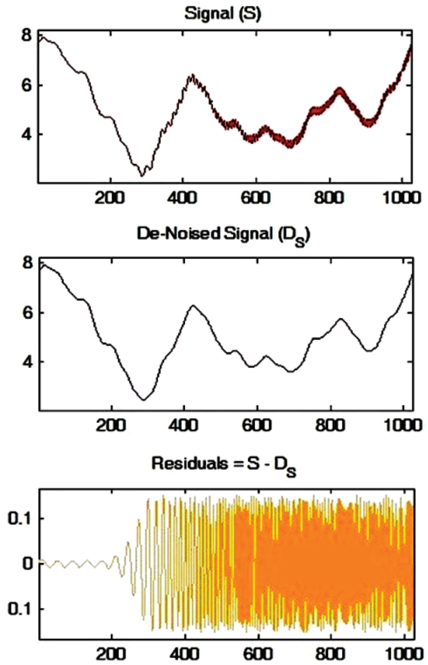

Figure 13 Removing the noise from the signal with the use of the wavelet transform

4 Experiment

Experimental part of the research work involved measurement of surface texture of steel plate, which is shown in Fig. 14.

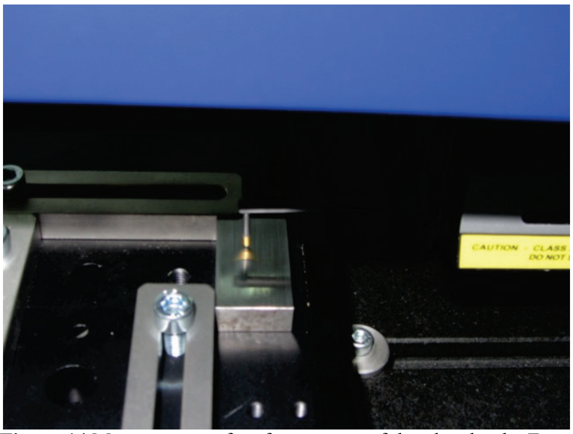

Figure 14 Measurement of surface texture of the plate by the Form Talysurf PGI 1230 [31]

The measurement was performed with the use of the instrument Form Talysurf PGI 1230. In the experiment a primary profile of the surface was measured and the evaluation length was equal to 4 mm. After the measurement the data were exported to the text file. The diagram showing experimental data is presented in Fig. 15.

The diagram presented in Fig. 15 shows that the investigated surface has not been horizontal to the measuring table during the experiment. Thus, in order to evaluate deviations of the surface texture it is necessary to process obtained measurement data.

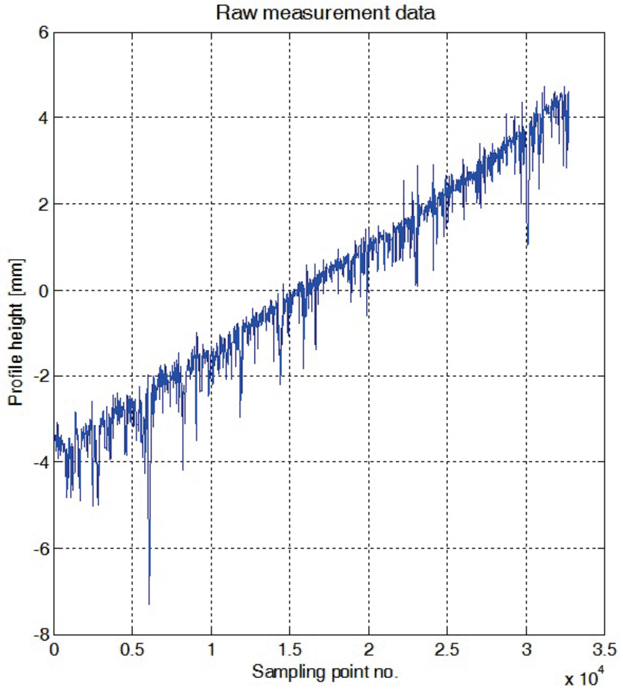

Figure 15 Measurement data obtained in the experiment

4.1 Preliminary measurement data processing

The diagram presented in Fig. 15 shows the obtained signal requires levelling. It can be easily done by the least squares method. In order to perform levelling the signal the following procedure has been applied, assuming that the line is fitted to the signal:

1) To calculate coefficients a and b of the line fitted to the signal, where the equation of the line is as follows: $y = ax + b$, by the least squares method
2) To correct measurement data according to the equation:

$$Y_{\mathrm{corr}} = Y_{\mathrm{meas}} - aX - b, \tag{9}$$

where:
Y_{corr} is the vector containing corrected values of the signal,
Y_{meas} is the vector containing original values of the signal,
X is the vector describing location of subsequent sampling points along the evaluation length,
a, b are the coefficients of the line fitted to the signal by the least squares method.

The procedure described above was applied in practice with the use of MATLAB package. Firstly, the coefficients a and b were computed. It was conducted by the function *polyfit*. Obtained values of the coefficients were the following: $a = 1{,}963$ and $b = -4{,}022$.

The coefficients were then used to correct obtained measurement data according to the Eq. (9). The diagram showing values of the corrected signal is presented in Fig. 16.

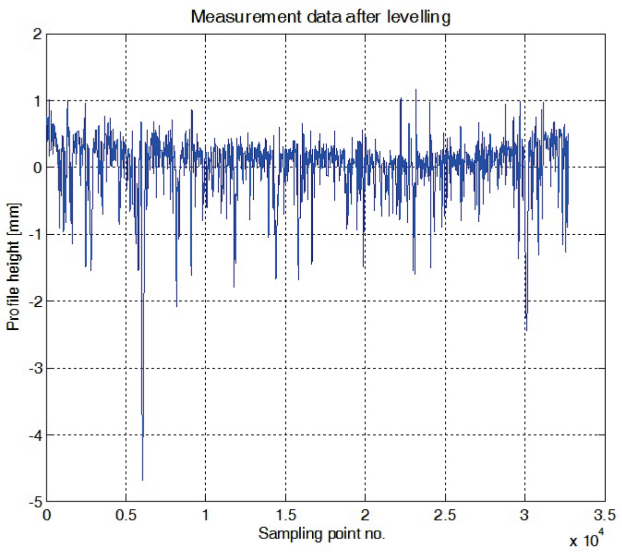

Figure 16 Measurement data after levelling

4.2 Data analysis

Similarly to the case presented in section 3 the obtained measurement data were investigated by two methods: the Fourier and the wavelet analysis.

4.2.1 Fourier analysis

Firstly, the signal shown in Fig. 16 was converted to the frequency domain through the Fast Fourier Transform. Fig. 17 illustrates amplitudes of the Fourier components of the signal.

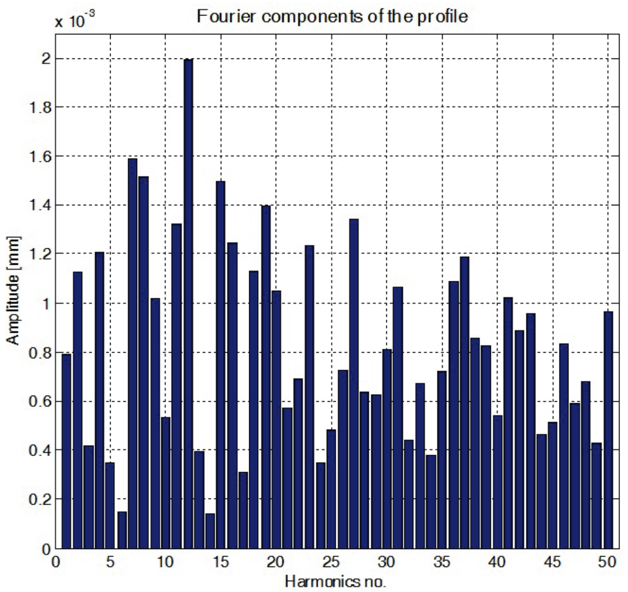

Figure 17 Harmonic components of the signal (range: 1 to 50)

The diagram presented in Fig. 17 shows that there are some harmonic components that are dominant in the signal. In the analysed range the amplitudes of the 1^{st}, 6^{th}, 12^{th}, 25^{th}, 28^{th}, 37^{th}, 41^{st} and 47^{th} component were much bigger than the other ones. This is useful information about the surface texture. However, it is obvious that such analysis cannot provide any information about defects of the surface if they are located randomly along the evaluation length. It is due to the fact that the Fourier transform is conducted in the frequency domain.

4.2.2 Wavelet analysis

Wavelets are local in time and therefore the wavelet analysis can be used to detect local disturbances of the signal [33]. Therefore the author assumed that wavelet analysis can be applied to identify in which area of the surface defects are located. Firstly, the one-dimensional continuous wavelet transform of the profile was conducted. It was performed with the use of the "Mexican hat" wavelet. Obtained coefficients of the wavelet transform are shown in Fig. 18.

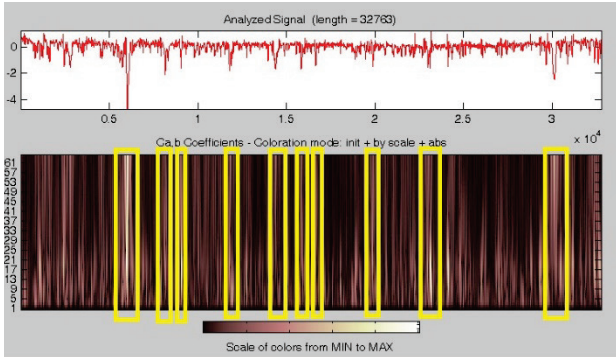

Figure 18 Coefficients of the one-dimensional continuous wavelet transform of the profile ("Mexican hat" wavelet)

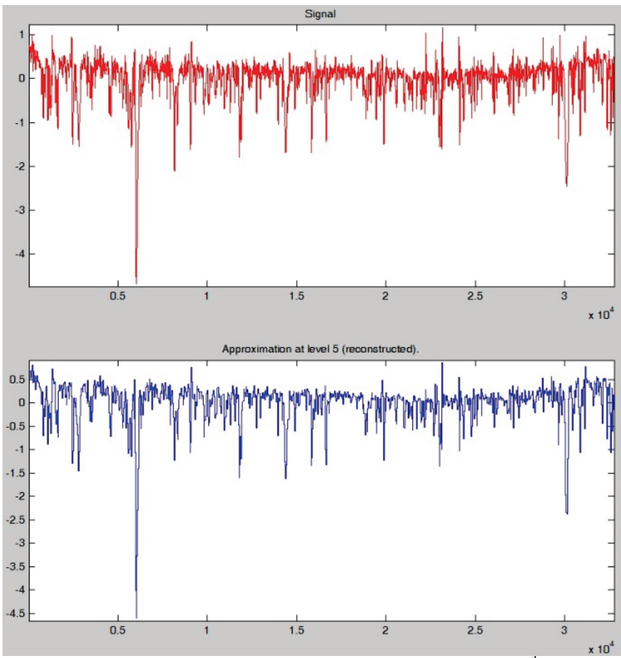

Figure 19 The original signal and its approximation at the 5^{th} level of decomposition (Daubechies wavelet)

The diagram presented in Fig. 18 shows that the wavelet analysis can be used to detect surface defects. It is obvious that coefficients of the wavelet transform change if there are scratches or cracks of the surface. The higher value of coefficient the brighter colour in the lower diagram (the areas of higher values of coefficients were pointed out by the squares). It is very easy to notice that bright bands in the lower diagram correspond to disturbances of the signal shown in the upper diagram.

The profile presented in Fig. 16 was also analysed with the use of discrete wavelet transform.

Fig. 19 illustrates the original signal and its 5th approximation with the use of the Daubechies wavelet.

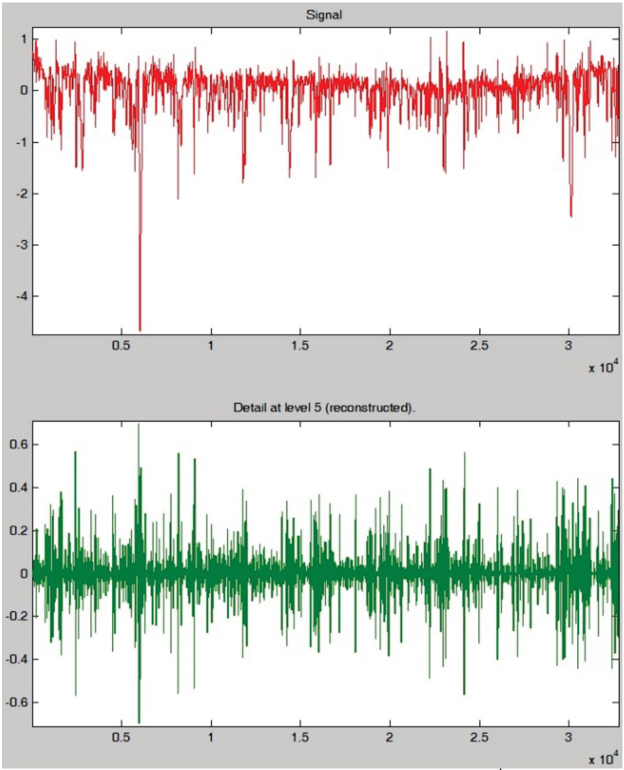

Figure 20 The original signal and its details at the 5th level of decomposition (Daubechies wavelet)

It is noticeable that due to the approximation the signal is less influenced by the noise. Fig. 20 illustrates the original signal and the details at the 5th level of decomposition.

In Fig. 20 it is noticeable that high values of the details correspond to high changes of the original signal.

5 Conclusion

It is estimated that about 90 % of all failures of machine parts are initiated due to surface damages such as fatigue or stress corrosion cracking, wear, erosion, etc. Thus, it is very important to observe and measure surface texture of machine elements. Modern measuring instruments are capable of accurate measurement and evaluation of form deviations, waviness and roughness. Besides the visual analysis of the investigated profile the most common method of evaluation of irregularities of surface texture is the Fourier analysis. The Fourier transform is extremely useful when analysing periodic signals. Therefore it is a very useful tool for an evaluation of roundness or cylindricity profiles. It usually allows obtaining accurate information on analysed surface, then. Wavelet transform does not provide such accurate information. However, because it is well localized in the time domain it can detect irregularities of the profile such as cracks or scratches of the surfaces. Wavelet transform is also a very convenient tool for denoising of the measuring signal.

Results of the simulations and the experiment that were presented in sections 3 and 4 show that if there are scratches, cracks or other significant disturbance of the profile, the results of application of the Fourier transform can be sometimes doubtful. However, such disturbances can be detected very easily if wavelet transform is applied. Therefore one can conclude that both types of transforms can complement each other when evaluating the surface texture. In the next stage of the research work the author plans to apply the wavelet transform to the analysis of 3D signals (for example for data obtained during measurements of flatness and cylindricity).

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