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DISTRIBUTION OF ROUGHNESS AND WAVINESS COMPONENTS OF TURNED SURFACE PROFILES

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Abstract

The paper presents a spectral formulation of surface profile irregularity in a wideband frequency range for roughness, waviness and shape components along the measured length. A unique distribution of roughness and waviness components is proposed, according to the nature of their origination in the course of machining with tools of defined cutting edge, as distinct from standard filtration in measurements of surface irregularities. Differences resulting from both formulations are outlined as well as the method of determining the frequency of component separation for surface roughness and waviness.

Keywords: surface irregularity, roughness, waviness, spectral analysis of surface irregularities.

1. Introduction

The surface geometrical structure (SGS) in its longitudinal and lateral profiles contains the complex character of surface irregularities with roughness, waviness and shape components along the measured length [1]. Depending upon the kind of machining, its accuracy and the technical condition of the whole machining system (MS), complex irregularities appear in the surfaces with the dominating character of a periodic component or a group of surface components. Very accurately machined surfaces may contain all components with varying degree of intensity, or only selected types of components. It should be pointed out that not often one may find surface geometrical structures with identical character of surface irregularity. In wideband analysis of surfaces, all irregularity components should be considered. Such an approach is important in the analysis of surface features and for practical application and evaluation of the technical and qualitative state of a SGS [2].

2. Standard distribution of surface profile irregularity components

During a measurement with a profile measurement gauge irregularities of the surface profile are filtered by introducing an appropriate limiting filter cut-off wavelength. In this way, low-frequency components of *e.g.* waviness and shape error along the measured profile length are being filtered. For roughness, values of such parameters as height and length or irregularity functions are given. It seems useful to filter – during a measurement – the shape error by introducing an appropriate, possibly highest value of the filter cut-off wavelength and to analyze surface roughness and waviness components in a common irregularity profile, as shown in Fig.1.

Because of the step-like filter values and their choice according to standard ranges of height and periodic irregularity spacing, inexact separation of waviness and surface profile roughness may occur [3, 4].

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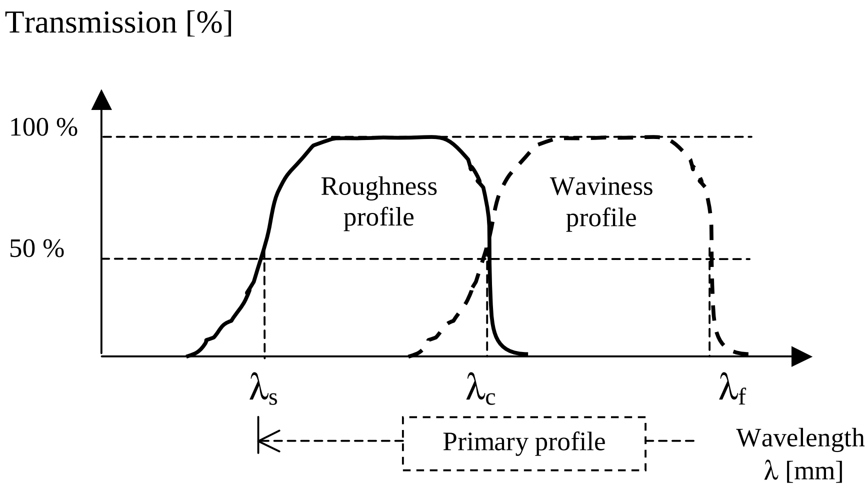

Fig. 1. Range of surface profile components with standard separation of waviness and roughness according to filtration of irregularities by cut-off wavelengths.

Depending on the size and character of irregularity of the measured surface, standards do not specify frequency but numerical values of limiting cut-off filter wavelength λc 0.08; 0.25; 0.8; 2.5; 8 [*mm*] respectively, as shown in Table 1.

Table 1. Standard values of "cut-off" filtering and the respective frequencies of surface irregularity components.

Cut-off	Sampling length	Frequency range
λc (mm)	lr (mm)	$\Delta\nu$ (1/mm)
0.08	0.08	12.5
0.25	0.25	4
0.8	0.8	1.25
2.5	2.5	0.4
8	8	0.125

These components may appear in the surface profile together and with the shape error along the measured length they influence the accuracy and quality of the machined surface. For this reason they should be analyzed in common and they should be considered separately according to the character of the surface irregularity components.

3. Wideband formulation of surface irregularity profile in frequency terms

In SGS the irregularities are represented by very complex multi-periodic signals disturbed by periodic and random components. In processes with determined shape and countable number of cutting edges, such as turning and milling, in the surface irregularities predominant periodic components appear together with disturbances of the machining system in the form of wideband noise. Processes with the use of single cutting edge tools generate surfaces with explicitly periodic character of mapping the tool's profile (PT) of the main irregularity components. Such SGS permit to attempt a frequency analysis of irregularities and their decomposition to determine their frequency-band components. For surface profile irregularities the amplitude spectrum is the simplest formulation. It permits an analysis of frequency components appearing in the investigated surface and easy physical interpretation of irregularity height for their individual wavelength components. Spectral functions give rational separation of surface errors on the frequency scale, ν [1/*mm*], or k – number of the

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frequency component for a wavelength of λ [μm], appearing in the surface irregularity along the measured surface length [5, 6, 7].

In the analyzed frequency range of surface irregularity, PT mapping components together with disturbances include:

– shape error as a single irregularity along the measured length;
– waviness appearing along the measured length;
– surface roughness as periodic transformation of the tool profile.

The notion of roughness in terms of SGS components is a narrowband limitation and relates only to the lowest irregularity heights with small distance in length. Irregularities with greater separation, described as waviness and shape error along the analyzed profile length, are essential for surface accuracy and quality. Their distinction is essential because of accuracy and real characterization of surface irregularity profile components.

Parameters such as height and length of individual profile irregularity components do not describe in an explicit and complex way the features of a surface in a wideband formulation. The commonly used evaluation of irregularities by height parameters does not take their shape or placement in the surface profile into account. The SGS contains a ‘surplus’ of information which is not being used, or only in a selected range in standard formulations of surface irregularity, as given in Table 1.

Total irregularities of profiles play an important role in the evaluation of surface quality, as well of exploitation and practical features of objects, when their shape and placement along the profile length are considered.

In creating surface irregularities by means of a single cutting edge tool, distinct orientation of machining traces can be clearly seen, described for SGS as anisotropic. Profiles transverse to the machining traces represent a dominant, periodic irregularity character.

Because of the repetition of PT mapping in surface profiles with a period of tool movement per object rotation *f*, traces can be analyzed on the frequency scale and their heights viewed through their amplitudes in the spectral analysis of irregularities. Just this formulation in frequency of SGS profile irregularities allows to look commensurably and in a wide band at the formation of distortion components at the higher and lower frequencies with respect to the PT mapping [2, 8].

In [9] the decomposition of surface components by means of wavelet filtration of irregularities. Roughness viewed through various length scales is treated in [10], while publication [11] characterizes waviness lengths by robust filtering. Publications [9–12] apply new methods of component filtration, but they are not related to standard formulations and are not linked by length of frequency with surface profile components.

4. Spectral distribution of surface profile components

To separate the various characters of irregularities, in spectral analysis we can use frequency-band filtration of components. This can occur for a specific irregularity frequency ν_k or a group of components from the range of surface error components. In spectral analysis of surface profiles, this method has an explicit connection between component wavelengths in the profile irregularities λ_k and their frequencies ν_k in fast Fourier transform (FFT) [2, 6]. Inverse Fourier transform (FFT^{-1}) of irregularities from the frequency spectrum divided into sub-ranges permits to recognize the character of the filtered components and helps in finding the kind and cause of surface profile irregularity.

Standard filtration in a measurement cuts away part of the components which are already lost in the signal. In such cases there is no return to the primary profile of surface irregularity. From irregularities measured in this way, standard parameters, distributions and functions are calculated which do not take into account the relations between components in their common formulation. On the other hand, spectral analysis presents such possibilities and shows the participation of surface irregularity components in the frequency range presentation.

Filtration of any component or a group of components of a digital irregularity signal in spectral analysis and the use of inverse Fourier transform allows to analyze the filtered-off components. This does not lead to loss of the primary (total) surface irregularity obtained in the measurement. Such a filtration which is carried out during a standard measurement on a profile meter is also possible.

This forms a convenient situation, to have the complete irregularity signal and the procedure of filtering an appropriate component or a band of components. This applies also to waviness, roughness or individual significant components, *e.g.* the tool feed spectral line v_f. It permits a return to irregularities for the filtered-off range of frequency components. It is significant for diagnostic and working discerning of irregularity disturbances by comparing them with the primary profile. This relates also to profile components in the filtered ranges and to comparisons between them, which is unattainable in standard valuation of filtered profile irregularities.

In accordance with calculated frequency values in Table 1 for wavelengths given in the standards, from the measured surface profiles the following can be filtered: shape error, waviness error and roughness. For a correctly chosen "cut-off" value of measured irregularities it is possible to filter waviness and roughness components or roughness itself, which can be measured by means of standard surface profile measurement gauges.

To display band filtering of individual irregularity components, the lateral profile was assumed of a turned surface obtained at the following parameters: f = 0.19 [*mm/rev.*], a_p=0.75[*mm*] and v_c = 160.5 [*m/min*], which is shown in Fig. 2 and its amplitude spectrum in Fig. 3.

The amplitude spectrum has been divided into frequency bands for component k numbers which correspond to filtration frequencies of irregularity components, respectively:

- F – form error for components with numbers $k = 1 \div 5$;
- W – waviness for component numbers $k = 6 \div 62$;
- R – roughness above components numbers $k > 62$.

Frequencies of components k are defined as numbers of FFT transformation lines and through the sampling interval h_p linked with the frequency values v_k according to formula [2]:

$$v_k = \frac{k}{N \cdot h_p}, \tag{1}$$

where: k – number of irregularity frequency component for FFT coefficients k – 1, 2, …, N/2, N – number of samples in the surface profile, h_p – sampling interval of profile irregularity.

The frequency ranges are calculated according to wavelength limits given in standards [3, 4] and in Table 1.

When in the surface roughness spectrum a narrowband range of waviness components appears, this speaks for improperly chosen filtration in the measurement. For shape error, the irregularity profile should be analyzed without filtering and then its component is analyzed along the measurement section length L.

It can also include an imprecise adjustment of the measurement surface in the instrument, but such a case ought to be eliminated in a subsequent measurement.

After separating spectrum components in the chosen frequency ranges and performing their inverse Fourier transform (FFT^{-1}) as well as returning to the surface signal, the separation of components occurs, as presented in Fig. 4.

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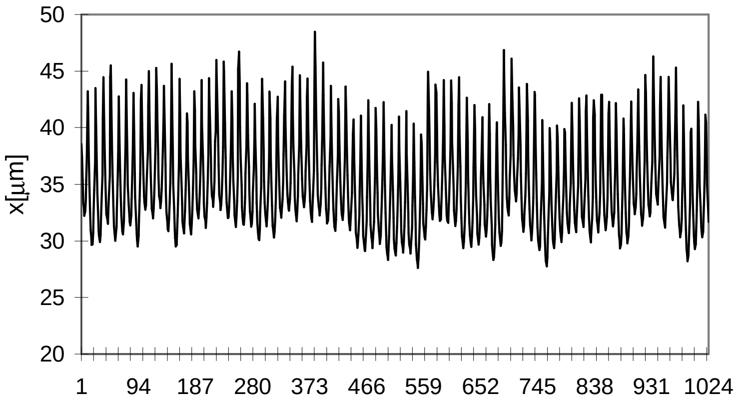

Fig. 2. Lateral profile irregularity of turned surface, with the following parameters:
f = 0.19 *mm/rev*., a_p = 0.75 *mm*, v_c = 160.5 *m/min*.

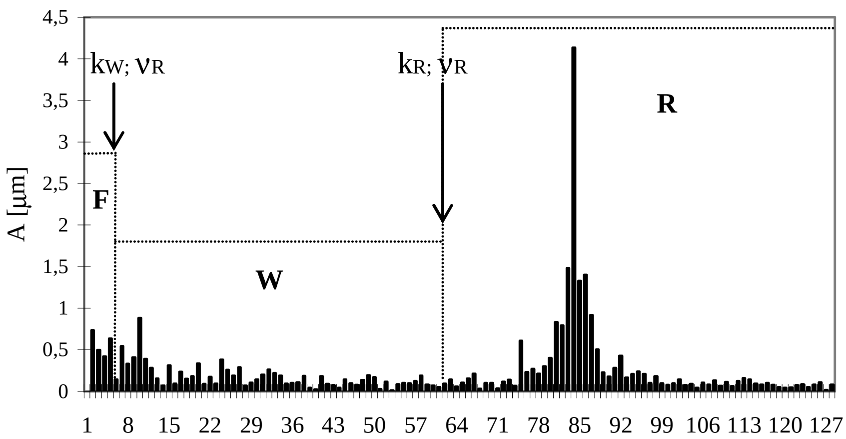

Fig. 3. Amplitude spectrum of lateral profile of turned surface, with the following parameters:
f = 0.19 *mm/rev*., a_p = 0.75 *mm*, v_c = 160.5 *m/min* with standard ranges of R, W components calculated for irregularity frequency components with values ν_R, ν_W.

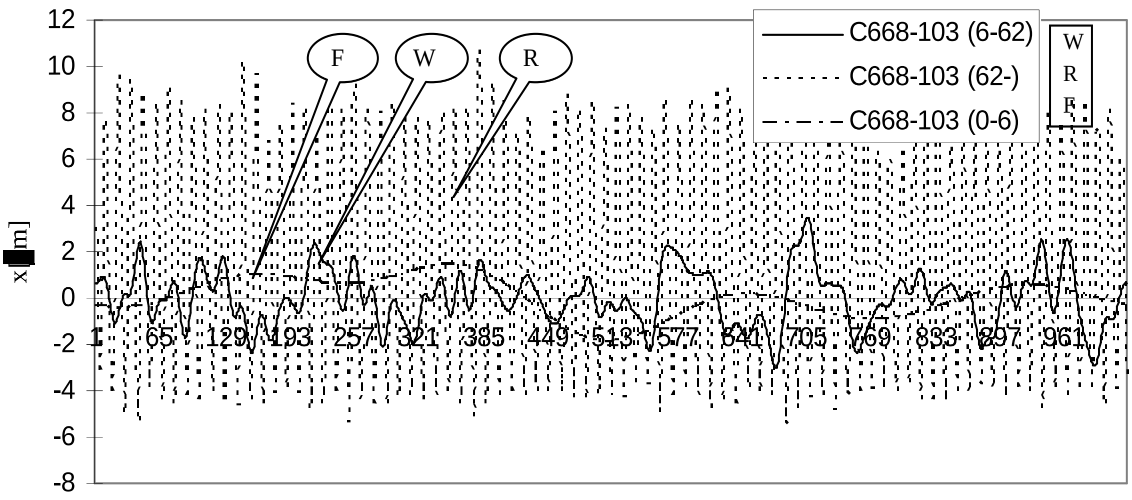

Fig. 4. Decomposed range components of lateral profile irregularities as:
F – form error, W – waviness, R – roughness, for the profile presented in Fig. 2.

The individual band-filtered and decomposed irregularity components are: a group of long wavinesses of surface *F* with a maximum height of 4 [μm], the *W* component which represents a shorter waviness group with a maximum height of 6.4 [μm], while roughness *R* is represented by high-frequency variations with amplitude-modulated irregularities in the range of 14 [μm].

Information on heights of individual irregularity components is relevant for surface accuracy and the responses depict the character of changes of band components in the length of the surface profile under consideration.

In a classical valuation of waviness and roughness this is unattainable. "Cut-off' wavelengths assumed from standards and re-calculated as frequency limits separate irregularity components in the spectra. In the presented surface example the shape error *F* includes components from the low-frequency waviness range for $k \leq 5$ and they change the course of waviness *W*. This is so because for measurements carried out by means of profile measurement gauges the standards provide stiff limits for the individual components through pre-determined and step values for non-periodic irregularities and length parameters for periodic profile irregularities [3, 4]. Standard parameters do not reproduce unequivocally the height and the character of the irregularity course in its length [2].

5. Proposal of distribution of waviness and roughness by frequency

With regard to the results of earlier analyses, the distribution of waviness and roughness components ought to be matched with the natural conditions in which they originate. It was proposed to assume a proper value for the frequency for the waviness and roughness range which should be linked with the frequency of the main periodic roughness component. It is represented by periodic mapping of the tool's profile. Disturbance by waviness of the map of tool's profile in irregularities occurs in a two times greater range that the value of its feed *f*, and the irregularity's waviness is formed in the profile. Therefore waviness should be discerned from roughness by the frequency for two feed values $\nu_R = 1/2f$. Also from simulation analyses of irregularity formation by a single cutting edge tool, an appropriate division boundary between waviness and roughness is the value proposed from dependence [2]:

$$\nu_R^p \geq \frac{1}{2}\nu_f, \tag{2}$$

$$\lambda_R^p \leq 2f, \tag{3}$$

where: ν_R^p – is the proposed boundary value of roughness, ν_f – tool feed frequency per object rotation, λ_R^p – proposed roughness filtering length, *f* – feed per revolution of the workpiece.

Irregularities with a frequency lower than $\nu < \nu_f/2$ result from the shift of the tool with respect to the object and, as envelopes of modulated irregularities from mapping of the tool's profile, they are within the waviness range $\Delta\nu_W$.

In connection with the choice of conditions in digital measurement of irregularity, assuming the sampling interval h_p and the number of measurement data *N* we determine the length of the measurement section *L*, thus the frequency range of surface profile irregularities [6]. For such a profile measured without filtering, the frequencies delimiting individual ranges of irregularity components should be chosen appropriately according to relations:

$$\Delta\lambda_W^p < \frac{1}{2f} = \frac{1}{2}\nu_f, \tag{4}$$

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$$\Delta v_R^p \geq \frac{1}{2f} = \frac{1}{2} v_f \,, \tag{5}$$

where: Δv_W^p – proposed frequency range of waviness components, Δv_R^p – proposed frequency range of roughness components, f – tool feed per revolution of the workpiece, v_f – tool feed frequency per object rotation.

6. Comparison of standard distribution and the proposed method for profile irregularity components

For the example of filtering of a turned surface, shown in Fig. 2, according to standard waviness boundaries, part of the low-frequency components exceed this range and determines the shape of the course. This does not correspond with facts, because this is waviness with longest periods and they have been arbitrarily and improperly divided by the assumed filter cut-off value λc.

In consequence of this it is proposed to choose the boundary between the shape and waviness errors in accordance with the definition of periodicity according to formula [2]. A value should be chosen which divides the wave components of lowest frequency for line k = 2, as shown in Fig. 5. In agreement with this, the division between individual components is as shown in Fig. 6. The character of the surface waviness has changed – it has been extended by the low-frequency waviness group for lines with k = 2 ÷ 5 which has not been heretofore taken into consideration in the standard method of waviness determination.

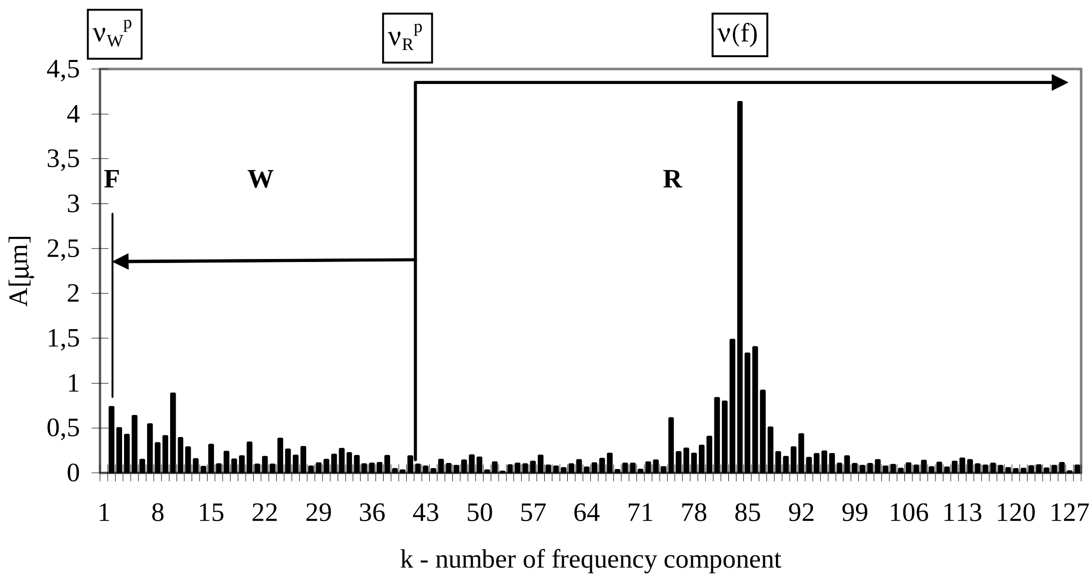

Fig. 5. Proposed band filtering of spectrum components from Fig. 2 as:
F – form error, *W* – waviness, *R* – roughness.

Interpreting the shape error, the zero spectrum component as a constant represents the position of the profile and constitutes a deviation of irregularity from the reference line in the performed measurement. The first component, as the longest waviness of irregularity can be interpreted for the lateral profile as one change in length.

It is proposed to treat the first irregularity spectrum component as the shape error F in the measurement length, and the subsequent components as wavinesses W which enter into the lower range of the waviness band of surface profile. This approach is closer to actual irregularities, as well as to conditions which exist in the measurement of the lateral SGS profile.

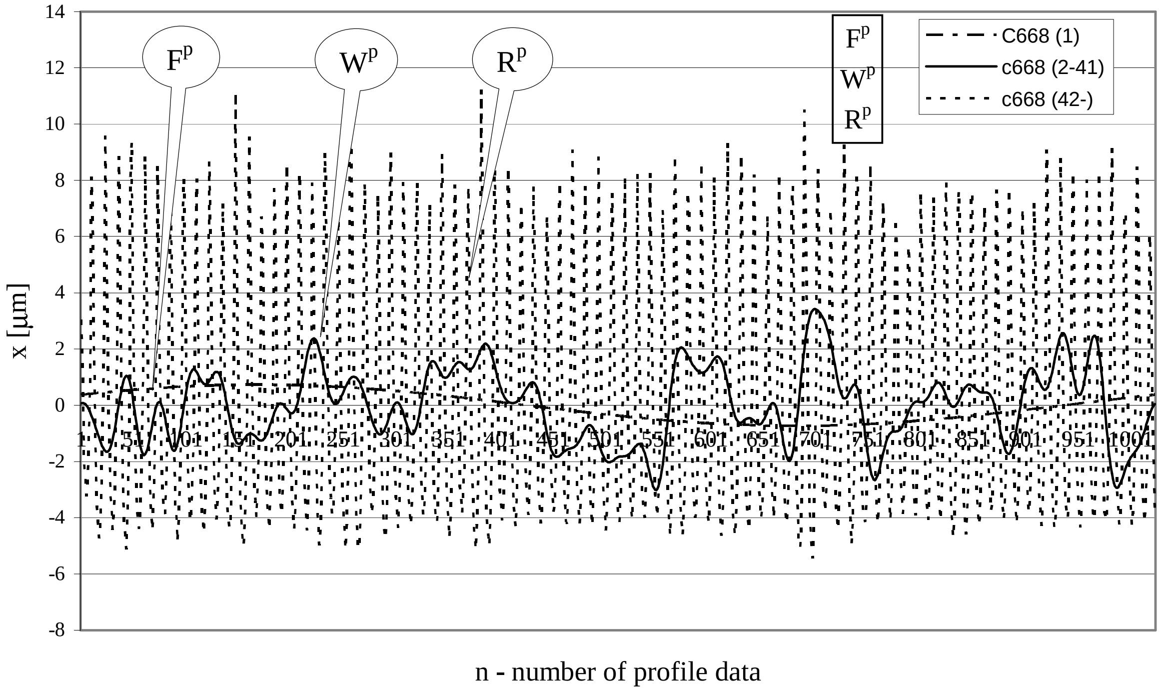

Fig. 6. Profile irregularity components F^p, W^p, R^p from the proposed band filtering in Fig. 5 for the surface from Fig. 2

The proposal to consider the shape error F constitutes one change with the longest irregularity wavelength on the whole length of the measurement section. Despite the fact that this is a single periodic change, it can be assumed as a shape error along the measurement section. The tangent to it constitutes the reference line for this error.

After calculation, in accordance with wave standards, the frequencies for defining the limit of shape error and waviness components ν_W can be 0.4; 0.25; 0.04 [$1/mm$] and for filtering of the roughness component ν_R they can appropriately be 0.4; 1.25; 4; 12.5 [$1/mm$]. Table 1 lists the calculated limiting values of surface profile irregularities as frequency values discerning components of waviness ν_W and roughness ν_R. In a common wideband surface analysis the individual irregularity components should be examined explicitly in appropriate sub-ranges according to formulas (2) and (3).

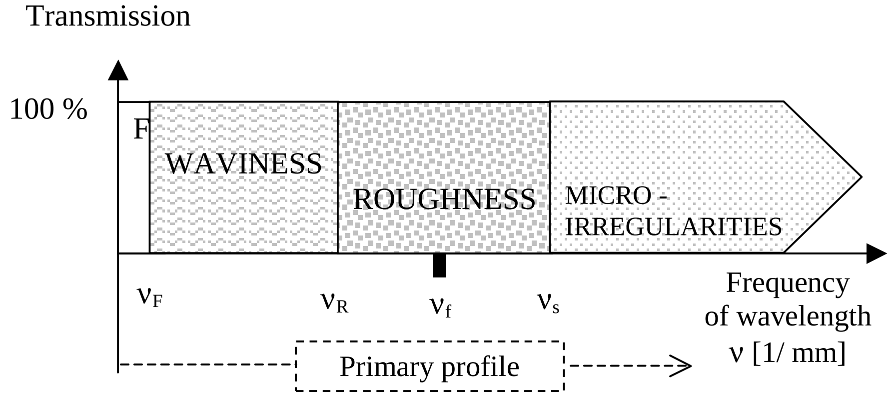

Fig. 7. The proposal to distribute irregularity profile components with periodic character by frequency with periodic/random disturbances, as an extension of the method of filtering with irregularity wave values according to standard.

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By submitting the classification of surface errors to the frequencies of the appearance of their components in irregularities, the frequency bands of their components should be determined according to relations (4) and (5). The heights or amplitudes of irregularities should be assessed in their limits, as shown in Fig.7. This is a new proposal for distribution of shape, waviness and roughness components by standards and frequency, in relation to the main periodic component v_f in the considered profile.

7. Conclusions

For standard wavelengths of filtering of irregularity components in the whole range or in sub-ranges, various aspects of the measured irregularities can by analyzed by frequency. They can result from conditions of the digital measurement and purposes of analysis. The periodicity of pre-dominant components in the irregularities can have an influence on the choice of measurement and filtration ranges. This is very important, because of the task and effects of the surface irregularity analysis by frequencies.

For the proposed analysis of irregularity by frequency, instead of boundary wavelengths for the "cut-off" filter, the boundary frequencies of irregularities of individual components should be applied. On the other hand, the effects should be physically interpreted with the surface as the number of periodic irregularity changes along the length of the measured profile section.

The presented results of procedures of irregularity components do not provide distortion in digital processing of the irregularity signal. They permit, through the use of FFT^{-1}, to return to the courses of individual components and to the primary irregularity in the non-filtered measurement of surface profile. This is a functional approach and proper determination of profile components and valuation of irregularity features in bands for accuracy, quality, diagnostics and tribology in the formulation of the total surface irregularity, such as appears in reality.

The presented wide-band formulation by amplitude-and-frequency of SGS irregularity profile facilitates multi-dimensional special applications such as:

1. Monitoring of surface profile irregularities and an analysis of their changes by frequency.
2. More accurate discrimination of waviness and roughness components for periodic irregularities, as opposed to arbitrarily assumed (step-wise and stiffly standardized) filtration boundaries.
3. Qualitative and quantitative analysis of profile components.
4. More effective analyses and evaluation of disturbances and distortions of irregularities occurring in processing and exploitation of objects.
5. New band-filtering procedures of surface irregularity components from the digital form of a non-filtered signal in measurements.
6. Proposal of a standard approach to analyze profile irregularities by frequency.

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