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THEORETICAL AND PRACTICAL INVESTIGATIONS OF V-BLOCK WAVINESS MEASUREMENT OF CYLINDRICAL PARTS

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Abstract

The paper relates to the problem of adaptation of V-block methods to waviness measurements of cylindrical surfaces. It presents the fundamentals of V-block methods and the principle of their application. The V-block methods can be successfully used to measure the roundness and waviness deviations of large cylinders used in paper industry, shipping industry, or in metallurgy. The concept of adaptation of the V-block method to waviness measurements of cylindrical surfaces was verified using computer simulations and experimental work. The computer simulation was carried out in order to check whether the proposed mathematical model and V-block method parameters are correct. Based on the simulation results, a model of measuring device ROL-2 for V-block waviness measurements was developed. Next, experimental research was carried out consisting in evaluation of waviness deviation, initially using a standard non-reference measuring device, and then using the tested device based on the V-block method. Finally, accuracy of the V-block experimental method was calculated.

Keywords: V-block method, roundness, waviness measurement, detectability coefficient, method accuracy.

1. Introduction

Nowadays, modern industries face a great demand to control process quality, meet product specifications corresponding with the customer needs, and assess their R&D activities. As a result, development of appropriate measurement methodologies for product evaluation becomes the critical issue [1]. Particularly important is development of measuring methods that can be used to perform in-situ measurements directly on a machine tool, often in unfavourable industrial conditions.

Cylindrical elements are a very important group of mechanical parts, because about 70% of all engineered elements have an axis of rotational symmetry [2]. These parts usually perform responsible functions, especially in internal combustion engines [3]. An important of a cylindrical surface is its texture for. From the structural point of view, any surface can be treated as overlapping three types of irregularities, *i.e.*, the form and position error (roundness error for cylindrical surfaces), waviness, and roughness [1, 4]. Because the proper interpretation of geometric tolerance in many cases is difficult, especially for universal students and inexperienced engineers, a graphical and multimedia software was developed in order to facilitate understanding the rules of geometrical tolerances [5, 6].

Examination of form deviations play a significant role in different research disciplines, *e.g.* in medicine. Based on measurement results of human internal organ shapes it is possible to determine their state of health. This problem is particularly important in cardiology, because basing on evaluation of the heart shape the operation parameters can be established [7].

In literature there is only a limited information related to measurement of waviness deviations of cylindrical surfaces. The waviness error of rotating parts generates vibrations and noise. This phenomenon is very dangerous, because it reduces the service lifetime of

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mechanical components and may cause their serious malfunctioning [8]. It is especially important in large machine components, for example crankshafts of ship engines, where every repair is difficult and is associated with high costs.

The form and waviness errors have the crucial impact on quality of cooperating elements of machine parts. This occurs especially in machines and equipment working in difficult conditions, *e.g.* excavators used for construction and road works [9].

Every waviness profile can be represented as the sum of the Fourier trigonometric series terms. Thus, the discrete amplitude spectrum of analysed profile can be obtained. Based on the evaluated values of harmonic amplitudes of a measured profile, properties of a machine tool used to machining the measured work-piece can be assessed, because excessive values of waviness components are caused by decreased stiffness of the machine tool. Therefore, the waviness and roundness measurements are very important. Numerous research works focus on the measurements and analysis of roundness deviation. However, only a small number of scientific research concerns on evaluation of waviness deviation, especially that of large cylinders. For this reason, it is necessary to develop a measuring method that can be used for this kind of measurements.

Traditionally, roundness and waviness of cylindrical parts are characterized using two main methods: a radius change method, also called a non-reference method, and a V-block method, known as a reference method. The radius change method is based on two types of measuring instrument: one employing a rotary sensor (Fig. 1a), and one employing a rotary table (Fig. 1b). This measuring method is widely used in laboratories and industrial facilities, because it is accurate. It is known, however, that these methods, despite of having a high accuracy, are ineffective for measuring large-size cylinders.

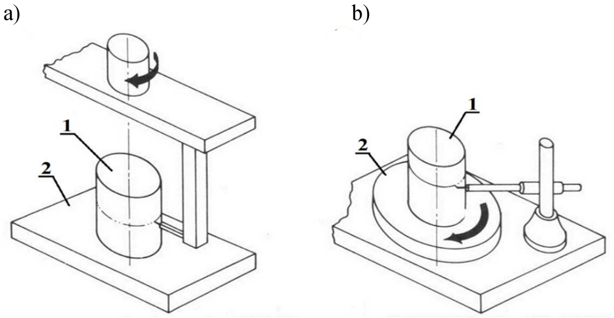

Fig. 1. The radial roundness measurement: a) using a rotary sensor; b) using a rotary table [10].

As it is shown in Fig. 1 [10], in the non-reference method a work-piece (1) should be placed on the measuring table (2) of the instrument. However, in many branches of industry, *e.g.* paper industry, metallurgical industry, shipbuilding, there are used large-size cylinders that cannot be placed on a measuring table. Furthermore, the radial roundness and waviness measurements are carried out under laboratory conditions. So, modern industry requires to develop measuring devices that are universal, cheap, easy to operate and can be used in industrial conditions. Although the coordinate measuring device can be used to measure roundness deviations, its application to the waviness measurement of cylindrical parts is limited [11]. Moreover, the CMM does not allow in situ measurement of cylindrical parts.

The V-block method meets this requirements. Known as the reference one, the method can be used as a two-point, three-point and n-point method. The most popular type is the three-point method implemented with use of a V-block and a measuring sensor. The first research related with the reference method was performed as early as in the early forties of the twentieth century by Berndt [12], who approximately determined the roundness deviation at various angles of a V-block. In 1966 Witzke [13] developed a measuring device equipment with two V-blocks and inductive probes to measure roundness. Kuosmanen in [14] described a measuring system based on the three-point reference method used to examine roundness deviations of large paper cylinders during manufacturing process. An interesting system used to evaluate the roundness profile during turning operation was presented in [15]. Additionally, the authors of this paper investigated an influence of cutting force on the roundness deviations. The subject of [16] focuses on development of a new mathematical algorithm used in the three point method to facilitate calculations. Interesting research works were performed at Kielce University of Technology. The results of research presented in [17] show that the V-block method can be used to measure the roundness deviation, because the difference between results of the V-block and radial methods lies within the interval 13−15% (for the assumed probability level P = 0,95). Another work was carried out in order to use the V-block method to the cylindricity measurement. The results of statistical verification of the V-block cylindricity measurement [18] show that its maximal error is equal to about 19% of the standard non-reference method error.

Thus, the research results presented in [12–17] show that the V-block method can be successfully used to measure the roundness and cylindricity deviations [18–19] of large cylinders and to perform in-situ measurements directly on a machine tool. However, there is no research associated with the V-block waviness measurement of cylindrical surfaces in the range of 16–50 UPR. In many cases, the measurement of roundness deviations only is insufficient, and it is necessary to evaluate irregularities of cylindrical surfaces in a wide range in the presence of waviness. For this reason, the concept of adapting V-block methods to the waviness measurements of cylindrical surfaces arose.

2. Mathematic model of V-block waviness measurements

The information presented in [20] suggests that the three-point V-block method is recommended for waviness measurements. For this reason, this type of reference method is analysed. In the V-block method there are the base points (S_2, S_3) and the point of measurement – S_1 (see Fig. 2.). Their positions in the assumed coordinate system is determined by two angles: α and β.

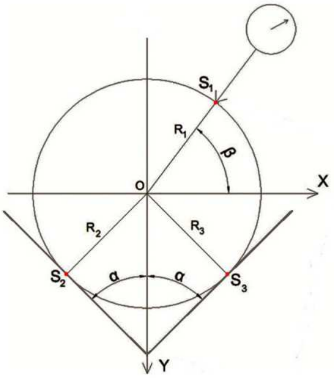

Fig. 2. The concept of roundness and waviness measurements by the V-block method [20].

The angle α is the angle between the tangents of supports of the measured object, whereas the angle β is the angle between the direction of measurement and the x-axis (Fig. 2). The values of α and β are angular parameters, which are responsible for detecting particular harmonic components of the measured profile.

In practice, the signal values read by the sensor depend on the deviations in the point of measurement S_1 and in the base points S_2, S_3. As a result, the profile $F(\varphi)$ measured by V-block method does not coincide with the real profile $R(\varphi)$ (see Fig. 3.). This was the basic problem of V-block method application. It was necessary first to determine the number of the predominant harmonic components, and then to calculate the approximate value of the roundness deviation ΔR using (3) [17, 20].

$$\Delta R \cong \frac{\Delta F}{K_n}, \tag{1}$$

where ΔF – the measured deviation, K_n – the coefficient of detectability for n-th harmonic.

The coefficient of detectability is a function of the method parameters – angles α and β, as well as the number n determined for regular profiles, the so-called n-lobbing.

Because of a low accuracy of the V-block methods they are usually applied only to the approximate roundness measurement. Therefore, a mathematical model was developed to increase the measurement accuracy of V-block method. Further information [20] deals with applicability of the mathematical models to V-block waviness measurements.

3. Computer simulation

The simulation was carried out with use of the Matlab software to obtain procedures and functions for checking whether the proposed model, its angular parameters and the transformation algorithm are correct. Another aim of the simulation was to verify the concept of adaptation of the V-block method to waviness measurements of cylindrical surfaces.

The computer simulation presented in this paper involves the following three steps: (I) generating the virtual profile $R(\varphi)$ which corresponds with the real roundness and waviness profile of the work-piece, (II) generating the profile $F(\varphi)$ obtained directly from the measuring sensor, (III) calculating the profile $R_p(\varphi)$ from the profile $F(\varphi)$ through its mathematical transformation.

First, the transformation was performed for 2−50 UPR (undulation per revolution), and next for 16−50 UPR.

3.1. Generation of real profile R(φ) and profile measured by sensor F(φ)

A real profile $R(\varphi)$ generated using computer simulation consists of the harmonic components 4, 6, 11, which cover the roundness deviation, and the harmonic components 18, 25, 32, 40, 43, 47, 50, which represent the waviness deviation of cylindrical surfaces. This profile is characterized by (2). This equation is described as the virtual measurement generated for exemplary roundness and waviness components. The real profile $R(\varphi)$ is the basis for further considerations.

$$\begin{aligned} \mathrm{R}(\phi)=\mathrm{R}_0&+0{,}001\cdot(\sin(\phi)+\cos(\phi)+3\cdot\cos(4\phi)+2\cdot\sin(8\phi)+\frac{1}{2}\cdot\cos(11\phi)+\sin(18\phi)+\\ &\frac{1}{2}\cdot\cos(25\phi)+2\cdot\sin(32\phi)+\cos(40\phi)+2\cdot\sin(43\phi)+\frac{1}{2}\sin(47\phi)+\cos\cdot(50\phi)), \end{aligned} \tag{2}$$

where R_0 = 25mm − the nominal cylinder radius, $\phi=\dfrac{2\cdot\pi\cdot n}{N}$ – the sampling angle, where $n = 0,1,2,\ldots,N$.

Having the real profile $R(\varphi)$, in the next step the profile $F(\varphi)$is calculated, measured by the sensor.

The authors [18] show that the V-block methods can be applied to measurement of cylindricity, if a mathematical transformation of the measured profile into the real one is performed. Therefore, the mathematical relationships presented in [18] have been used to obtain the profile $F(\varphi)$ by (3):

$$\begin{aligned} F(\phi) &= R(\phi+\beta) + E_X(\phi)\cos\beta + E_Y(\phi)\sin\beta \\ &= R(\phi+\beta) - \frac{1}{2}R(\phi+\alpha)\left[\frac{\cos\beta}{\cos\alpha} + \frac{\sin\beta}{\sin\alpha}\right] - \frac{1}{2}R(\phi+\pi-\alpha)\left[-\frac{\cos\beta}{\cos\alpha} + \frac{\sin\beta}{\sin\alpha}\right], \end{aligned} \tag{3}$$

where $\alpha = 60°$, $\beta = 30°$.

The profile $F(\varphi)$ is calculated from the (3) for the given method parameters, *i.e.*, $\alpha = 60°$, $\beta = 30°$ (see Fig. 2). In order to show two profiles, namely the real profile $R(\varphi)$ and the profile $F(\varphi)$ measured by sensor, comparison of their profiles in the Cartesian coordinate system is presented in Fig. 3.

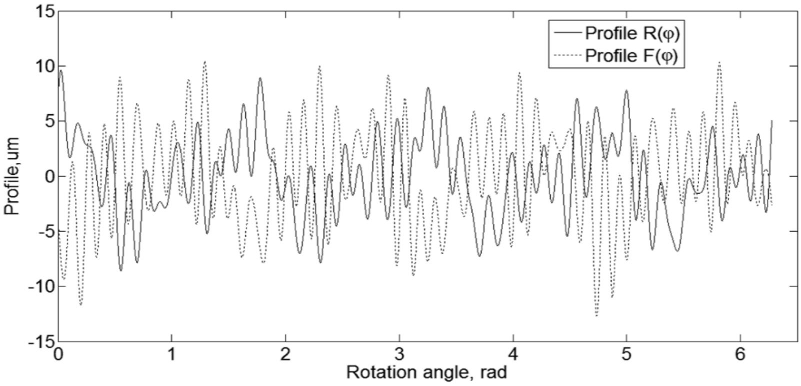

Fig. 3. Comparison of the profile $F(\varphi)$ measured by sensor with the real profile $R(\varphi)$.

As it can be seen in Fig. 3, there is a difference between the inspected profiles. Thus, the deviation ΔF measured by sensor does not coincide with the real roundness and waviness deviation ΔR. For that reason, in order to increase the measurement accuracy of V-block methods, it is necessary to transform the measured profile $F(\varphi)$ into the reconstructed profile $R_p(\varphi)$ using the following relationships.

3.2. Transformation of measured profile F(φ) into reconstructed profile R$_p$(φ)

Let us consider (3). In this equation only the profile $R(\varphi)$ is unknown. Thus, the equation should be solved relating $R(\varphi)$. The problem, however, can be simplified when the measured and real profiles are presented in the form of complex Fourier series [18].

Let $\hat{F}_n$ and $\hat{R}_n$ be the n-th components of expansion of profiles $F(\varphi)$ and $R(\varphi)$ in the complex Fourier series $n = -\infty,\ldots,-1,0,1\ldots,\infty$, that is:

$$R(\varphi) = \sum_{n=-\infty}^{\infty} \hat{R}_n\, e^{in\varphi},\ F(\varphi) = \sum_{n=-\infty}^{\infty} \hat{F}_n\, e^{in\varphi}. \tag{4}$$

Then, we obtain from (3):

$$\hat{F}_n = \hat{R}_n \cdot \hat{K}_n, \tag{5}$$

where $\hat{K}_n$ is the coefficient of detectability for the n-th harmonic of profile defined by the following formula [18]:

$$\hat{K}_n = e^{in\beta} - \frac{1}{2} e^{in\alpha}\left[\frac{\cos\beta}{\cos\alpha}+\frac{\sin\beta}{\sin\alpha}\right] - \frac{1}{2}\left(-1\right)^n e^{-in\alpha}\left[-\frac{\cos\beta}{\cos\alpha}+\frac{\sin\beta}{\sin\alpha}\right] \overset{def}{=} \frac{\hat{R}_n}{\hat{F}_n}. \tag{6}$$

Application of the above relationships in computer procedures allows to perform transformation of the measured profile $F(\varphi)$ into the reconstructed profile $R_p(\varphi)$.

Firstly, the simulation was performed in the range 2–50 UPR, which covers roundness and waviness components. Fig. 4 shows superimposed real profiles $R(\varphi)$ and reconstructed $R_p(\varphi)$ in the Cartesian coordinate system. The diagram in Fig. 5 presents the bar chart of amplitudes of subsequent harmonic components (for the range 1–50) of the inspected profiles.

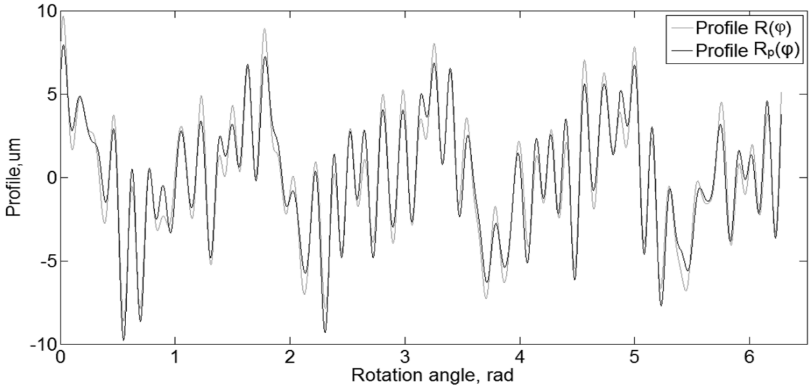

Fig. 4. Superimposed reconstructed profile $R_p(\varphi)$ with real profile $R(\varphi)$.

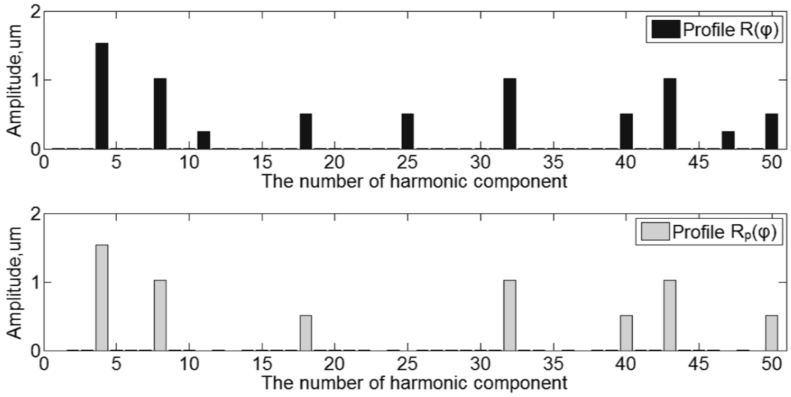

Fig. 5. The bar chart of harmonic components for the profiles: the upper chart – real profile $R(\varphi)$, the lower chart – reconstructed profile $R_p(\varphi)$.

As it can be seen in Fig. 4, the reconstructed profile $R_p(\varphi)$ largely overlaps with the real profile $R(\varphi)$. The compatibility of compared profiles is very high. A difference between profiles $R_p(\varphi)$ and $R(\varphi)$ is caused by inability to detect the eleventh, twenty-fifth and forty-seventh harmonic components of reconstructed profile $R_p(\varphi)$ using V-block method parameters: $\alpha = 60°$

and β = 30° (see Fig. 5). In order to wider analyze the difference between inspected profiles, the diagram in Fig. 6 presents the difference between the points of profiles illustrated in Fig. 4.

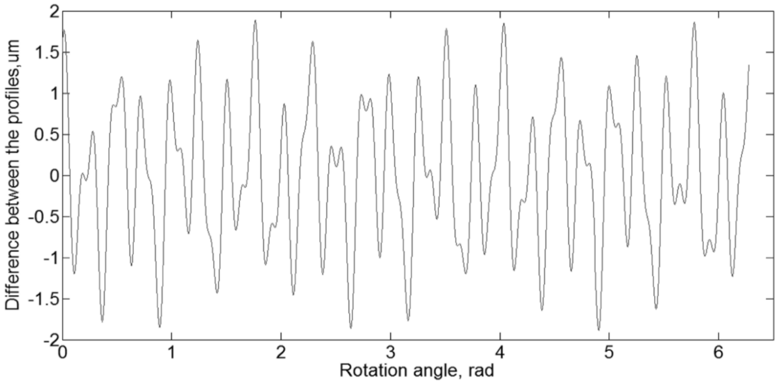

Fig. 6. The difference between the profiles $R(\varphi)$ and $R_p(\varphi)$ in the range 2–50 UPR.

The maximum value of the difference between considered profiles is equal to 1.89 µm (see Fig. 6). Therefore, a very high level of compliance between profiles was achieved. The simulation results show that the proposed parameters of V-block method and the mathematical model can be successfully used to measure the roundness and waviness profiles in the range 2−50 UPR.

The next step in computer simulation consisted in transformation of the measured profile $F(\varphi)$ into the reconstructed profile $R_p(\varphi)$ in the range 16−50 UPR, which covers only waviness components.

In order to apply the V-method to waviness measurements, the real profile $R(\varphi)$ and the profile $F(\varphi)$ measured by sensor were filtered to delete their roundness components and leave only the waviness components from the range 16–50 UPR (see Fig. 8).

The profiles were filtered using a cut-off Fourier filter based on harmonic analysis with Fast Fourier Transformation.

Then the profile $F(\varphi)$ was transformed into the reconstructed profile in the range 16–50UPR, which covers the waviness components. Fig. 7 presents both profiles in the Cartesian coordinate system, while Fig. 8 shows the bar chart of amplitudes of harmonic components for the range 16–50.

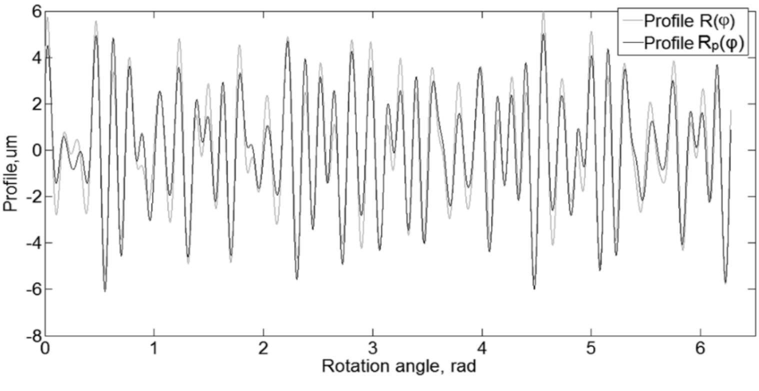

Fig. 7. Superimposed reconstructed profile $R_p(\varphi)$ with real profile $R(\varphi)$ in range 16–50 UPR.

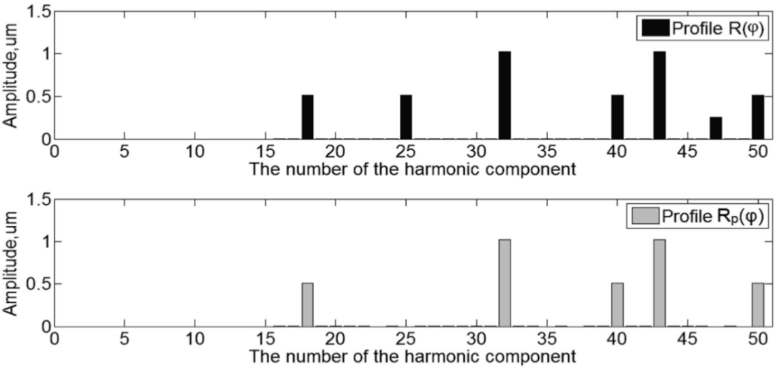

Fig. 8. The bar chart of harmonic components for the profiles in range 16–50 UPR: the upper chart – real profile $R(\varphi)$, the lower chart – reconstructed profile $R_p(\varphi)$.

As expected, the reconstructed profile $R_p(\varphi)$ generally corresponds with the real profile $R(\varphi)$ in the range 16−50 UPR (see Fig. 7 and Fig. 8). In this case, similarly to transformation in the range 2–50 UPR, the compatibility of the compared profiles is very high. The difference between two profiles, caused by inability to detect the twenty-fifth and forty-seventh harmonic components of reconstructed profile $R_p(\varphi)$, was also presented in the diagram in Fig. 9.

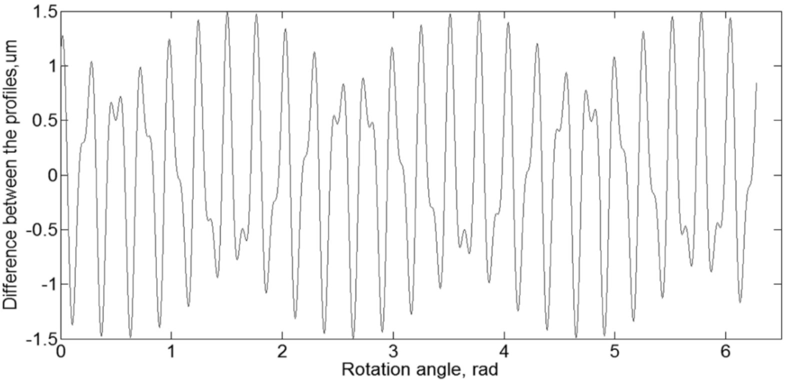

Fig. 9. The bar chart of harmonic components for the profiles in range 16–50 UPR: the upper blue chart – real profile $R(\varphi)$, the lower red chart – reconstructed profile $R_p(\varphi)$.

The diagram shown in Fig. 9 confirms that the difference between the inspected profiles is very small. The maximum difference between the real profile $R(\varphi)$ and the reconstructed profile $R_p(\varphi)$ in the range 16−50 UPR is equal to 1.49 µm. The computer simulation results proved that the projection accuracy was high in the range of 2−50 UPR, as well as for waviness in the range 16−50 UPR, which confirms correctness of the proposed mathematical model and V-block method parameters.

4. Model measuring stand for V-block waviness measurement

Based on the theoretical research [20] and computer simulation presented in Section 3, the model measuring device ROL-2 was developed (see Fig. 10) to measure waviness deviations of cylindrical surfaces in the range 16–50 UPR.

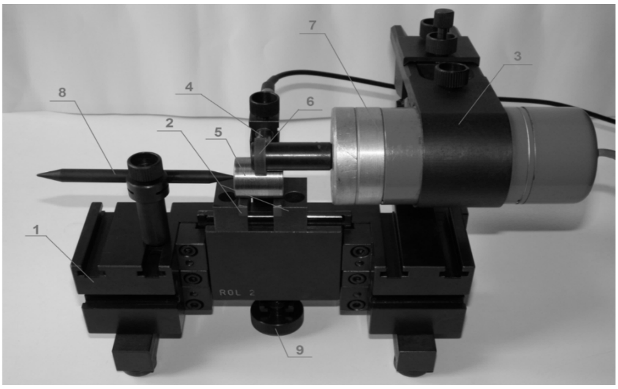

Fig. 10. The model measuring device ROL-2 for V-block waviness measurement: 1 – the main body; 2 – the V-blocks; 3 – the motive unit; 4 – the measuring sensor; 5 – the work-piece; 6 – the motive disc; 7 – the electric engine; 8 – the bracket; 9 – the regulation screw.

The construction of model measuring device ROL-2 is based on − proposed in [20] − the three-point inverted reference method for $\alpha = 60°$ and $\beta = 30°$. In the considered device ROL-2 (see Fig. 10) the measured work-piece (5) is lied on two V-blocks (2). One of them is the measuring V-block, whereas the second one is the supporting V-block. The work-piece (5) is put in rotation by the motive disc (6) built in the motive unit (3). The rubber-covered motive disc (6) is driven by the electric engine (7). The correct position of measured work-piece (5) on the V-blocks (2) is ensured by the bracket (8). The regulation screw (9) is used to set an appropriate height of V-block with measured object in relation to the position of measuring sensor (4). The principle of working model measuring device ROL-2 is presented in Fig. 11.

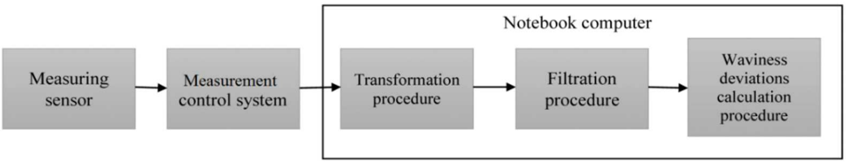

Fig. 11. A block diagram of the model measuring device ROL-2.

During the measurement process, the sensor tip moves along circumference of the measured cylinder. Signals from the measuring sensor are processed by the measurement control system and transmitted using RS-232 to the computer. The points of measured profile are saved in a text file. Then, using computer procedures developed in the Matlab software (see Section 3.2), the profile measured by sensor $F(\varphi)$ is transformed into the reconstructed profile $R_p(\varphi)$. The obtained profile $R_p(\varphi)$ is filtered by a Gaussian filter in the range 16–50 UPR. The waviness deviation *RONt* is calculated based on the Last Squares Circle.

5. Experimental research

In order to verify experimentally the concept of application of the V-block method to waviness deviation measurements of cylindrical surfaces in the range 16–50 UPR, the comparative research was carried out. The research consisted in measuring the waviness deviation of cylindrical parts using the measuring device ROL-2 (see Fig. 10) based on the V-block method. Next, the same cylindrical parts were measured by Talyrond 365 Taylor Hobson

Company based on the non-reference method with a rotary table, located in the Laboratory of Computer Measurements of Geometric Quantities at Kielce University of Technology.

Fifty cylindrical samples were used in the experimental research. The measured parameter was the waviness deviation *RONt* determined on the basis of the last square circle (LSC) in the range 16–50 UPR. The measured profiles were filtered using a Gaussian filter – in order to delete the roundness and roughness components and leave only the waviness components.

Based on the waviness deviation *RONt* obtained using ROL-2 and Talyrond 365, the experimental relative method error was calculated [21]:

$$w_{RONt} = \frac{RONt_o - RONt_b}{RONt_b}, \tag{7}$$

where $RONt_o$ – the waviness deviations obtained using the reference method (ROL-2), $RONt_b$ – the waviness deviations obtained using the non-reference method (Talyrond 365).

The experimental relative method error calculated with the. (7) is the result of many partial systematic and random errors examined by the measuring system based on the V-block method of evaluating waviness deviations.

Based on the error values calculated by the experimental relative method for fifty cylindrical samples, the statistical research was carried out, consisting of [21]:

- the procedure for estimation of the mean value of the error obtained by the experimental relative method;
- the procedure for estimation of the variances and mean square deviation of the experimental method error;
- the procedure for estimation of the V-block method accuracy DM.

The V-block method accuracy DM calculated with the (8) is used to assess qualitatively the measurement accuracy of examined measuring device ROL-2 used to perform the V-block waviness measurements [21].

$$DM = \left|\overline{w}_{RONt} \pm u_p s\right| \cdot 100\%, \tag{8}$$

where $\overline{w}_{RONt}$ – the mean value of experimental relative method error, u_p – the expansion coefficient for probability $P = 0{,}95$, s – the mean square deviation of a singular difference.

The results of experimental investigation with the statistical analysis of experimental relative method error are presented in Table 1.

Table 1. The results of statistical analysis of experimental relative method error of the V-block waviness measurement using ROL-2.

Cylindrical samples		
Number of samples	n_p	50
Experimental relative method error	$w_{RONtmax}$	–0.049 µm
	$w_{RONtmin}$	–0.315 µm
	$\overline{w}_{RONt}$	–0.161 µm
Mean square deviation of a singular difference	s	0.061 µm
Variances for experimental relative method error	s^2	0.004 µm
Confidence interval of a single experimental relative method error	$P = 0.95$ ($u_p = 1.96$)	–0.161 ± 0.120 µm
V-block method accuracy	DM	28.1%

6. Summary and conclusions

This paper addresses the concept of adaptation of the V-block method, known as the reference method, to waviness measurements of cylindrical surfaces. The fundamentals of V-block method and the characteristic of mathematical model used in this method were presented. The V-block mathematical model was used in computer procedures to increase accuracy of V-block waviness measurement. This concept was verified using computer simulations and experimental research.

The computer simulations were carried out to achieve two mains goals. The first was to check whether the proposed mathematical model and V-block method angular parameters are correct. The second goal was to verify correctness of the computer procedures used for transformation the profile measured by sensor to the reconstruction profile. The simulation procedures were written in the Matlab language. The simulations were carried out in two ranges: The first range was 2–50 UPR, which covers the roundness and waviness components, and the second one was 16–50 UPR, which corresponds to surface waviness.

The visual comparison of real $R(\varphi)$ and reconstructed $R_p(\varphi)$ profiles showed that the profile obtained by computer transformation is to a great extent consistent with the real profile. The compared maximum difference values of the profiles are: 1.89 μm in the range 2–50 UPR and 1.49 μm in the range 16–50 UPR. Therefore, it can be concluded that the differences between profiles are insignificant. The results of computer simulation show that the proposed mathematical model, V-block method parameters and transformation procedures are correct and can be used to construct a measuring device that can be applied to accurate V-block waviness measurement of cylindrical surfaces.

The model measuring device ROL-2, developed on the basis of theoretical investigations and computer simulation, was used to perform the experimental verification concept of adaptation of the V-block method to waviness measurement. For this purpose a filthy cylindrical work-piece was measured on both the model measuring device ROL-2 and the high-quality non-reference instrument Talyrond 365 Taylor Hobson Company. The results of statistical analysis of experimental relative method error indicate that the V-block method accuracy is equal to about DM = 28.1%. Taking into account a possibility of application of the V-block method to measure the waviness deviation *RONt* in the range 16−50 UPR in industrial conditions, the calculated value of experimental method accuracy is satisfactory, because in some cases the acceptable accuracy limit of a measuring system used in industrial conditions is 30% [22, 23]. However, it is necessary to introduce some improvements in order to increase the measurement accuracy of V-block method. It seems reasonable to identify the real values of angle parameters applied in the measuring device ROL-2 that is used to assess waviness deviations of cylindrical surfaces, because − as showed in section 3 – the values of angular parameters influence the detectability coefficient. Next, the real values of angle parameters should be included in computer transformation procedures of sensor readings. It will be the subject of future research.

The research results presented in this paper will be fundamental in developing a measuring system that could be used to measure waviness profiles of large cylinders directly on a machine tool.

Acknowledgements

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