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# Research on Influence of Angular Method Parameters on the Result of the V-Block Cylindricity Measurement

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Original scientific paper

At the Kielce University of Technology a novel method for in situ cylindricity measurement has been developed. It has been called a V-block method and its fundamental is using a set of two connected V-blocks. Along the element connecting V-blocks the measuring sensor moves. The method is characterized by so-called detectability coefficient that is responsible for detection of the harmonic components in observed profile. The value of the coefficient depends on the angular method parameters, i.e. V-blocks angle and the position of the sensor. The paper presents fundamentals of the V-block method and results of the research work on influence angular method parameters on measurement results.

**Keywords**

*Cylindricity*
*Measurement*
*Error*
*Form*
*Deviation*

**Istraživanje utjecaja metode kutnih parametara na rezultate V-blok mjerenja cilindričnosti**

Izvornoznanstveni članak

Na Tehničkom sveučilištu Kielce razvijena je nova metoda za in situ mjerenje cilindričnosti. Naziva se V-blok metoda i temelji se na korištenju dvaju povezanih V-blokova. Mjerni senzor se pomiče uzduž elementa koji povezuje V-blokove. Metoda se odlikuje tzv. detektabilnim koeficijentom koji je odgovoran za otkrivanje harmoničkih elemenata u promatranom profilu. Vrijednost koeficijenta ovisi o metodi kutnih parametara, odnosno kutu V-blokova i položaju senzora. U radu su prikazane osnove V-blok metode i rezultati istraživanja utjecaja metode kutnih parametara na rezultate mjerenja.

**Ključne riječi**

*Cilindričnost*
*Mjerenje*
*Pogreška*
*Oblikovanje*
*Odstupanje*

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## 1. Introduction

Cylindrical elements belong to a numerous and important group of machine parts. Cylindricity measurement of small elements has reached a high metrological level, with instruments of high accuracy [1]. For accurate cylindricity measurements radius change methods are usually applied [2]. In these methods the workpiece should be placed on the measuring table of the instrument. However, in shipbuilding, power industry, paper industry, metallurgical industry, etc., there are large-size cylinders that cannot be placed on the table of the measuring instrument. Therefore producers operating in these areas of industry need methods that would enable in-situ measurement of cylindricity profiles of large cylindrical workpieces during the manufacturing process and during its exploitation [3]. The solution of this problem can be the V-block method [4, 5].

In V-block methods a signal is obtained in relation to a physical reference, which is constituted by points of support of the workpiece and contact points of the measuring sensor and the workpiece [6, 7]. In V-block methods the difference between the maximum and minimum value of the sensor reading is considerably different from the real deviation. It is because the measured value of the signal depends not only on the value of the real deviation measured at the contact point of the sensor and the workpiece but also on the value of deviation at the contact point of the workpiece and the supports. Thus, the difference between the sensor readings and the real profile is usually quite large.

The research work on this subject, of which some were supported by the Polish National Committee for Scientific Research (Project No 7T07D04008) [8], show that the V-block methods can be applied to exact measurements of roundness profiles, if one performs a mathematical transformation of the sensor readings. The results of the research work on V-block methods presented in [8] show that the results of measurement of the roundness deviation by the traditional V-block method ranges from 22 % to 63 % in relation to the result obtained by a highly accurate radius change method (for assumed probability level P=0,95).

**Symbols/Oznake**

| | | | |
|---|---|---|---|
| $F$ | - sensor readings<br>- očitanja senzora | $\varphi$ | - rotation angle, rad<br>- kut rotacije |
| $K$ | - Detectability coefficient<br>- koeficijent detektabilnosti | | **Subscripts/Indeksi** |
| $L$ | - distance between the V-blocks<br>- udaljenost između V-blokova | $_0$ | - initial V-block<br>- početni V-blok |
| $n$ | - number of harmonic component<br>- broj harmonijskih komponenata | $_1$ | - first support point<br>- prvi oslonac |
| $R$ | - profile value<br>- vrijednost profila | $_2$ | - second support point<br>- drugi oslonac |
| $S$ | - support point<br>- točka oslonca | $_L$ | - final V-block<br>- završni V-blok |
| $X$ | - horizontal coordinate of the cylinder<br>- horizontalna koordinata cilindra | $_n$ | - nominal parameter value<br>- nominalna vrijednost parametra |
| $Y$ | - vertical coordinate of the cylinder<br>- vertikalna koordinata cilindra | $_r$ | - real parameter value<br>- stvarna vrijednost parametra |
| $Z$ | - cylinder height<br>- visina cilindra | | |
| | **Greek letters/Grčka slova** | | |
| $\alpha$ | - angle of the V-block, deg<br>- kut V-bloka | | |
| $\beta$ | - angle of position of the sensor, deg<br>- kut položaja senzora | | |

However, thanks to applying computer-aided measurements this difference between the result of the V-block and the radius change method lies within the interval of $13 \div 15$ %.

Successful finish of the research work on computer-aided V-block roundness measurement resulted in design and construction of measuring instruments allowing in-situ measurements of roundness profiles. In authors opinion similar measuring instrument allowing V-block cylindricity measurement can be designed and constructed. In hitherto practice the V-block method was used usually to measure simplified cylindricity. Katsurada et al. in [9] describe the V-block measurement of simplified cylindricity of parallel rollers (roundness profiles in three cross-sections of the workpiece are measured : two cross-sections were defined by the V-blocks and one cross-section in the middle). Such approach allows only rough evaluation of cylindricity if measured element is long.

Considering the requirements of the Geometrical Product Specifications standards [10-12], the measuring instrument should allow evaluation of the entire surface of the element [13-16].

## 2. The Concept of V-block cylindricity measurements

There are methods that make it possible to measure cylindricity directly on a machine tool using, for example, a multisensor systems [17] and optical systems [18]. However, most methods that are described in the literature use the measuring system that is fixed to the individual machine tool. Therefore, they cannot be applied to measure cylindricity of elements during their exploitation. This problem can be solved by the application of the V-block method. The scheme of measurement of roundness by the V-block method is shown in Fig. 1.

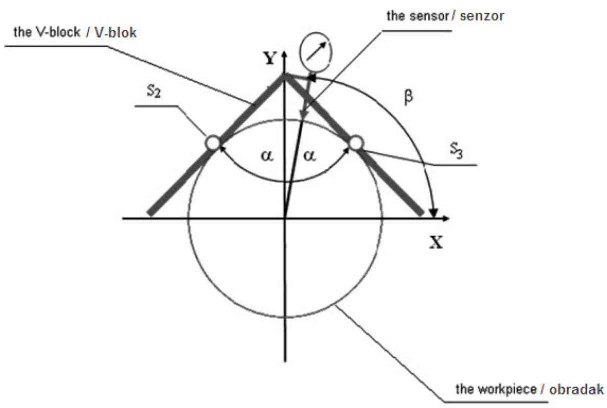


**Figure 1.** Concept of the V-block roundness measurement

**Slika 1.** Koncept mjerenja kružnosti pomoću V-bloka

In the V-block method sensor readings are obtained in relation to a physical datum, that is constituted by points of support of the workpiece and contact points of the measuring sensor and the workpiece. Mutual location of these points is defined by angular method parameters – angles $\alpha$ and $\beta$ (see Fig. 1). They are responsible for detecting particular harmonic components of the measured cylindricity profile.

In order to obtain accurate measurement results sensor readings need to be mathematically processed. It is usually performed with use of Fast Fourier Transform [19, 20].

The first investigations on reference methods were conducted in Germany in the 1940s by Dr G. von Berndt. Further development of measurements using a prism as a datum is described in Boerdijk's works [21]. Boerdijk proposed to use the Fourier series to evaluate the sensor signal recorded by applying the three-point method. Boerdijk [21] and Canfield [22] also suggested that roundness measurements for different prism angles should be repeated, and, in this way, individual harmonic components of the profile could be detected. Further investigations related to reference roundness measurements led to publishing a large number of papers and dissertations, for example, those by Reason [23]. The three-point method became a subject of great interest in the 1970s. A large number of new concepts basing on it were developed, for example, by Witzke [24] and Whitehouse [25]. In the late seventies, Kakino and Kitazawa [4] presented a new method for measurement of cylindricity performed directly on a machine tool. The new method was based on the concept of the three-point method. A severe disadvantage of the new method was that it required a physical straightness etalon to be used.

On the fundamental of solutions existing in the field of roundness measurements, at the Kielce University of Technology, a concept of V-block cylindricity measurement has been developed [26, 27] (see Fig. 2).

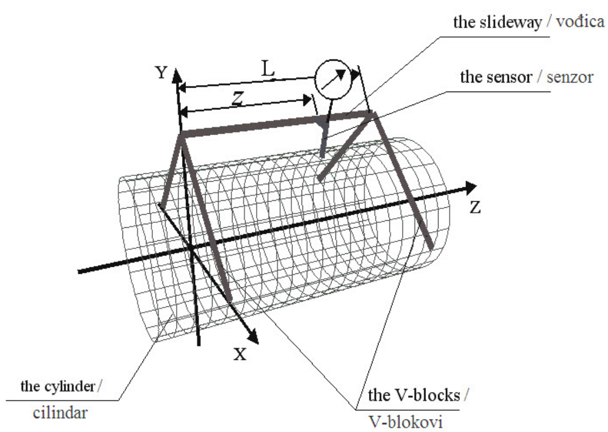


**Figure 2.** Concept of the V-block cylindricity measurement [28]

**Slika 2.** Koncept mjerenja cilindričnosti pomoću V-bloka [28]

The proposed concept assumes that the measured object is placed on a machine tool or on the working stand. Two interconnected V-blocks adhere to its surface. The connecting element of the V-block functions additionally as a guide, along which an induction sensor is shifted. The V-blocks are slightly pressed down to the measured object by means of a set of springs, which ensures their stable contact with the object in rotation. In the measuring instrument, both the object's angle of rotation and the sensor's displacement are controlled by means of a computer controller. The cylindricity measurement of an object implies appropriate scanning of the object's surface with a measuring sensor, along the suitably designed trajectory, through appropriate steering of the object's angle of rotation and sensor's displacement [29].

After successful finish of the theoretical research work efforts aiming at practical verification of the developed concept were taken. In order to do that it was necessary to design and construct the measuring system allowing cylindricity measurements by the V-block method. Such system has been finally designed and constructed at the Rolling Bearings Factory "Kraśnik" (Poland) in the framework of the research project sponsored by Polish Ministry of Science. The system is shown in Fig. 3.

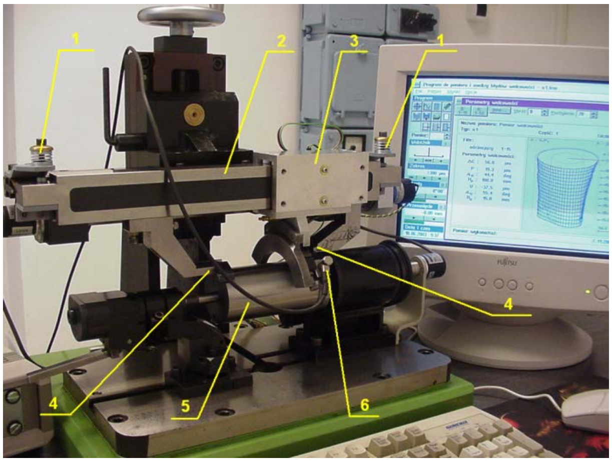


**Figure 3.** Model measuring device PSA 6 for the V-block method cylindricity measurements

**Slika 3.** Model uređaja za mjerenje PSA 6 cilindričnosti pomoću V-blok metode

The workpiece (5) is fixed in the tailstock and in the spindle. The rotation of the workpiece is controlled by the computer. The system of two connected V-blocks (4) lies on the surface of the workpiece. The V-blocks are fixed to the beam (2). The beam (2) is suspended on the system of springs (1). The measuring sensor (6) is fixed to the support (3) that can move along the beam (2). The system was adjusted to the strategy of measurements of subsequent cross-sections. So, roundness profiles in predefined cross-sections of the workpiece are measured. After the measurement the system automatically joins them into cylindrical data.

The device shown in Fig. 3 was used in the experiments aiming at evaluation of the accuracy of the cylindricity measurement by the V-block method.

The cylindricity deviation for each sample element was determined with two methods: the investigated V-block method and the highly accurate radial method. The conducted tests, the results of which were published in [30], showed that the difference between the results of cylindricity deviation measured by the V-block and the highly accurate radius change method lies within the interval ±19 % (for a probability level P=0,95).

The next step in investigation on the application of V-block method to accurate cylindricity measurements was to look for its improvement and measurement accuracy enhancement [31]. The work mainly involved the analysis of potential sources of measurement errors, and their elimination or compensation through specially developed procedures. This article refers to the analysis of potential sources of measurement errors related to angular parameters of the method - angles α and β (see Fig. 1).

The results of the roundness measurements conducted by means of the V-block method prove that the method angular parameters values influence the recognition of particular harmonic components of the profile. Changing them will then influence, to a certain degree, the obtained profile values. In order to investigate the influence of errors related to the method parameters on the obtained results, the theoretical analysis of the problem, further backed up with computer simulations, was carried out. The following sources of errors were considered:

a) errors of the angle α (the angle of the V-blocks)
b) errors of the angle β defining the position of the sensor.

## 3. Influence of the sensor position on measurement results

The position of the measuring sensor is defined by the value of angle β, which is one of the method parameters, as it was shown in Fig. 1. Values of the angles α and β are responsible for detecting the particular harmonic components of a profile. Therefore, it is very important to identify and establish their real values as well as to investigate the influence of the difference between the real and nominal values on measurement results [32]. This is the reason why, a computer simulation was performed so as to determine the interdependence of the nominal and the real values of the angle β and their influence on measurement results. The simulation required:

- generating a model cylindricity profile $R(\varphi, z)$,
- generating sensor readings $F_{\beta_n}(\varphi, z)$ for the nominal value of the angle $\beta = \beta_\mathrm{n} = 90°$,
- generating sensor readings $F_{\beta_n}(\varphi, z)$ for the real value of the angle β (for the simulation purposes, the real value was assumed to be $\beta = \beta_\mathrm{r} = 89°$),
- transforming the profiles $F_{\beta_n}(\varphi, z)$ and $F_{\beta_r}(\varphi, z)$ into the processed profiles $R_{\beta_n}(\varphi, z)$ and $R_{\beta_r}(\varphi, z)$,
- calculating the orientation of the mean cylinders axes for the profiles $R_{\beta_n}(\varphi, z)$ and $R_{\beta_r}(\varphi, z)$,
- calculating the deviations for the profiles $R_{\beta_n}(\varphi, z)$ and $R_{\beta_r}(\varphi, z)$ from the mean cylinders,
- comparing the deviations of the profiles $R_{\beta_n}(\varphi, z)$ and $R_{\beta_r}(\varphi, z)$.

The simulation made it possible to establish the difference between the profiles. A change in the angle β causes a change in the detectability coefficient. The diagram in Fig. 4 was plotted to illustrate how the change in β affects the change in the detectability coefficients.

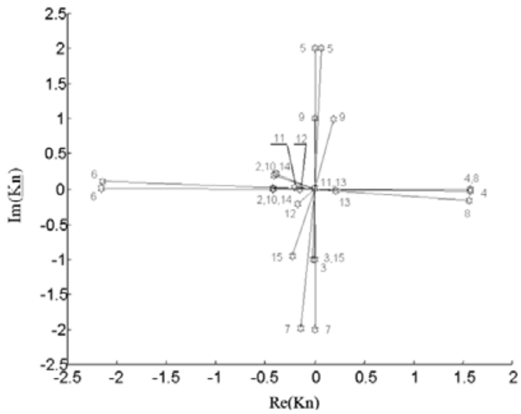


**Figure 4.** The values of the detectability coefficient for $\alpha = 60°$, $\beta = 90°$ and for $\alpha = 60°$, $\beta = 89°$ – the range of harmonic components: $2 \div 15$

**Slika 4.** Vrijednosti koeficijenta detektabilnosti za $\alpha = 60°$, $\beta = 90°$ i za $\alpha = 60°$, $\beta = 89°$ – raspon harmonijskih komponenti: $2 \div 15$

The values of the detectability coefficient $K_n$ for the nominal values of the angles α and β ($\alpha = \alpha_\mathrm{n} = 60°$ and $\beta = \beta_\mathrm{n} = 90°$) are plotted in blue, and the values of $K_n$ for the simulated values of α and β ($\alpha = \alpha_\mathrm{n} = 60°$ and $\beta = \beta_\mathrm{r} = 89°$) are plotted in red. In a general case, the values of $K_n$ are complex numbers, therefore in the X axis there are values of $\Re(K_n)$ and in the Y axis we have values of $\Im(K_n)$. For each value of the coefficient $K_n$, in the range of harmonic components $2 \div 15$, a segment was plotted. The initial point of the segment lies at point (0,0) and the end of the segment was the point with co-ordinates $(\Re(K_n),\Im(K_n))$. The end of each segment was marked with a star and the number next to the star corresponds to the number of a respective harmonic component.

From the diagram in Fig. 4 it is clear that a one-degree change in the angle β causes a change in the detectability coefficient, this change being different for different harmonic components. For example, for $n=3$ the change in $K_n$ is very small, but for $n=12$ the value of $K_n$ changes significantly. We can also see that if the angular combination is $\alpha=60°$ and $\beta=89°$, then the values of $K_n$ for $n=11$ and $n=13$ are not equal to zero, and therefore the eleventh and thirteenth harmonic components can be detected. Results of work presented in [25] show that these harmonic components cannot be detected if the combination is $\alpha=60°$ and $\beta=90°$. Analysing the change in the detectability coefficient, we report that for $\alpha=60°$ and $\beta=90°$ the imaginary or the real part of $K_n$ is equal to zero, and for the combination $\alpha=60°$ and $\beta=89°$ both parts are different from zero.

The different values of the detectability coefficient cause a change in the profile values $R_{\beta_n}(\varphi,z)$ and $R_{\beta_r}(\varphi,z)$, calculated for $\beta=\beta_{\mathrm{n}}=90°$ and for $\beta=\beta_{\mathrm{r}}=89°$, respectively. Figure 5 presents roundness profiles in one of the cross-sections of the generated cylinder. In Figure 5 the coincidence of compared profiles is high.

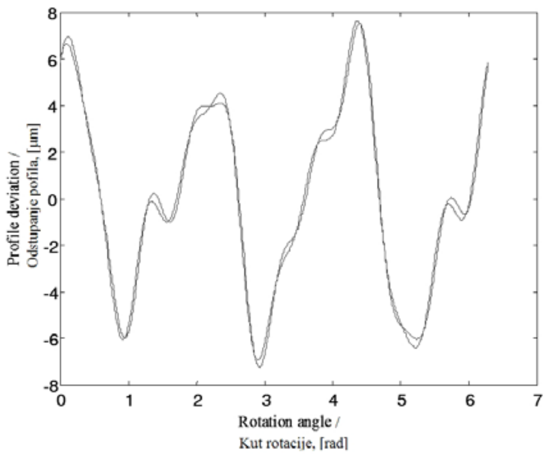


**Figure 5.** Roundness profiles $R_{\beta_n}(\varphi,z)$ and $R_{\beta_r}(\varphi,z)$ in one of the cross-sections of the generated cylinder

**Slika 5.** Profili zakrivljenja $R_{\beta_n}(\varphi,z)$ i $R_{\beta_r}(\varphi,z)$ u jednom od presjeka generiranog cilindra

Figure 6 shows the difference between the profiles illustrated in Fig. 5.

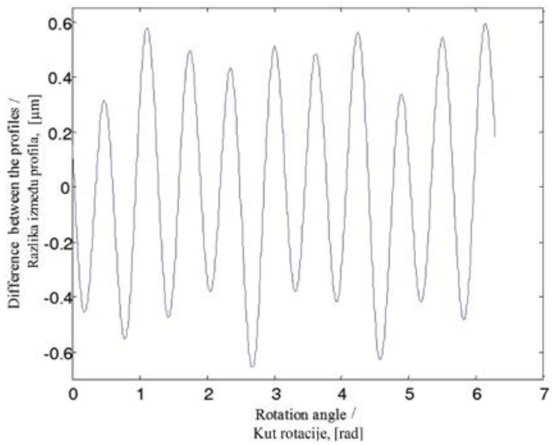


**Figure 6.** The difference between the profiles $R_{\beta_n}(\varphi,z)$ and $R_{\beta_r}(\varphi,z)$ in one of the cross-sections of the analyzed cylinder

**Slika 6.** Profili zakrivljenja $R_{\beta_n}(\varphi,z)$ i $R_{\beta_r}(\varphi,z)$ u jednom od presjeka analiziranog cilindra

Figure 7 shows a 3D diagram of the difference between the profiles on the entire surface of the inspected cylinder.

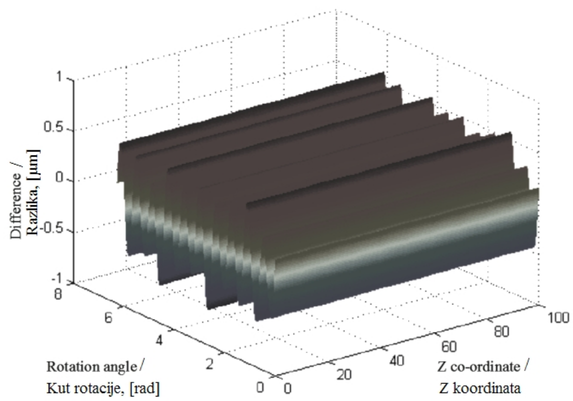


**Figure 7.** The difference between the profiles $R_{\beta_n}(\varphi,z)$ and $R_{\beta_r}(\varphi,z)$ in all cross-sections of the analyzed cylinder

**Slika 7.** Razlike između profila $R_{\beta_n}(\varphi,z)$ i $R_{\beta_r}(\varphi,z)$ u svim presjecima analiziranog cilindra

The maximum value of the difference between the profiles equals 0.63 µm, which constitutes about 4.5 % of the cylindricity deviation. Considering the fact that both profiles were calculated for the angles $\beta_{\mathrm{n}}$ and $\beta_{\mathrm{r}}$, whose difference is rather large ($\beta_{\mathrm{n}}-\beta_{\mathrm{r}}=1°$), we can assume that the influence between a real and nominal value of the angle $\beta$ on the result of the reference cylindricity measurement is rather small.

## 4. Influence of errors of the angle of V-blocks on measurement results

In the discussion over the influence of the error of α on the measurement result, a following notation will be used: $\alpha_0$ will stand for half the angle of the initial V-block, and $\alpha_L$ will stand for half the final V-block. Also, the nominal value of α will be denoted by $\alpha_n$, whereas $\alpha_r$ will stand for the real value of α. While analyzing the error of α one can deal with two cases:

- angles of both V-blocks are different from the nominal value, being equal to each other, that is $\alpha_0 \neq \alpha_n$ and $\alpha_L \neq \alpha_n$, but $\alpha_0 = \alpha_L$,
- angles of both V-blocks are different from the nominal value and different from each other, that is $\alpha_0 \neq \alpha_n$ and $\alpha_L \neq \alpha_n$, but $\alpha_0 \neq \alpha_L$.

### 4.1. Case of equal angles of V-blocks

The case analysis of equal angles in the both V-blocks $\alpha_0 = \alpha_L$ was conducted analogically to the case of angle β error, described in 3. Appropriate computer procedures helped make a simulation of profiles obtained for the ideal case, which is when angles of both V-blocks are equal to the nominal value, and for the discussed case – that is when angles of both V-blocks are equal to each other but different from the nominal value. Figure 8 presents the difference in profiles obtained for $\alpha_0 = \alpha_L = \alpha_n$ and for $\alpha_0 = \alpha_L = \alpha_r$, where $\alpha_n = 90°$ and $\alpha_r = 89°$.

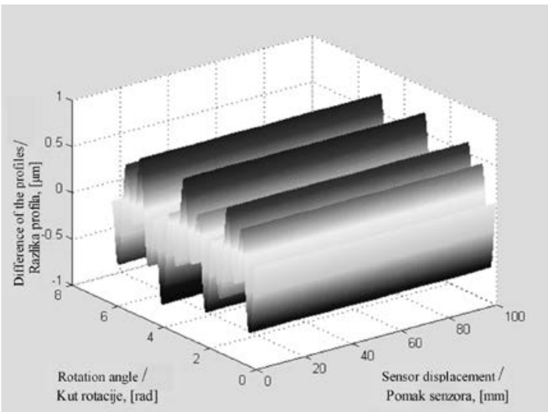


**Figure 8.** The difference between the model profile and the profile obtained through the simulation of the error of $\alpha$

**Slika 8.** Razlika između modela profila i profila dobivenog simulacijom pogreške $\alpha$

The difference maximum value for the compared profiles is 0,76 μm, which is about 5,2 % of the cylindricity deviation value. As both profiles were defined for angles $\alpha_n$ and $\alpha_r$, the difference of which is considerable ($\alpha_n - \alpha_r = 1°$), we can assume that when the both V-blocks have equal angles, the influence of the difference between the nominal and real value of α on the cylindricity V-block measurement result is insignificant.

### 4.2. Case of unequal angles of V-blocks

While analyzing the case of unequal angles of the V-blocks, two kinds of errors are encountered:

- calculation error caused by failing to use calculation procedures in which the nominal value of α is present for transforming the profiles obtained by means of the V-blocks, whose Vee angles are equal to $\alpha_0$ and $\alpha_L$ respectively,
- the error caused by the guide's axis tilt relative to the measured object, due to the fact that $\alpha_0 \neq \alpha_L$.

Computer simulations helped analyze the first case through the simulation of the profile obtained by means of the system with V-blocks angles equal to the nominal value and for the system with unequal V-block base angles (with the analysis of the guide's axis tilt to be conducted later). The difference of the generated profiles is show in Fig. 9.

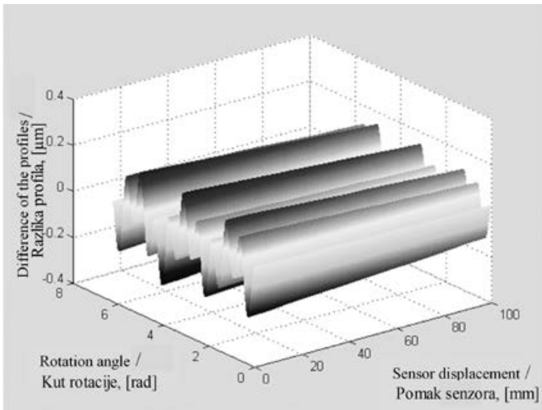


**Figure 9.** The difference of the model profile and the profile with the considered computational error caused by the V-blocks angles difference

**Slika 9.** Razlika između modela profila i profila s uračunatom računalnom pogreškom zbog kutova V-blokova

As shown in Fig. 9, the value of the profiles difference changes together with the sensor displacement along the element of the cylinder. The error results from the guide's axis tilt relative to the base cylinder's axis, which will be discussed later in the paper. The compared profiles difference maximum value is 0,23 μm, which is about 1,5 % of the cylindricity deviation value. One can thus assume that the computational error related to the mathematical transformation of the cylindricity profile, obtained with the V-blocks of unequal angles of Vee, has little influence on the result

of V-block cylindricity measurement. Let us discuss the guideway's tilt relative to the measured object, caused by unequal V-blocks angles, and its influence on the measurement result.
In order to do that, Figure 10 will be helpful.

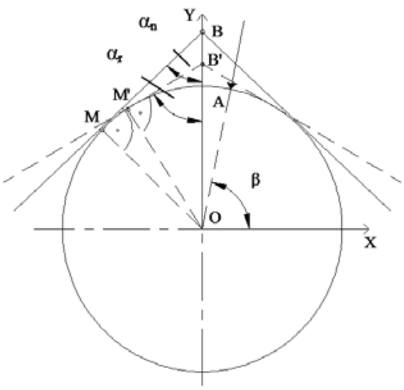


**Figure 10.** Displacement of the guide way caused by the difference between the real and nominal value of *α*

**Slika 10.** Pomak vodilica uzrokovan razlikom između nominalne i stvarne vrijednosti *α*

Let us assume that the distance between points *B* and *B'* is equal to *d*. It is obvious that *d* will be the function of *z*. The conducted analysis showed that the influence can be described with the following dependences:

$$F_{\alpha 0 \alpha L}(\varphi, z) = F(\varphi, z) + d(z)\sin\beta\,, \tag{1}$$

where:

$$d(z) = \frac{d_0(L-z) + d_{\mathrm{L}} z}{L}\,, \tag{2}$$

$$d_0 = R\left(\frac{1}{\sin\alpha_{\mathrm{n}}} - \frac{1}{\sin\alpha_0}\right), \tag{3}$$

$$d_{\mathrm{L}} = R\left(\frac{1}{\sin\alpha_{\mathrm{n}}} - \frac{1}{\sin\alpha_{\mathrm{L}}}\right). \tag{4}$$

In the above mentioned dependences, $F_{\alpha 0 \alpha L}(\varphi, z)$ is the profile recorded for the tilted axis of the guide, $F(\varphi, z)$ is the nominal cylinder profile, φ is a cylinder rotation angle, *z* is a measuring point coordinate, where axis Z coincides with the cylinder's axis, $\beta$ is the previously defined method parameter (see Fig.1.), *R* is a radius of the cylinder's nominal profile, $\alpha_0$ is an angle of the initial base V-block, $\alpha_L$ is an angle of the final base V-block, and $\alpha_n$ is the nominal value of the angle of base V-blocks.
Dependences (1)-(4) helped carry out a computer simulation for the influence of the guide's axis tilt, caused by the difference of V-blocks angles, on the obtained signal value. For the purpose of the simulation, the following method parameters values were adopted: $\alpha_0 = 59{,}95°$, $\alpha_L = 59{,}97°$, $\alpha_n = 60°$, $\beta = 90°$. An ideal cylinder with a radius of $R_0 = 20$ mm was the nominal profile. The simulations showed that the difference of base V-blocks angles would bring about the recording of the profile's conicity virtual deviation. The diagram shown in Fig. 11, resulting from the simulations, features the difference of the nominal profile and the profile recorded by the sensor, caused by the tilt of the sensor's guide's axis.

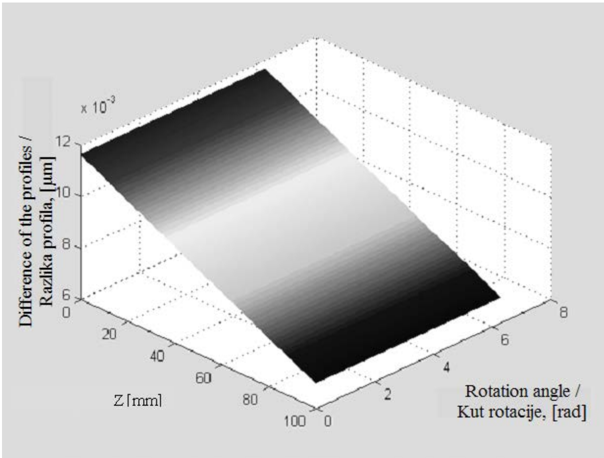


**Figure 11.** Difference of the model profile and the profile recorded by the sensor moving along the guide tilted relative to the object's axis

**Slika 11.** Razlika modela profila i profila zabilježenog pomicanjem senzora duž vodilica relativno nagnutih u odnosu na objekt osi

Figure 11 illustrates the difference between profiles changes linearly, together with the change in value of *z*, which corresponds to the sensor's displacement along the element of the measured cylinder. The profiles difference maximum value is about 11,7 µm. Such a considerable difference, obtained for a small difference of V-blocks angles, equal to $\alpha_{\mathrm{L}} - \alpha_0 = 0{,}02°$, implies that the V-blocks angles difference will have a huge influence on the obtained measurement results.

## 5. Summary

Developed concept of cylindricity measurements by the V-block method meets requirements of modern technological processes. Described method allows accurate in situ measurements of form deviations of large cylinders that are used in electric, paper or naval industry. The main disadvantage of the method is that some harmonic components of the profile cannot be detected by the measuring system. Detection of harmonic components of roundness profiles depends on values of angles *α* and *β*, that are the method parameters. There are high possibilities of increasing its accuracy through elimination or compensation of the errors related to the method angular parameters, and other possible sources of errors, e.g. rectilinearity deviation of a guide, etc. The analysis of the effect of the method parameters angular values on the obtained measurement result shows that the accurate determination of angles $\alpha$ and $\beta$ can contribute to a significant enhancement of measurement accuracy. Particular emphasis should be placed on ensuring that the angles of both base V-blocks are equal. A little difference causes a huge measurement error (in the analyzed case the difference of $0{,}02°$ caused an error of about 11,4 μm). Other analyzed here cases did not cause such errors. However, in order to enhance the cylindricity V-block measurement accuracy, the impact of each potential errors source should be eliminated or compensated.

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