The Comparison of Cylindricity Profiles Using Normalized Cross Correlation Function

[1]S. Adamczak, [2]D. Janecki, [3]K. Stępień

[1]Faculty of Mechatronics and Machinery Design, Kielce University of Technology, Al. 1000-lecia P. P. 7, 25-314 Kielce, Poland
Email: adamczak@tu.kielce.pl
[2]Centre of Laser Technologies of Metals, Kielce University of Technology, Al. 1000-lecia P. P. 7, 25 314 Kielce, Poland
Email: djanecki@tu.kielce.pl
[3]Faculty of Mechatronics and Machinery Design, Kielce University of Technology, Al. 1000-lecia P. P. 7, 25-314 Kielce, Poland
Email: kstepien@tu.kielce.pl

Abstract. *Nowadays the possibilities of carrying out cylindricity measurements in industrial conditions are s limited. Therefore at the Kielce University of Technology concept of using so-called reference method for cylindricity measurements has been proposed. Proposed concept was the base for building up a model measuring stand for reference cylindricity measurements. The paper presents the principles of the reference method. It presents also the procedure of comparing cylindricity profiles, which consists in applying the normalized cross-correlation function.*

Keywords: cylindricity, measurement, correlation

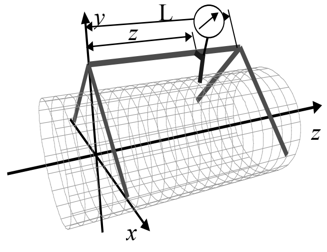
1. Introduction

The knowledge of the measurement of cylindricity profiles is relatively limited. The works available on the subject concern the application of non-reference methods [1,3]. The non-reference measurements of cylindricity profiles are of a high metrological level. However, this is true only in the case of instruments applied to the evaluation of the surface of small workpieces under laboratory conditions. But the industries manufacturing or applying cylinders expect that measurements of cylindricity profiles will be conducted directly on a machine tool or a processing machine. That is why the concept of reference measurements of cylindricity has been proposed.

2. Concept Of Reference Measurement Of Cylindricity Profiles

The principle of the reference measurement of cylindrical profiles is presented in Fig. 1.

a



b

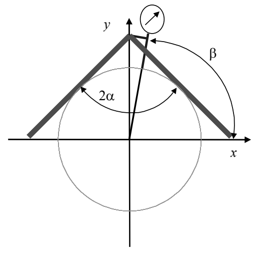


Fig. 1. Principle of a reference cylindricity measurement (the quantities L, α and β are the method parameters)

Let us assume that, if the axis of the nominal cylinder coincides with the axis of the real cylinder, the distance between any point of the profile and the surface of the nominal cylinder is equal to $R(\varphi, z)$, where φ and z are the co-ordinates of the profile point. If the deviation, R, is zero, then the indications of the sensor do not depend on the co-ordinates φ and z. Thus, the indications of the measuring sensor are proportional to the distance of a given point of the profile from the surface of the nominal cylinder. In the reference method, the distance of the profile at the point of contact with the sensor from the nominal cylinder is equal to:

$$F(\varphi, z) = R(\varphi + \beta, z) + E_x(\varphi, z)\cos\beta + E_y(\varphi, z)\sin\beta \qquad (1)$$

where $E_x(\varphi,z)$ and $E_y(\varphi,z)$ are the Cartesian co-ordinates of the intersection of the axis of the cylinder turned through the angle φ with a plane perpendicular to the Z axis with the co-ordinate z. From the Ref. [1,5] we know that the dependencies useful for the transformation of the measured profile into the real profile can be defined as follows:

$$\hat{F}_n(z) = e^{in\beta}\hat{R}_n(z) - \left(\frac{L-z}{L}\hat{R}_{n0} + \frac{z}{L}\hat{R}_{nL}\right)\hat{M}_n; \qquad (2)$$

$$\hat{M}_n = \frac{1}{2}e^{in\alpha}\left[\frac{\cos\beta}{\cos\alpha} + \frac{\sin\beta}{\sin\alpha}\right] + \frac{1}{2}(-1)^n e^{-in\alpha}\left[-\frac{\cos\beta}{\cos\alpha} + \frac{\sin\beta}{\sin\alpha}\right] \qquad (3)$$

The harmonic components $\hat{R}_{n0}$ and $\hat{R}_{nL}$ in the first and last cross sections (with the coordinate *z* equal to *0* and *L*, respectively) can be determined from equations (4)-(6).

$$\hat{F}_{n0} = \hat{R}_{n0}\hat{K}_n;\ \hat{F}_{nL} = \hat{R}_{nL}\hat{K}_n;\ \hat{K}_n = e^{in\beta} - \hat{M}_n \qquad (4)\text{-}(6)$$

K_n is the so-called coefficient of detectability.

3. The Comparison of Cylindricity Profiles Using Normalized Cross Correlation Function

Suppose that an actual cylindricity profile is described in a cylindrical system of coordinates by means of the function $R(\varphi, z)$, $0 \le \varphi < 2\pi$, $0 \le z \le H$, where φ is the polar angle, and z is the value of the shift along the Z-axis [2]. To measure a cylindricity profile, one needs to determine the profile value at a certain number of measuring points having the coordinates (φ_k, z_k) for $k = 1,2,...,N$. A set of the coordinates of measuring points will be called a measuring strategy. Suppose that the same measuring strategy (φ_k, z_k) for $k = 1,2,...,N$, where N is the number of measuring points, is used to analyze the results of two different measuring devices, the following values of the measured profile are obtained: R_k^r, R_k^e for $k = 1,2,...,N$. If two devices are employed, one acts as the reference device, the other is compared with it. In order to compare the results we shall define the coefficient of profile coincidence

$$\rho = \frac{2\sum_{k=0}^{N} R_k^r R_k^e}{\sum_{k=0}^{N}(R_k^r)^2 + \sum_{k=0}^{N}(R_k^e)^2} \qquad (7)$$

It is easy to show that the inequality is satisfied $\rho \le 1$ and that $\rho = 1$, if and only if $R_k{}^r = R_k{}^e$.

The closer the value of the coefficient of coincidence is to one, the smaller the mean square error of the analyzed device in relation to the reference device. The coefficient ρ is assumed to be a measure of coincidence of the measured profiles. The coefficient of coincidence was defined for a case when measurements were performed at exactly the same points and with the same measuring strategy. Yet, normally, the measured profiles are shifted in phase. The method for determination of the coefficient of coincidence involves defining the properly normalized cross correlation function. Taking into account formula (7) we can define the normalized cross correlation function as follows:

$$r(\tau) = \frac{2\sum_{k=1}^{N} R^r(\varphi_k + \tau, z_k) R^e(\varphi_k, z_k)}{\sum_{k=1}^{N} {R^r}^2(\varphi_k, z_k) + \sum_{k=1}^{N} {R^e}^2(\varphi_k, z_k)} \tag{8}$$

We obtain a relation $r(\tau) \le 1$, with $r(\tau) = 1$, if and only if $R^r(\varphi + \tau, z) = R^e(\varphi, z)$.
Thus, the coefficient of coincidence of the compared profiles will be defined as:

$$\rho = \max r(\tau) \tag{9}$$

whereas the value of τ, at which the maximum of the cross correlation function occurs, will be regarded as the phase shift between the profiles. The value of the shift can be used for graphical representation of the measured cylindrical surfaces in one diagram.

4. Experimental Verification Of Applying The Normalized Cross Correlation Function To The Comparison Of Cylindricity Profiles

The concept presented in the previous paragraph has been applied in pratice to determine the coefficient of coincidence between the profiles shown in Fig. 2. The profile shown in Fig 2a was obtained by radial method and the second one, shown in Fig. 2b, by the reference method.

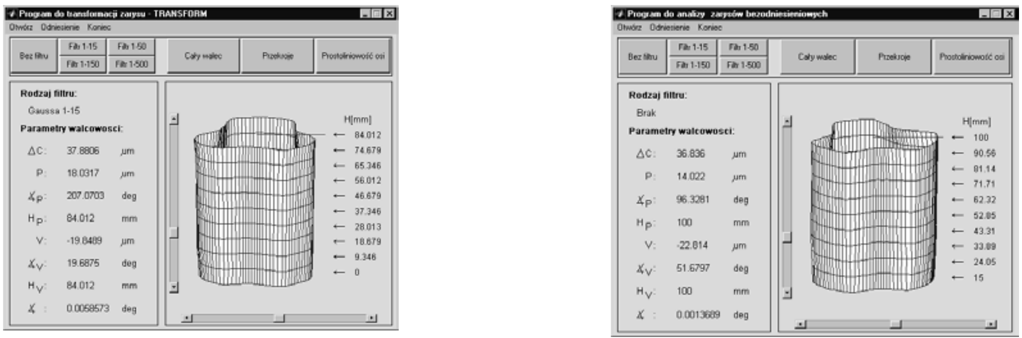


Fig. 2. Profiles obtained by: a) radial (non-reference) method; b) reference method

In order to determine the value of the coefficient between profiles shown in Fig. 2, it was necessary to calculate the values of the normalized cross correlation function for the phase shift from zero to 2π. Tha maximum value of the function is 0.989, so taking to account the formula (9) we can write that $\rho = 0.989$. The function reaches its maximum value for the phase shift $\tau = 1.75 rad$. This value of the phase shift can be used for representing both profiles in one graph, which will permit their visual comparison. Figure 3 shows the coinciding plots of the compared profiles.

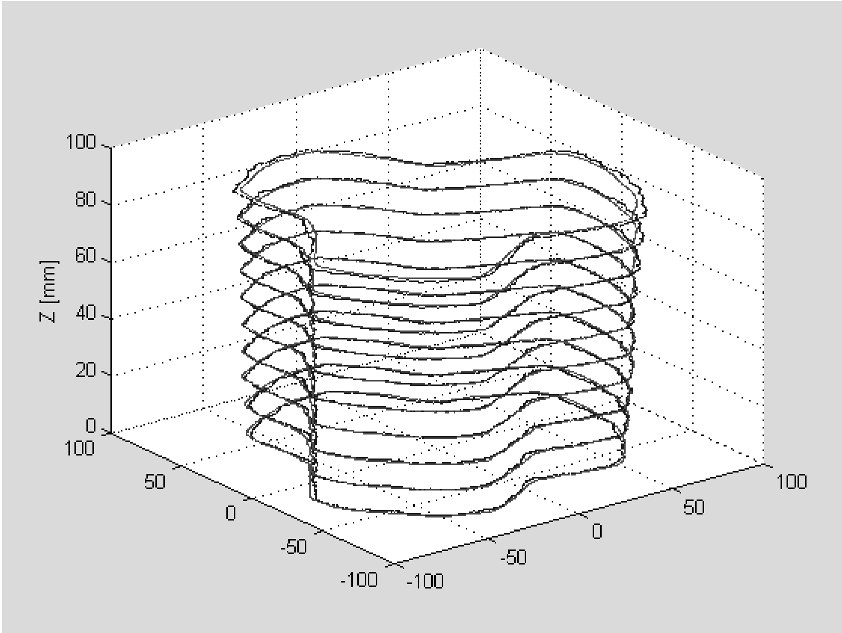


Fig. 3. Coinciding plots of the compared profiles after their shifting in relation to each other at τ=1.75 rad.

5. Conclusions

The results show that the concept of applying the cross correlation function to compare cylindricity profiles can be of great significance to industry. The method permits not only determining quantitatively the coincidence of cylindricity profiles but also representing them visually in one graph (due to the occurrence of the phase shift). Basing on the concept, it is possible to develop new procedures for the comparison of cylindricity profiles measured with different strategies [4]. A very high value of the coefficient of coincidence, i.e. ρ=0.989, between cylindricity profiles obtained in the course of the reference and non-reference measurements, respectively, testifies that the reference method can be applied to accurate measurements of cylindricity. The experimental results concerning the accuracy of reference measurements were confirmed in a statistical analysis, the details of which can be found in Ref. [5].

References

[1] Janecki D., Stępień K.: Experimental verification of the concept of reference measurements of cylindricity profiles. 5th „Transcom 2003", Żilina 2003, pp. 139 – 142.

[2] Whitehouse D. J.: Handbook of Surface Metrology. Institute of Physics Publishing, Bristol-Philadelphia 1994.

[3] Maduda M.: Metrologia odchylki valcovitosti. Konferencja "Strojarska technologia a valiva loziska'97". Uniwersytet w Żilinie (SK), Żilina 1997, pp. 19-21.

[4] Janecki D., Stępień K.: Applying the normalised cross correlation function to the comparison of cylindricity profiles. Metrology and Measurement Systems, Vol. XI, No. 3/2004, pp. 209-220.

[5] Final report of the research grant of KBN, No. 7T07D00617 Teoretyczno-eksperymentalne podstawy odniesieniowych pomiarów zarysów walcowości części maszyn, Politechnika Świętokrzyska w Kielcach, 2003, pp. 17-18, 28-38.