Imaging and computer analysis in the shape error measurements and in the cylindrical objects stereometry

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Abstract. In the work, the application of the imaging method and computer analysis of the results of cylindrical surface measurements are presented. Experimental studies focused on determining the measurement of shape, surface roughness and surface stereometry. The measurements were taken on Taylor-Hobson's Talyrond 365 computerized stand. The selected parameters describing the profiles of cylindricity were analyzed in detail, which allowed to reflect the three-dimensional shape of the analyzed cylindrical surface and determine the shape errors. The results of the roughness measurements are shown in the form of a stereometric images developed cylinder surface. Computer analysis of the results allowed to isolate waviness and surface roughness. The results of the computer analysis were verified by stereometric measurements on the profilograph. Analysis of the achieved results confirmed shown satisfactory compatibility.

1. Introduction
The measurements of the shape of the machined surfaces and the analysis of their roughness are of great importance in manufacturing processes [1–6]. For many years, conventional methods based mainly on mechanical methods have been used. For the measurement of parameters of surface roughness and waviness are used profilometers contact and contactless (interferential, confocal and others) [7]. The development of optical (laser), electronic (CCD – charged couple device, LCD – liquid crystal display screen) and computer image analysis techniques enabled the use of more advanced methods as laser method [8–10] and phase-measuring deflectometry [11], as well a DIA (Digital Image Analysis) [12, 13].

In the course of analyzes aimed at determining the suitability of selected surface treatments and their parameters for making objects characterized by expected operational properties, an important role is played by the assessment of their technological quality determined by the machining process [14, 15]. Particular attention in research carried out for several years now at the Institute of Mechanical Technology of the Czestochowa University of Technology has been given to the surface treatment of burnishing [16, 17]. It allows one to improve both the parameters of surface stereometry and the improvement of mechanical properties of the surface layer of burnished details [18]. Due to the significant forces occurring during the burnishing process, it is essential that in the consideration of this treatment, be able to perform detailed analyzes regarding both shape changes and changes in the stereometry state of the cylindrical objects obtained. These measurements are often carried out in separate stands. The paper presents the possibility of performing these measurements on one integrated measuring stand [19].
2. Measurement of shape errors and surface mapping of cylindrical objects

The measuring laboratory of the Institute of Machine Technology and Production Automation of the Czestochowa University of Technology is the Reference Laboratory of Taylor - Hobson. The laboratory is equipped with, among others, the Talyrond 365 measuring stand with "Ultra Roundness 5.17" software enabling comprehensive evaluation of cylindrical surface errors (figure 1) [20]. This stand is equipped with a table that allows precise rotation of the analyzed object at any angle. The measuring arm traveling on a vertical column, moved in a horizontal axis, allows the selected measuring tip to be approached to the surface of the test and measurement with a resolution of 1.3 nm (depending on the operating range of the measuring head). Positioning of the measuring head on the column is carried out on the basis of an incremental straight-edge. The described measuring stand enables carrying out, before starting the actual measurement, automatic coordination of the position of the axis of rotation of the table and axis of the analyzed cylindrical surface.

As a result of the measurements, the actual surface of the product (a set of elements that exist physically and separate the entire product from the surrounding medium) is transformed into a peripheral line observed (roundness) being an approximate representation of the intersection of the real surface and the plane of roundness. This line is determined with a certain approximation resulting from the accuracy of the measuring equipment, the radius of the measuring tip and other factors affecting the accuracy of the measurement. With her appointment becomes possible to determine the circular errors of the analyzed cylindrical surfaces (figure 2a). It becomes possible to determine the deviations of roundness $RON_t (RON_t = RON_p + RON_v)$ determined relative to any reference circle (MZC, LSC, MIC, MCC), as well as to determine a number of other parameters used to assess the outlines of roundness. During this measurement, points are collected in digital form in an amount (optional) of 3 600 or 18 000 for 1 spindle rotation. The positioning resolution of the measuring table is 0.02 degrees. The resolution of the measuring head is 1.3 nm (in the range of 0.08 mm), 6.3 nm (in the range of 0.41 mm) and 31.4 nm (in the range of 2.06 mm). The measuring station also allows precise stopping and blocking of the tested sample in any angular position and giving the measuring tip vertical movement. It allows to determine the vertical straightness of the selected forming the analyzed cylinder (figure 2b). It is also possible to determine selected parameters used to assess the outlines of straightness determined relative to the selected reference line. The resolution of the measuring head related to the vertical displacement is 0.25 μm (i.e. 4000 points/mm are collected during the measurement).
Figure 2. Determination of complex characterization of roundness errors (a) and straightness forming (b) cylindrical surface.

The stand also allows measurements of surface flatness and surface coaxiality measurements. Measurements of roundness errors and rectilinearity are illustrated (figure 2) on the example of measuring cylindrical sample burnished oscillatingly (the radius of the burnishing ball $R_k = 8$ mm, bursting force $F = 0.5$ kN, angle of intersection of traces $\varphi = 45^\circ$).

Implementation of a series of rounded correlations of roundness in parallel (displaced measuring planes offset from each other) is one of the most popular measurement strategies to assess the profile of cylindricity together with the determination of cylindricity deviation $\text{CYLt} = \text{CYLp} + \text{CYLv}$ and its other parameters. In the course of measurements of cylindricity deviations the most commonly used is the reference cylinder determined by the least squares method [21]. It is also possible to determine reference cylinders using a different method (similarly as in the case of determination of reference circles for roundness measurements).

Of course, the numerical value of selected parameters describing the profiles of cylindricity does not seem to be sufficient. It also seems to be important to analyze the spatial shape of shape deviations, i.e. to analyze groups of cylindrical profiles, which are influenced by the change of the object's dimensions along the axis (conicity, saddness, barreliness), dependent on distortion of the center line of the object (single, double bend), outline group with a distorted surface (objects with regular and irregular outlines of several margins), and overlapping profiles of cylindricity from individual groups. To carry out this type of analysis, it seems necessary to obtain a three-dimensional image of the shape of the analyzed cylinder during the measurements. It becomes possible thanks to the use of modern computer software to analyze the results.

Because during this measurement not a single circular measurement is performed, but a few or a dozen of such measurements, it is possible to virtually reflect the three-dimensional shape of the analyzed cylindrical surface on the basis of the analyzes carried out in this way (figure 3). At the same time these measurements will be carried out so that they are correlated with each other in terms of angular position, being offset vertically from each other by the assumed pitch.
3. Measurement of roughness and stereometry of the cylindrical surface

Measurements of roughness and stereometry are usually performed on profilographometers equipped with a table that allows the sample to be moved a certain amount in a direction transverse to the basic motion. Such measurements allow for the visualization of specific features of the topography of the measured surface. Particular problems may arise, however, when measuring stereometry carried out on cylindrical surfaces, especially those with small diameters. The most convenient measurement is to take the direction of the measurement needle travel parallel to the axis of the cylindrical surface measured – along the cylinders forming. However, it is obvious that with the offset of the measurement path (and the vertical measurement plane) with respect to the vertical plane passing through the axis of the tested surface by the size $\Delta Y$, the position of the measuring track changes. This may (especially for surfaces with small diameters) prevent the measurement from being carried out, as the height change $\Delta Z$ may exceed the measurement range of the measuring tip. It is also worth noting that during subsequent transitions, the measurement takes place not in the normal plane to the cylindrical surface with radius $R$, but in the vertical plane inclined with respect to that normal angle $\alpha$. This angle is different for each measurement transition made – $\alpha = \arcsin(\Delta Y / R)$. Thus, it depends on the displacement of the measurement path with respect to the vertical plane passing through the axis of the examined cylindrical surface $\Delta Y$. The cross-section of the area measured with a plane perpendicular to the direction of travel of the measuring needle is shown in figure 4.

Taking this into account, it can be stated that there is a need to use stereometric cylindrical surfaces for other measurement methods during measurements. This method can be used to determine the
stereometry of cylindrical surfaces on the basis of successive straightness measurements carried out at regular angular intervals on a roundness measurement device. In this method, all measurements are made in planes normal to the surface of the cylinder. The radial position of the measuring path does not change (all measurements are carried out on a radius of the same value). Thus, the measuring arm of the device does not move radially during measurement. This enables testing of any cylindrical surface sections without the risk of going beyond the measuring range due to the cylindrical shape of the measured surface.

Figure 5. Measurement of surface stereometry on a roundness measuring instrument.

For the roughness and stereometry measurements on the Talyrond 365 measuring instrument a measuring tip in the form of a diamond needle with radius $5 \mu m$ was used (figure 5). As a result of the measurement an image of a selected fragment of the side surface of the roll is obtained. On one of the axes, the course of subsequent measurements is shown along the following cylinders (in mm), on the other axis the angular position (in degrees) on which the subsequent forming points are determined. Taking into consideration the actual radius of the cylinder in the tested area, it is possible to convert this angular position to the distance from the first one forming the expressed in mm. The measurement possibilities of the device are illustrated on the example of the measurement of a fragment of the cylindrical surface pressed with burnished with ball-burnishing tool ($R_z = 5 \text{ mm}$, $F = 3 \text{kN}$, $f = 0.35 \text{ mm rev}^{-1}$). The results were processed using the TalyMap Platinium 5.1.1 program. The obtained image of the development of the lateral cylindrical surface is shown in figure 6.

Figure 6. The stereometry of the lateral surface development of the cylinder: a) a contour map of the measured area (b) a stereometric image of the measuring zone.

Digital processing of the obtained measurement allows for the filtration of the analyzed area leading to the separation of waviness and roughness (figure 7).
Figure 7. Numerically separating the waviness (a) and roughness (b) of the area under analysis (cut-off 2.5 × 2.5 mm).

This is the starting point for the determination of selected parameters of the stereometry of the analyzed area (height parameters $Sa = 2.05 \, \mu m$, $Sq = 2.38 \, \mu m$, $Sz = 15.1 \, \mu m$, $Sp = 6.23 \, \mu m$, $Sv = 8.86 \, \mu m$, etc.), the distribution of ordinates of the area (figure 8a), area capacity curve (figure 8b) and many other possible to analyze parameters [22, 23]. It is also possible to extract any profile that is a cross-section of the analyzed development. Figure 9 shows the profile defined along the selected forming cylinder.

Figure 8. Distribution of ordinates (a) and capacity curve (b) of the analyzed area.

Figure 9. Profilogram defined along the forming cylinder.
For the obtained profile it is possible (after removal of waviness) to perform a full analysis of several dozen parameters describing the surface roughness (amplitude parameters $Ra = 1.85 \, \mu m$, $Rq = 2.14 \, \mu m$, $Rz = 7.05 \, \mu m$, $Rp = 4.41 \, \mu m$, $Rv = 2.63 \, \mu m$, etc.). It is also possible to determine a number of functional parameters of the analyzed roughness profile, such as the distribution of profile elevations and the material share curve.

4. Comparative measurement of stereometry on a profilograph
Comparative measurements of the same fragment of the cylindrical surface fed by a rolling ball were made using a New Form Talysurf 2D/3D 120 profilograph with Ultra Surface 5.21 and TalyMap Platinium 5.1.1 software (figure 10).

![Figure 10. Measurement of the stereometry of the selected area carried out on the profilometer.](image)

The profilograph allows comprehensive measurement of surface roughness and stereometry parameters of the surface layer in 2D and 3D with the resolution of the measurement head from 3.2 nm. Measuring tip in the form of a diamond needle with a radius of 2 \( \mu m \) was used in the measurements. The three-dimensional image of the registered deformation zone is subjected to digital processing allowing its leveling (figure 11).

![Figure 11. The stereometry of the selected area of cylindrical surface (a) contour map (b) 3D view.](image)

Further digital processing of the analyzed area allows removing the shape (cylinder) from the image (figure 12). It is also possible to determine a three-dimensional view of the analyzed stereometry (figure 13).

Also in this case, the digital processing of the obtained measurement allows for the filtration of the analyzed area leading to the separation of undulations and roughness. Selected parameters of the
The stereometry of the analyzed area were determined (altitude parameters $S_a = 2.10 \, \mu m$, $S_q = 2.43 \, \mu m$, $S_z = 17.0 \, \mu m$, $S_p = 6.58 \, \mu m$, $S_v = 10.4 \, \mu m$, etc.), the distribution of ordinates and the bearing capacity of the area (figure 14) [1, 22].

**Figure 12.** Image of the stereometry of the selected area of the cylindrical surface: (a) contour map of the flat area (b) the removed shape component – cylindrical.

**Figure 13.** Three-dimensional image of the stereometry of the selected area.

**Figure 14.** Distribution of ordinates (a) and capacity curve (b) of the analyzed area.
Profiles (figure 15) along the forming cylinders were also designated. For a selected profile (after filtration) it is possible to determine the roughness parameters of the analyzed profile (amplitude parameters \( Ra = 1.97 \mu m \), \( Rq = 2.26 \mu m \), \( Rz = 7.39 \mu m \), \( Rp = 4.54 \mu m \), \( Rv = 2.85 \mu m \), etc.), and the distribution of profile elevations and curve material share.

![Figure 15. Profilogram defined along the forming cylinder.](image)

5. Conclusion
The use of complex shape errors and simultaneous measurements of stereometry parameters of cylindrical surface of computerized measuring stations based on roundness measuring instruments allows for a significant increase in the number and increase of transparency of information possible to obtain as a result of measurement. It is possible to perform a number of different measurements at one stand. It is useful when it is necessary to simultaneously determine the shape of the analyzed cylindrical surface, as well as to determine the errors of roundness, cylindricity, or the straightness of the selected forming the surface. This method of measurement can be particularly useful for determining the stereometry of areas with significant widths, measured on cylindrical surfaces with small diameters, i.e. in situations where the traditional measurement on a profilograph does not pass due to exceeding the measurement range (illustrated in figure 4).

The results of roughness and stereometry measurements made using this method presented in the study do not differ significantly (differences do not exceed a few%) from the same parameters obtained on a 3D profilographometer. Only in the case of measuring the maximum depth of the depression \( Sv \) of the analyzed area, the differences are noticeably greater (difference 17.4%). This can probably be explained by the fact that during the measurement carried out on the Talyrond 365 roundness device a measuring needle with a radius of 5 \( \mu m \) was used. The New Form Talysurf laboratory profilograph is equipped with a measuring needle with a radius of 2 \( \mu m \), characteristic for this measuring equipment. This needle penetrated the deepest points of the studied area better. Therefore, the depth determined on the profilograph was greater. This resulted not from the adoption of another measurement method, but from the use of a measuring tip with a different radius of rounding. The analysis of parameters of selected profiles of surface roughness determined with both methods along selected cylindrical faces allows to conclude that in both cases the differences between the most commonly used parameters are insignificant. It can therefore be concluded that the method of measurement of cylindrical surface stereometry presented on the basis of successive straightness measurements carried out at regular angular intervals on a roundness measuring instrument is fully useful in practice and can be used in modern laboratory measurements.

6. Nomenclature
\( CYLt \) the largest distance of the points of the actual profile, being the sum of the largest positive and absolute value of the highest negative local cylindricity deviation measured against the reference cylinder determined by the least squares method,
CYLp value of the largest positive local deviation measured against the reference cylinder determined by the least squares method,

CYLv the absolute value of the largest negative local deviation of the measured cylindrical mass relative to the reference cylinder determined by the least squares method,

LSC an average circle for which the sum of squared distances from it to the measured or reshaped profile tends to the minimum,

MCC the smallest possible circle that can be described on the measured or transformed profile (profile) of the outer cylindrical surface,

MIC the largest possible circle that can be entered in the measured or transformed outline (profile) of the inner cylindrical surface,

MZC the largest possible circle that can be entered in the measured or transformed outline (profile) of the inner cylindrical surface,

Ra arithmetic mean deviation (arithmetic average value of the profile departure from the mean line),

Rq root mean square deviation (root mean square deviation of the profile from the mean line),

Rz maximum height of profile (highest peak to valley),

Rp maximum profile peak height (largest peak deviation of the roughness profile from the mean line),

Rv maximum profile valley depth (largest valley depth of the roughness profile from the mean),

RONt the largest distance of the points of the actual outline, which is the sum of deviations of the roundness of the elevation and the hollow,

RONp the value of the largest positive local roundness deviation,

RONv the absolute value of the largest negative local roundness deviation,

Sa arithmetic average surface roughness deviation,

Sq average square surface roughness deviation,

Sz the maximum surface height,

Sp the maximum height of surface elevation,

Sv the maximum height of the recess surface.

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