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An analysis of methods of measurement and evaluation of sphericity deviations

Analiza metod pomiaru i oceny odchyłek kulistości

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Problems relating to measurements and evaluation of sphericity deviations are not described in contemporary standardization documents. Apart from coordinate measuring machines, in global market there are no commercially available systems allowing such measurements. The paper presents methods and systems for measurements of sphericity deviations that are described in the scientific literature as well as a prospective of their application under industrial conditions.
KEYWORDS: measurement, form deviation, sphericity

National and international standards do not define the concept of sphericity deviation, nor do they provide recommendations for measuring the outlines of sphericity. Information on this subject can be found only in industrial documents.

Industrial standardization documents describe the following strategy for measuring spherical elements: the outlines of roundness are measured in three mutually perpendicular sections of the part under study (fig. 1). The results of the measurements are plotted on polar diagrams, and on their basis the value of the sphericity deviation is approximated. Such a method, of course, gives only approximate results, because a significant part of the surface of the element is not investigated. It should be noted, however, that most often the measurement of the outlines of the shape of spherical elements is limited to the control of the value of roundness deviation in one cross-section.

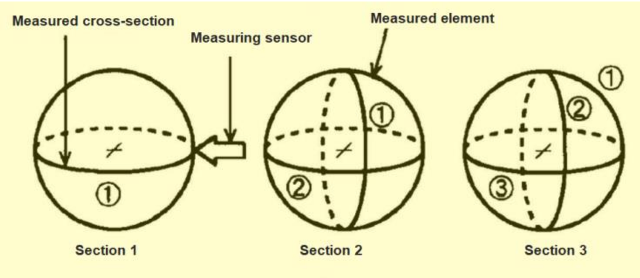

Fig. 1. Strategy of assessing spherical deflection described in industrial standards [1]

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Industry norms most often determine that the best reference element in assessing the value of deviations in the shape of spherical parts of machines is the smallest circle described on the measured outline.

Methods of measuring the outlines of sphericity

Assessment of deviations of the shape of spherical elements on the basis of the results of roundness profiles measurement does not require the use of specialized systems to measure sphericity profiles - in such cases typical devices for measuring roundness profiles are used. These are well known, technically advanced instruments based on the principle of measuring radius changes, used to control deviations of the shape of rotating elements (e.g. in the bearing industry).

For this reason, the Kielce University of Technology has developed a concept for using a radial device to measure sphericity profiles. It is based on the use of a highly accurate radial device additionally equipped with a system for positioning the measured element [2]. This system allows a controlled rotation of the object around the horizontal axis and the spindle axis of the device. When rotating an object, contours of roundness are registered in many cross-sections. Measured contours form a grid of measuring points, on the basis of which the reference surface is determined and shape deviations are calculated [3]. This concept is shown schematically in fig. 2.

In order to accurately assess deviations of the shape of the surface based on the measured outlines of roundness, it was necessary to solve a number of theoretical problems, in particular concerning:

- selection of the measurement strategy,
- development of the method of folding and filtering outlines,
- calculation of reference sphere parameters,
- defining the sphericity parameters,
- approximation of the measured profile by means of a surface.

Theoretical work on the development of the method was successful and resulted in the construction of a position for measuring the deviations of sphericity of machine parts. Results of the research and experimental verification of the concept are included in the works [2-4].

The literature also describes attempts to use the three-point reference method for assessing spatial deviation (e.g. [5]). Of course, using the principle of reference measurement, it should be remembered that some harmonic components of the measured outlines will not be detected by the measurement system.

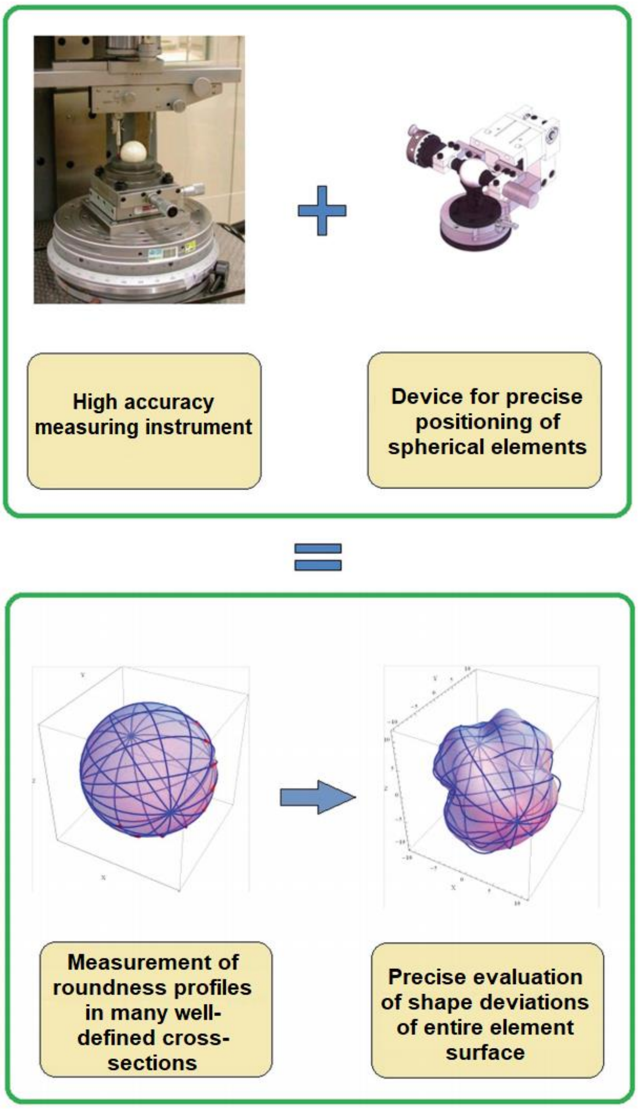

Fig. 2. Scheme of the concept of measuring radial contours using the radial method [2]

In addition to contact methods, the interest of many researchers is the measurement of spherical surfaces using optical methods. Interestingly, already in the sixties of the last century, in former Czechoslovakia, a machine for controlling the surface quality of the bearing balls was produced, functioning on the principle of registering changes in the intensity of light reflected from the surface of the ball. The balls during the measurements were rotated by means of a system of rollers in contact with them. The surface of the balls was illuminated with a focused light source, and a beam of light reflected from the surface was falling on the photodiode. When it fell on the damaged part of the surface, the intensity of the reflected beam changed [6].

Currently, work is underway to measure topography of spherical surfaces using laser interferometers, as described, for example, in [7]. In the method presented there, small fragments of the sphere are measured with the Fizeau interferometer, and then the measured areas are numerically bonded so as to obtain an image of the entire surface of the sphere. It is necessary to know the exact position of the ball during subsequent measurements, because without it, it is impossible to numerically glue the measured fragments. Therefore, the rotation of the ball and its displacement are carried out by special controllers. The diagram of such a measurement system is shown in fig. 3.

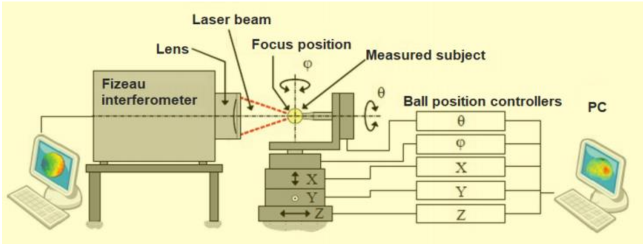

Fig. 3. Scheme of ball measurement using the Fizeau interferometer proposed in paper [7]

A similar measuring system has been described in [8]. This system also uses a properly modified Fizeau interferometer and small fragments of the sphere are measured in subsequent stages. Similarly to work [7], the image of the whole surface is created by the numerical combination of the measured parts of the sphere (so-called stitching), and this principle is shown in fig. 4.

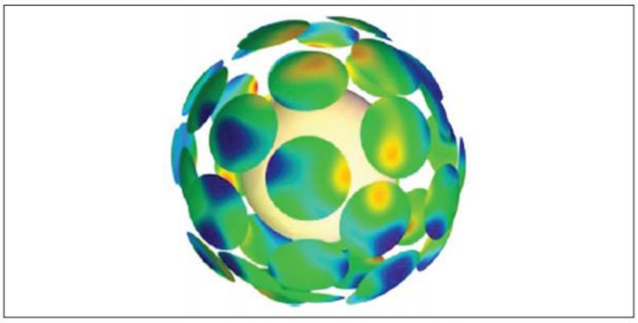

Fig. 4. Reconstruction of the surface image based on the measured fragments (stitching) [8]

In turn, in the paper [9], the method of determination of sphericity deviations of the spherical part of the electrode used for EDM machining by means of digital image processing techniques is described. The measuring device here is a properly calibrated camera that records the image of the tip of the electrode. The coordinates of the edge points of the measured surface, visible in the image, are determined using the software. Then, rotate the object to the next position and repeat the procedure. In this way, a matrix is obtained containing the coordinates of the points of the measured surface. On the basis of these values, the corresponding deviations of roundness and sphericity are calculated. An exemplary image of the electrode tip is shown in Fig. 5.

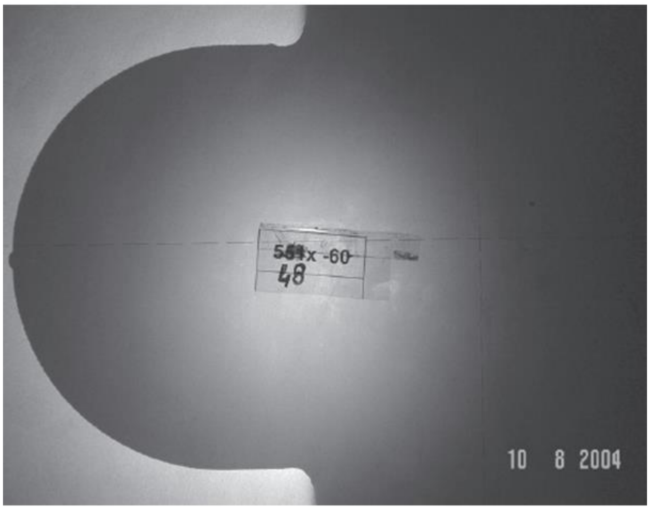

Fig. 5. Example of a camera image, on the basis of which deviations of the sphericity of the spherical electrode tip are determined [9]

An interesting solution regarding the measurement of sphericity deflections using the optical method is presented in [10]. The authors proposed the use of digital processing techniques to determine a three-dimensional surface image based on its 2D view. Of course, it is possible to generate a hemispherical view from a single two-dimensional image. In the described method, a two-dimensional surface image is recorded using a calibrated camera. The distances of the respective surface points from the camera are different, therefore the intensity of the gray scale at these points changes. From the analysis of intensity changes, a three-dimensional surface image is generated. The example two-dimensional image obtained from the camera and the three-dimensional view generated on its basis are shown in fig. 6.

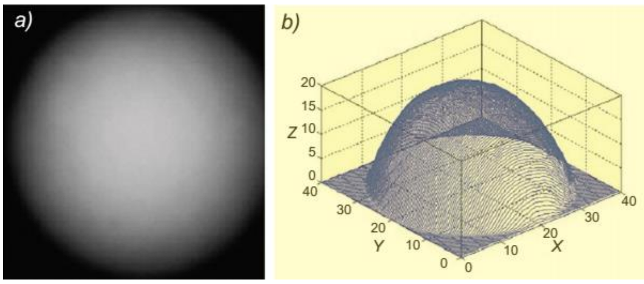

Fig. 6. Reconstruction of a three-dimensional surface view based on the analysis of changes in the intensity of gray scale of a two-dimensional image: *a*) image from the camera, *b*) generated three-dimensional view [10]

In addition to intensive work on the application of optical methods, many scientific centers deal with the use of coordinate technology for measuring deviations of sphericity. Due to the dynamic development of this field of metrology, it can be assumed that measurement with coordinate measuring machines will in the future be one of the leading methods of assessing sphericity deviations as well as other deviations of shape. Currently, coordinate measuring machines, however, do not offer measurement accuracy satisfactory for manufacturers of precision parts (e.g. in the bearing industry).

Methods of assessing deviations of the shape of spherical elements

In addition to the work on the methods of measuring the outlines of sphericity, many research and development centers conduct research on methods for assessing the value of sphericity deviations. It should be noted that the term "evaluation method" is not synonymous with the term "measurement method". The measurement method refers to the physical principle of acquiring measurement data, whereas the evaluation method describes the way in which measurement data are processed in order to calculate the deviation value.

Usually, during the evaluation of deviations of sphericity, a similar methodology is used as in the measurements of roundness profiles, whereby two-dimensional elements and parameters in the case of roundness measurements are replaced by three-dimensional ones in the measurement of sphericity. For example, if the reference element in measuring the roundness deviation is the minimum zone circles, then in measuring the sphericity deviations they will be the spheres of the minimum zone, as shown in fig. 7.

Research in the area of deviations evaluation of sphericity includes, among others calculation of reference elements on the basis of measurement data. Various approaches are used. Quite frequently, numerical methods are used, especially in relation to measurement data obtained from coordinate measuring machines [11-13].

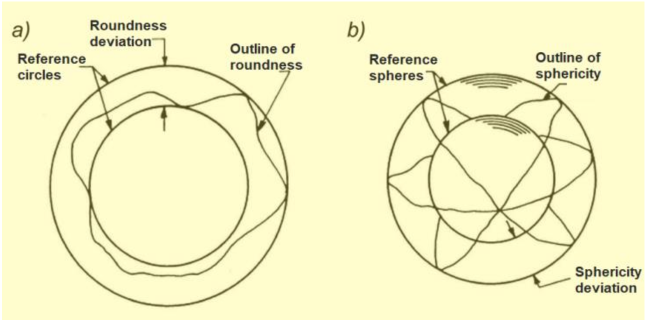

Fig. 7. Comparison of the deviation value assessment of: *a*) roundness, *b*) sphericity [11]

Another method of calculating reference elements in the case of sphericity measurements is the application of the calculation technique of substitute geometric elements, most often with the use of so-called Woronoj diagrams (fig. 8), which was described in detail in [14, 15].

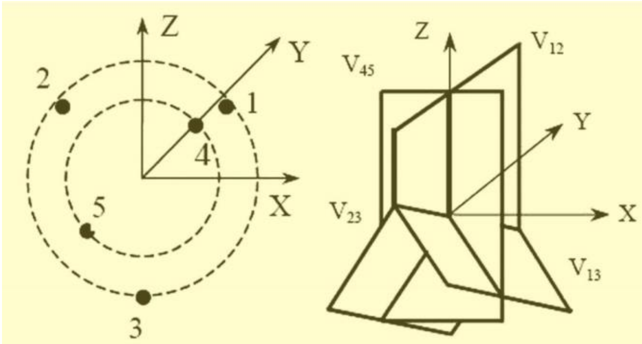

Fig. 8. Determining the parameters of the reference sphere using Woronoj diagrams [11]

The coordinates of points 1-3 (fig. 8) define the sphere described in the outline, while the coordinates of points 4 and 5 - the sphere inscribed in the outline. To determine the coordinates of the center of the outer and inner sphere of the minimum zone, Voronoi diagrams are plotted. First, the diagrams between pairs of points were defined: 1 and 2, 1 and 3 as well as 2 and 3. These areas in fig. 8 were marked as: V_{12}, V_{13} and V_{23} respectively. The intersection of these areas creates a straight line. The point of intersection of this line through the Woronoj area, defined for points 4 and 5 (designated as V_{45} in fig. 8), is the center of the minimum zone spheres.

Among other methods of assessing spherical deviations described in the literature, one should mention the method of using the theory of the minimum potential energy [16] and the analysis of statistical parameters [17].

Conclusions

Issues related to the assessment of deviations are one of the most complex problems in the area of shape deviations of machine parts. Instruments for measuring sphericity profiles should be equipped not only with systems enabling acquisition of measurement data with considerable accuracy, but also with systems for registering the ball's position during measurements. What's more, the analysis of measurement data requires the use of an extremely complicated mathematical apparatus (including, for example, harmonic functions on the sphere). This is probably why there are no systems on the market to accurately measure and assess the outlines of sphericity. However, the development observed in the area of machine technology, automation and signal processing techniques allows the development and production of such systems using both contact and non-contact methods.

Among the systems described in this article, attention should be paid to the radial contours measurement system. Its undeniable advantage is that it is based on roundness measuring devices that are commonly used in the bearing industry. The proposed concept requires only retrofitting the device with a ball positioning device, which is relatively cheap. However, it should be noted that in order to apply the proposed system in industrial conditions, the following problems should be solved: the rotation of the measured element should be automated, while the software for assessing deviations should be equipped with a user-friendly and legible interface.

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