How to cite this article:

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Title of article: „Analiza strategii pomiaru odchyłek kształtu elementów obrotowych" ("An analysis of strategies of form deviations' measurements of rotary elements")

Mechanik, Vol. 92, No. 2 (2018): pages 113–117

DOI: https://doi.org/10.17814/mechanik.2018.2.25

An analysis of strategies of form deviations' measurements of rotary elements

Analiza strategii pomiaru odchyłek kształtu elementów obrotowych

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DOI: https://doi.org/10.17814/mechanik.2018.25

Uniform sampling strategies are commonly applied to measure form deviations of rotary elements. However, such strategies do not always provide desired results, if there are significant local irregularities on the surface. In such cases it is better to apply non-uniform sampling strategies that allow fitting the scanning trajectory to predicted or detected model of irregularities. The paper presents a critical review of strategies for measurements of form deviations of rotary elements that are described in international standards and in the scientific literature.

KEYWORDS: measurement, form deviation, adaptive strategy, non-uniform sampling

Rotating elements constitute a significant and numerous group of machine parts, occurring in many branches of industry (e.g. in bearing, automotive and energy industries). The most frequently used rotating parts of machines are cylinders and spherical elements, however, often these elements can have the shape of a cone, barrel or saddle. The requirements for dimensional accuracy of rotating elements are very high. Therefore, it is important to use an appropriate method to measure their shape deviations. Usually, the shape deviation control of rotary elements is carried out based on the analysis of 2D measurement results.

It is less common to measure spatial parameters that apply to the entire surface, not just to 2D outlines. At present, measurements of 3D parameters are in practice limited to measurements of cylindricity deviations. The contours of cylindricity are measured using specialized systems using the principle of measuring radius changes. Modern systems of this type can also be used to measure straightness forming and the deviation of flatness of the frontal plane of elements. Radial instruments have very high accuracy, usually <1 µm. Nevertheless, the area of application of these systems is limited to measurements of roundness, cylindricity and - in some cases, as mentioned - for the measurements of straightness profiles forming, as well as the deviations of planes flatness.

In the area of metrology of geometrical quantities, dynamic development of coordinate metrology is observed. The accuracy of coordinate measuring machines grows and for this reason they are more and more often used in measuring deviations of the shape of rotating elements, if of course the tolerances of the measured parts are significantly greater than the maximum permissible error of the machine.

An important issue in the measurement of 3D parameters of rotating parts is the selection of a measurement strategy. This term should be understood as the distribution of measuring points on the measured surface. Thus, it is a term strictly related to the trajectory, after which the measuring sensor moves relative to the surface of the element. The applied strategy should ensure accurate coverage of the surface with a grid of measuring points. On the other hand, it should be remembered that the more measurements, the longer the operation time.

Generally, the strategies for measuring rotational elements described in standards and scientific literature can be divided into three groups (fig. 1): strategies of uniform sampling, strategies in which the trajectory of scanning is matched to the predicted model of surface unevenness, and so-called adaptation strategies.

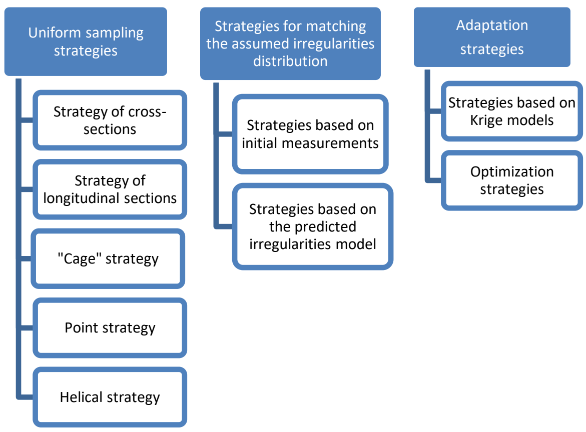

Fig. 1. Classification of measuring strategies for rotating elements

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Of the schemas presented in fig. 1, only uniform sampling strategies are common in industry. Strategies based on matching the assumed distribution of inequalities and adaptation strategies are the object of research of scientists, available as an option in commercial measurement systems software.

Uniform sampling strategies

Uniform sampling strategies are typical for contour measurements of cylindrical parts of machines. Most often, such measurements are carried out using the cross-sectional strategies or longitudinal cross-section strategies, which are shown in fig. 2.

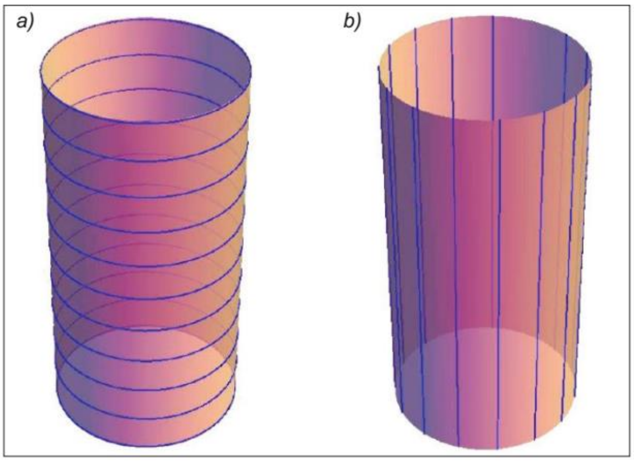

Fig. 2. The most frequently used strategies for measuring profiles of cylindricity: *a)* cross-sectional strategy, *b)* longitudinal sectioning strategy

More detailed information about the unevenness of the measured surface is obtained using the so-called frame strategy. It is a composite of cross-sectional strategies and longitudinal section strategies.

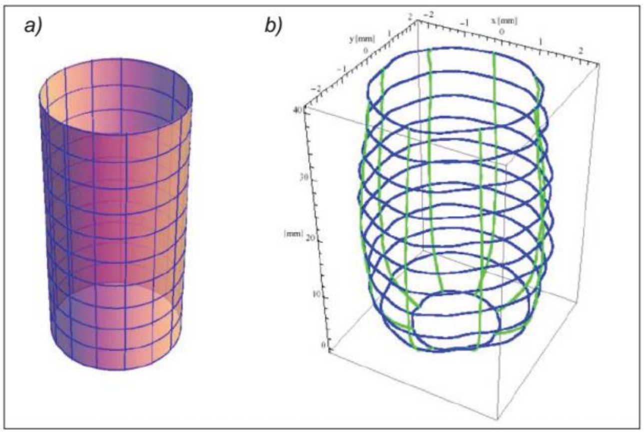

Fig. 3. "Cage" strategy: *a)* trajectory of the scan, *b)* example of application

Due to calculation difficulties, the "cage" strategy for a long time was not available in the measurement systems software. Currently, however, there are radial systems on the market for measuring deviations of roundness and cylindricity with the option of measuring according to the "cage" strategy. The most important advantage of this strategy is the exact covering of the surface with a grid of measuring points. The biggest limitation is the long measurement time.

The point strategy is less frequently used to measure deviations of the shape of rotating elements. Due to the small number of measuring points, it does not allow to obtain accurate information about the unevenness of the analyzed surface.

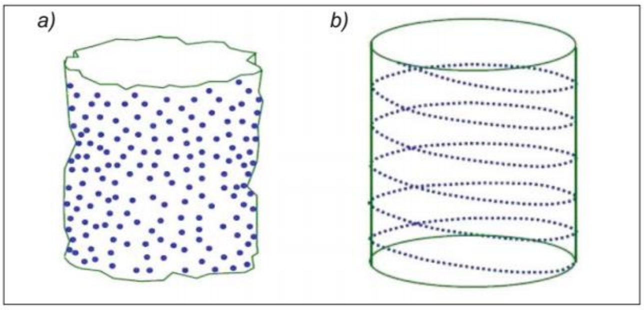

Fig. 4. Point strategy (*a*) and helical strategy (*b*) [1]

The helical strategy is not described in the standards, but relatively often is found in practice. It constitutes a compromise between the strategy of cross-sections and longitudinal sections. The point strategy and the helix strategy are presented in fig. 4.

Strategies presented in figs. 2-4 allow for even surface sampling. This means that the entire surface of the object is sampled in the same way. Thus, in the case of cross-sectional views, longitudinal sections and "cage" strategies, the linear distances between cross-sections and angular distances between longitudinal sections are identical. Also the helix strategy according to the literature data allows even sampling, as the parameter that describes the sampling density, i.e. the helix angle, remains constant during the measurement. The practical application of the point strategy also requires an approximately uniform distribution of the measurement points. Therefore, this strategy can also be included in the strategy of even sampling. In this case, the measurement points can be selected randomly or using numerical methods, e.g. by using the Hammersley sequence [2].

In the case of measurements of deviations of the shape of highly precise elements, the tolerance of roundness or cylindricity is a few micrometres, or even less. Specialist systems based on the principle of measuring radius changes are used, e.g. Talyrond 365 from Taylor Hobson - fig. 5.

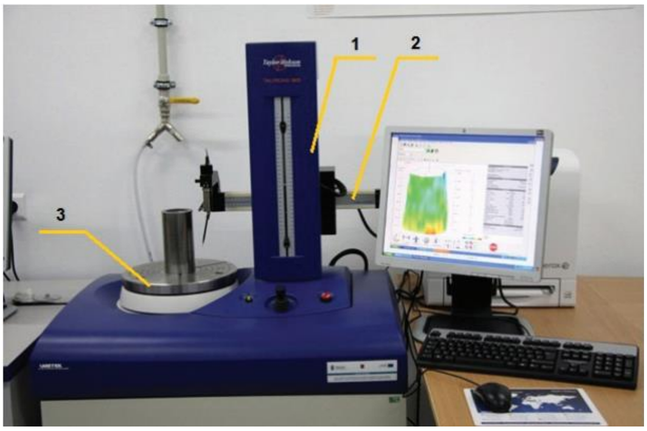

Fig. 5. Specialized system for measuring the roundness and cylindricity profiles using the Talyrond 365 radial method by Taylor Hobson: 1 - column, 2 - horizontal arm, 3 - rotary table

Instruments using the principle of radius change measurement are often called radial short. In this group, one can distinguish systems with a rotary table and a rotating sensor. The object being measured is placed on the measuring table. It is important that the axis of rotation of the object coincides with the axis of rotation of the table or sensor (depending on which of these elements can rotate). Therefore, the proper measurement is always preceded by the centering of the object, and the measurement of deviations of cylindricity - also leveling it

The most popular radial instruments enable the application of a uniform sampling strategy, such as: cross-sectional strategy, longitudinal section strategy and helical strategy. The "cage" strategy is only available in the software of selected instruments, e.g. in the Hommel Etamic Roundscan 535 system or Taylor Hobson Talycat instruments modernized at the Department of Mechanical Technology and Metrology at the Kielce University of Technology.

Radial devices enable a comprehensive analysis of measurement results, both qualitative and quantitative. What's more, if a series of measurements is carried out, statistical analysis of the results is possible. An example of the measurement protocol for deviations of cylindricity generated by the Talyrond 365 system is shown in fig. 6.

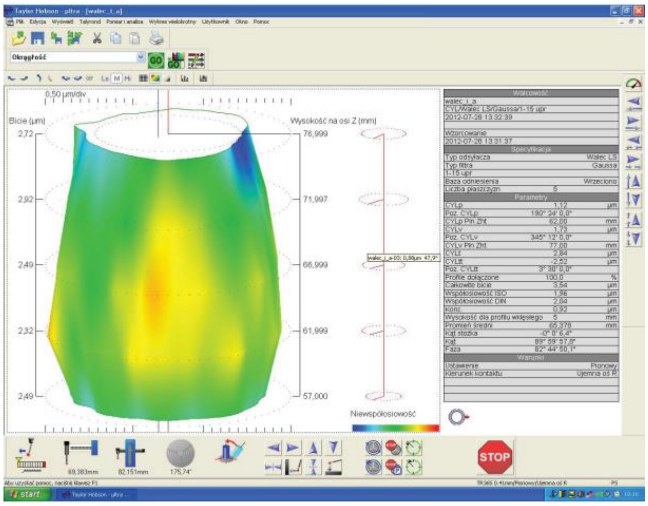

Fig. 6. Measurement protocol for deviations of cylindricity generated by the Talyrond 365 instrument software

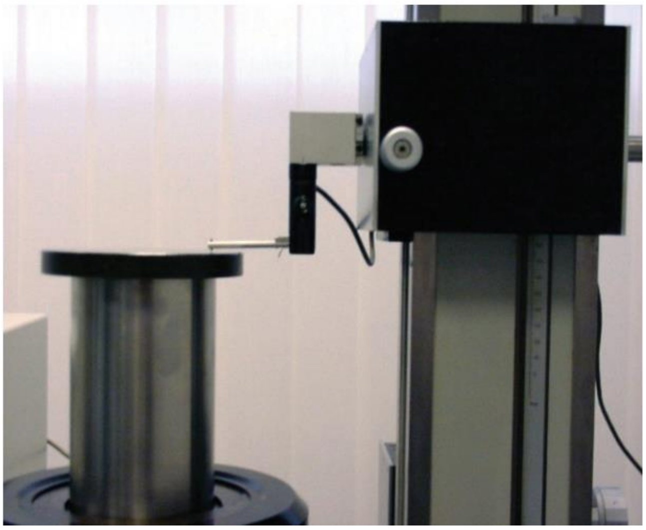

Fig. 7. Flatness measurement of the face of the cylindrical element on a radial device

Modern radial systems also make it possible to change the position of the measuring sensor's axis from vertical to horizontal. The horizontal position of the sensor makes it easier to measure the deviation of straightness or flatness of the face of the cylindrical element, as shown in fig. 7.

The report of measurement of flatness deviation made on a radial device is shown in fig. 8. During this measurement the object performs a rotary motion, while the sensor moves linearly. Submitting these two movements allows you to probe points from the face of the object along the spiral path.

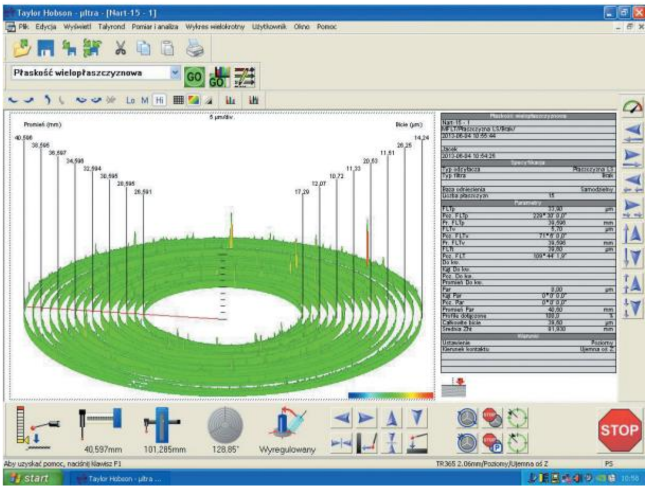

Fig. 8. Report of measuring the deviation of flatness of the forehead

Uniform sampling strategies are extremely useful if the analyzed surface is characterized by a fairly regular distribution of inequalities. However, in some cases, significant inequalities only occur in certain areas of the surface. Such area should be sampled using more points than the other fragments. Numerous research centers are working on developing strategies that would allow for denser surface sampling in areas where significant local unevenness may occur.

Strategies for matching the assumed inequality distribution

These strategies consist in the fact that the distribution of measuring points is matched to the measured area on the basis of the expected distribution of inequalities. Information about the technological process, as a result of which the analyzed area was created, in many cases allow predicting the most probable locations of inequalities. For example: in the cross-sections of cylindrical elements subjected to the rolling process and placed during this treatment in the three-jaw self-centering handle, the third harmonic is often dominant. Another example are elements placed during machining in centers. Then, sadness deviation along the forming element is observed.

An example of using a strategy based on the anticipated saddle error is shown in fig. 9.

Strategies for matching the predicted inequality model can be designed based on data from initial measurements or assumed distribution of inequalities. An example of the first of these methods is the harmonic matching concept described in [4].

It uses statistical assessment of the characteristics of individual Fourier components of the outline to define the least number of data points of measurement data that would allow a reliable assessment of deviations in the shape of the tested surface. The second method is presented in paper [5]. Here a preliminary model of surface shape errors is assumed. This model is described mathematically by means of a combination of a set of basic functions (e.g. polynomials, Fourier components or own functions). It is then used to generate the coordinates of the measurement points. After the measurement, on the basis of the outline value at predefined points, the coefficients of the assumed linear combination model are calculated (taking into account the uncertainty of matching). These coefficients are used to reconstruct the image of the entire surface.

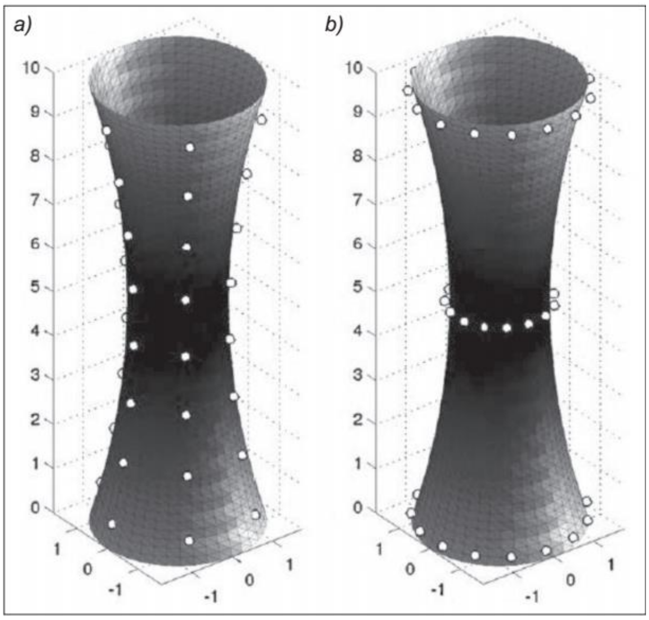

Fig. 9. Strategy of measuring the outline shape of an element with the dominant saddle-test error: *a*) strategy usually used, *b*) strategy developed on the basis of the expected inequality model [3]

Strategies based on the predicted inequality model are not widespread in industry. They are constantly subject to research in various scientific centers. In the scientific literature, these strategies are usually applied based on data sets obtained during the measurement of objects using coordinate measuring machines.

Adaptation strategies

The adaptive strategies described in the scientific literature are of an iterative nature. In strategies of this type, sampling is carried out in several stages. The first of them is preliminary measurement with the use of even sampling. Then, on the basis of obtained measurement data, an algorithm is used, which searches for areas of the surface where there is a risk of significant local inequalities. The next step is to carry out additional measurements in these areas. Next, the previously calculated coefficient is calculated, the value of which indicates whether the measurements are to be completed or whether they should be continued using denser sampling.

Such a procedure often uses the so-called Krige's models. The name of these models comes from the South African engineer who first used them in the sixties of the twentieth century. Currently Krige models are used to predict the location of subsequent measurement points. The signal is modified in them by means of a set of basic functions and their coefficients supplemented by a random component with an expected value equal to 0, for which the covariance of the input and output signals remains constant [6].

Fig. 10 contains an algorithm showing the application of the Krige model in the evaluation of shape deviations by means of an adaptive strategy, proposed in the paper [6]

In addition to the Krige models, the coordinates of the points in which the surface is to be sampled can be carried out using optimization techniques, e.g. Tabu Search or Hybrid Search methods [7].

The adaptation strategies described did not go beyond the phase of laboratory tests. As in the case of strategies based on the predicted inequality model in the scientific literature, the application of these strategies to the measurement of shape deviations by means of coordinate measuring machines is described above all.

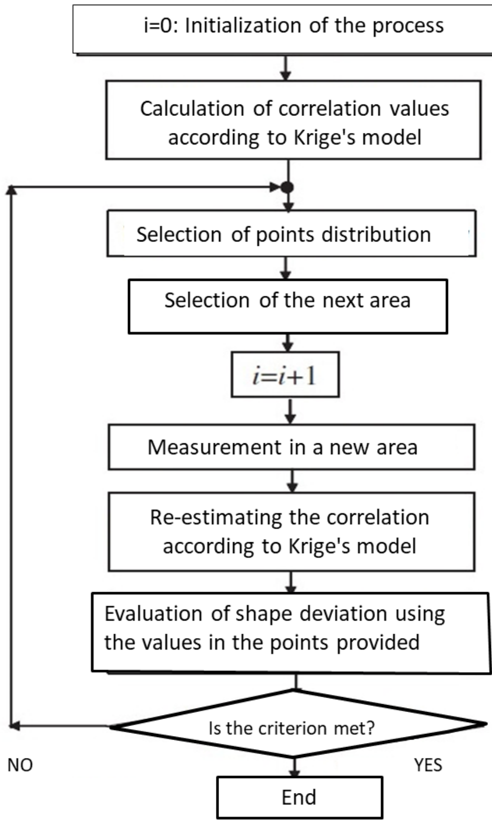

Fig. 10. Algorithm of the Krige model application for the development of the strategy of adaptive measurement of shape deviation, proposed in the paper [6]

Conclusions

Even sampling strategies are well recognized and easy to apply. However, they have some drawbacks. First of all, the high density of sampling points significantly extends the measurement time, which is an undesirable effect, especially on the production line. For this reason, many research centers are working on strategies that would allow for denser sampling only in selected areas, without losing information about surface shape errors. Presented strategies based on the assumed inequality model have not yet emerged beyond the laboratory testing phase. They have many advantages, but also serious limitations. First of all, in real technological processes there are disturbances, which may cause that the distribution of inequalities of the object will differ from the predicted one (especially when the process becomes statistically unregulated).

In turn, adaptation strategies are iterative and therefore complex in terms of computation. Their use on coordinate measuring machines can be troublesome due to the risk of collision between the measuring tip and the element being measured [8-10]. It results from the fact that sample points can be different in general for elements whose nominal dimensions are the same. What's more, most CMMs are equipped with scanning heads that allow you to measure the profile in a very large number of points in a relatively short time. Thus, the methods in which areas are searched that require denser sampling on 2D outlines are slowly becoming useless. They are still used in the case of measurements with electrostatic heads, but these heads are now rapidly displaced by scanning heads.

It can be concluded that the problem of developing measurement strategies that would take into account the distribution of surface unevenness requires intensive research work, both theoretical and experimental.

The article was developed as part of a research project entitled "Theoretical and experimental problems of integrated spatial measurements of the surface of objects", No. 2015/19/B/ST8/02643, ID: 317012, financed by the National Science Center.

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Translation of scientific articles, their computer composition and publishing them on the website www.mechanik.media.pl by original articles in Polish is a task financed from the funds of the Ministry of Science and Higher Education designated for dissemination of science.

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